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ORIGINALLY

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CORRIGENDA TO VOL. 68.

Page 270, col. 1, second line above equation (42): For " F " read " E."

,, 274, Fig. 6: The ordinates should be multiplied by 10 000.

,, 447, col. 2, tenth line from bottom of page: *For* " voltage-drop " *read* " voltage."

,, 452, col. 1, sixth line from bottom of page: *For* " condenser C_s and resistance r_s " *read* " condenser C_a and resistance r_a."

,, 457, col. 1, line 4: For " n " read " f."

,, 462, col. 2, Fig. 23: *For* " Table 5 " *read* " Table 6."

,, 468, col. 1, eighth line from bottom of page: *For* " 35·5 " *read* " 33·5."

,, 470, Table 9, col. 7: *For* " − 0·15 " *read* " − 0·015."

,, 471, col. 2, line 3: Read " $R = 1{\cdot}79$ ohms $l = 3\,467$ nautical miles."

,, 737, col. 2, line 20: *For* " positive " *read* " negative."

,, 737, col. 2, line 21: *For* " negative " *read* " positive."

,, 738, col, 1, first line above Fig. 4: *For* " negative " *read* " positive."

,, 738, col. 1, seventh line from bottom of page: *For* " positive " *read* " negative."

,, 744, Table 9, col. 7, sixth line from bottom of column: *For* " 29 " *read* " 32."

,, 1126, col. 2, thirteenth line from bottom of page: *For* " scientific " *read* " unscientific."

,, 1173, col. 1, thirteenth line of Mr. Dunton's communication: For " $\sqrt{[(s/a)^2 + 1 - 1]}$ " read " $\sqrt{[(s/a)^2 + 1]} - 1$."

T. F. Purves

PRESIDENT 1929-1930

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INAUGURAL ADDRESS

By Colonel Sir THOMAS F. PURVES, O.B.E., President.

(*Address delivered before* THE INSTITUTION *24th October,* 1929.)

I shall not attempt to express here my sense of the honour which you have conferred upon me in electing me to the position of President of this great Institution. I accept it with warm appreciation as a tribute of friendship and good will to myself, and as a gracious compliment to the branch of public service engineering to which almost the whole of my working life has been devoted.

It is no light matter to step into the shoes of a long line of illustrious predecessors many of whom have written their names enduringly in the history of science and of the material progress of our country.

I cannot hope to add to the lustre of those well-worn shoes, but I draw some comfort from the thought that they must surely by this time have acquired the habit of carrying their wearer automatically in the paths of wisdom and discretion.

THE INSTITUTION.

At any rate I can promise, with assurance, that you will not find me lacking in endeavour, or in loyalty to the causes which the Institution has at heart and which it exists to further.

Its work is on a high level, and we are all entitled to a sense of gratification and pride in its position and its prospects. For the past 8 years it has enjoyed the dignity of a Royal Charter, the grant of which signalized the completion of 50 years of useful life since its foundation in the year 1871. With a membership roll now approaching 14 000 it is the largest professional institution in the Empire, and it is still rapidly advancing, both in numbers and in influence.

It has shown its interest in, and its desire to help, every branch of electrical industry by the recent formation of specialized autonomous sections, which enable their members to obtain all the advantages of direct association and discussion with colleagues having the same immediate interests, while at the same time they enjoy the general professional services, and the powerful backing, of the main Institution. As a result of this policy the Wireless Section and the Meter and Instrument Section have already been launched under conditions which promise permanent satisfaction and success.

At the close of last session the Institution adopted a revised classification of its grades of membership which, I venture to think, has brought its constitution into greater harmony with the conditions of to-day, and has provided a framework on which it will be able to develop itself for many years and to play, I hope, a worthy part in the work which kindred institutions throughout the world are doing to foster the progress of the great profession of engineering, upon which the welfare of nations so greatly depends.

THE ELECTRICAL ENGINEER.

The sphere of the engineer, like that of science, has no definable limits. No matter what the subject of action may be, it is his business to think out the process of "least action" that will secure the desired result. The conservation of energy is always his goal—the expenditure of time, money, and material in the most effective way.

The application of electrical science to industry and to the general service of the human race has become a tremendous undertaking, still young and immature, but growing and branching in unexampled fashion and destined, beyond any question, "to inherit the earth and subdue it," for as long as mankind endures.

Just as the science of electricity is penetrating, and shaping anew, the whole realm of fundamental physics, so will its engineering penetrate the whole field of industry and mould its practices. It has been well said that "the science of to-day is the engineering of to-morrow," and it is our business to make sure that, in the electrical field, engineering shall follow closely and continuously on the heels of science.

EDUCATION.

A great responsibility rests to-day upon the teachers of scientific technology, whose task it is to equip the normal human brain, in a limited term of years, with the elements of knowledge which will best enable the coming generation to take up and carry forward the intellectual side of the world's constructive work. More and more has science become the basis of intellectual advancement, and more and more has it become essential to make a rigorously limited selection of the conceptions of nature's structure and law which can most helpfully be gathered together and impressed upon the mind of youth as a directive guide to the lines of well-balanced progress. No longer is it possible to turn out a finished student into the stream of life. We shall have to be content—and we may well be content—if the graduates of our science and engineering colleges are men with sound fundamental knowledge and with faculties trained to continue the processes of absorption and assimilation; men who know what the tools of science and technology are and how they can be used, and who will be all the better if they have some general idea of the wonderful visions of ultimate things that the most advanced minds of the world are glimpsing to-day from mountain-tops that, to most of us, are still away in the far distance.

The need for specialization is, of course, greater than ever and will go on increasing, but the same may be said of the disadvantage of too early specialization. It is generally the hard and continuous specialist who "delivers the goods," but he can only do that after his college training has been supplemented by intimate contact with the problems of his profession.

The time is rapidly approaching—if, indeed, it has not already arrived—when the teaching of the detailed applications of technology to professional subjects, in full-time educational establishments, will have to be abandoned. The fundamental technique of electrical science and engineering, and its general applications, already furnish more than sufficient material for a full college course. The student will have to wait until he has left college, and has selected and entered his branch of the profession, before he can really begin to learn how his knowledge must be applied in practice. He will learn it then all the better, and all the quicker, because he will be in touch with actual things and actual needs, in association with working experts, and will have the continual stimulus of his natural desire to advance himself in his chosen career.

I should like to appeal to all employers of young electrical engineers to recognize this condition—as, indeed, many already do—and to encourage its application. They should not expect youths straight from college to do useful productive work from the commencement. They should rather be glad to find that a young man knows nothing whatever of how to apply his education to the special problems of the industry, if it means that the precious years of his college courses have been devoted entirely to equipping him with basic knowledge which he would have much less effective opportunity of acquiring in later years, and which has increased his personal potentialities and his aptitude to acquire and use the special knowledge that his experience in the industry will show him to be necessary.

In my own personal sphere I experienced no particular pleasure in finding that a young man who has come to the Post Office from one of our engineering universities has been studying practical telegraphy or telephony or radio communication. On the contrary I am inclined to feel that it will probably take him some time to readjust the focus of what he has learned, and that he might have been better equipped for a life-work in association with those subjects if the time he had already spent in studying them had been devoted to general electrical science and the mathematics of wave propagation. Every branch of the electrical industry should be prepared to train the young men who enter its ranks in the details of their profession, to encourage systematic post-graduate study, and to guide it into the most fruitful channels. It means appreciable immediate sacrifice on the part of employers, but in the ultimate interests of progressive national efficiency it is richly worth while.

We who are getting on in life and have had experience of simpler days, cannot but feel a keen sense of sympathy with the young recruits who are now flocking to join us. The calls made upon them are going to be very severe. The mass of knowledge to be assimilated before one can get reasonably abreast of the leading waves of progress becomes ever greater, and the task of the pioneer who would use them as a point from which to plunge further "into the brown" of the unknown becomes ever harder. I have heard the hope expressed that some day, perhaps in the far-distant future, the balance between Nature and Man will be finally struck. In the meantime, however, there is no escape; we have still to toil on, and we have finished with the casual age.

ELECTRICAL COMMUNICATIONS.

In considering to what particular subject I should direct your attention to-night, I have not been unmindful of the sound old adage that the cobbler is generally well advised to stick to his last, and, on that principle, I propose to say a little on some aspects and activities of the engineering of electrical communications that have contributed to the wonderful expansion of the range of telephony which has taken place since the last reference was made to the subject in an address from this chair on the occasion of Mr. Gill's Inaugural Address in 1922.*

At that time the only places abroad with which a British telephone user could communicate were Paris and Brussels. To-day one can speak from this building, or from any other telephone in this country, to nearly 90 per cent of the telephone stations of the world, and the statement that speech has been interchanged between any two points on the surface of the globe is no longer sensational. The problem of world-wide telephony has now advanced to that of providing public services in such a way that they can be depended upon to operate as and when required by the needs and convenience of the users.

Electrical communications engineering represents the main field of what is known as "light current" engineering. It was the first branch of electrical engineering to be developed into a public service and, as you all know, it was as the Society of Telegraph Engineers that our present Institution was founded in 1871.

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* *Journal I.E.E.*, 1923, vol. 61, p. 1.

Rapid developments in the generation and utilization of electrical energy on a large scale soon extended the scope of electrical engineering, and the scope of this Institution, far beyond their original narrow boundaries, in ways so striking and so resounding that the mere "milliampere man" began to feel that he had been relegated to quite a humble position among his co-workers in the electrical field. In more recent years, however, he has felt increasingly inclined to lift up his head again. While the power engineer has gone on from strength to strength, piling up volts and amperes on a great scale and doing marvellous things with them, the "light current" engineer has achieved dignity in the opposite direction by converting himself into a micro-volt and a micro-ampere man. I think he may reasonably claim that the intricacy of the problems which confront him and the delicacy of the means and methods which he has devised for dealing with them, will bear comparison with those of any other branch of electrical engineering. The dissemination of power and light, and high-speed loads, by electrical means are great achievements in the service of humanity, but the communications engineer may find inspiration in the reflection that his *métier*—the transmission of thought, intelligence and information—is a no less worthy contribution to the status and to the legitimate pride of the electrical engineer.

Telegraphy and Telephony.—The present position of the Telegraph Service in this country is most interesting and might well have supplied the material for an address, but I shall have to leave it untouched and pass at once to the branch of communications engineering which at the present day provides the most extensive field of operations, namely, the transmission of human speech by the public intercommunicating telephone. It is a branch which involves particularly intimate relations between the supplier and the user of the service. The concern of the public in its efficiency is direct and personal. Any failure to provide without delay for the easy interchange of conversation, on business or pleasure, with any desired correspondent is a flagrant failure of function which may sometimes be excused but can never be concealed. As a result, public telephone services are generally carried on in a stimulating atmosphere of critical vigilance on the part of the users, and this country is assuredly no exception to the rule.

The story of the invention of the telephone, and of the successive stages of its development into an essential tool of business and social life, has often been told and I need not attempt to repeat it. The progress of telephone exchange design is a typical example of the gradual displacement of manual effort by the machine. Multitudes of time-saving inventions have contributed to the progressive restriction and refinement of the part played by the human operator in the working of an exchange.

The Automatic System.—At the present day the installation of full automatic systems, in which even the selection and interconnection of the lines is performed by electromagnetic machines, is being pushed forward with increasing momentum all over the world, and in all kinds of localities from the smallest villages to the largest cities, with improved results in the economy and quality of the service—sometimes, unfortunately, obscured to some extent by the occasional special difficulties of the transition period in large areas where the change-over has to be made in more or less piecemeal fashion. I am pleased to be able to say that the system specially evolved for the service of London, which I had the privilege of describing in advance to this Institution nearly five years ago,* is realizing in practice the hopes that had been founded upon it. Twenty-one large exchanges with an aggregate capacity for about 132 000 lines have already been brought into service in London, in addition to the main junction switching-centre known as the "Mechanical Tandem" Exchange. The provision of 26 further exchanges, with capacity for about 125 000 lines, is now in hand and it is expected that equipment for about 50 000 lines will be added annually to the London automatic system until the conversion of the area, which at present has a total of about 650 000 working telephone stations, is completed and all the manual exchanges are removed. In order to effect plant economies it is proposed to provide auxiliary automatic tandem switching centres, and an automatic switching centre for "Toll" circuits is also contemplated. It is anticipated that in 7 years' time the number of automatic exchanges in the central London business area will have reached 100, leaving only 5 manual exchanges for subsequent conversion. This great grafting and transforming operation—one of the greatest and most complex ever attempted in the electrical field—has necessarily to be carried through while the London telephone organism continues to perform without interruption its function of providing service to all its subscribers by day and by night, and I can say quite definitely that the difficulties and mishaps which have so far been experienced have been considerably less than one was inclined to anticipate at its inception.

The Telephone Exchange System.—It may be mentioned here that in this country as a whole we now have 163 automatic exchanges in operation in urban areas, with an aggregate capacity of about 300 000 lines (say 500 000 stations), and that the planning and construction of 126 further exchanges is at present in hand. The manual system remains in use at the present moment at 487 exchanges having a capacity exceeding 300 lines, and at 3 790 smaller exchanges, serving, in all, about 1½ million stations; and exchange equipment of the automatic type capable of serving about 100 000 lines is being installed annually. It is of interest to record that, at the present rate of development, one new public exchange and about 1 000 new telephones are installed for each working day throughout the year. Rural exchanges have, until quite recently, been entirely manual, but automatic equipment for exchanges serving small communities has now been designed on a basis which promises favourable economic results, and a start has been made in its installation. Up to the present, 60 such village automatic exchanges have been brought into operation, and about 110 more are in hand. The minimum exchange unit provides for 25 lines, and further units can be added up to a maximum of 200 lines. They are accommodated in simple, extensible buildings of the "garage" type and are left unattended. A maintenance man normally visits them about once a week for the purpose of attending to the power plant, renewing the supply of calcium chloride by which the air of the building is maintained in a dry state, and making a general maintenance inspection. One important advantage of these small automatic exchanges is that they provide an all-night service, both locally and to the outer world via junction lines to the nearest "parent" exchange. The expense of providing night attendance at village exchanges of the manual type is invariably out of all proportion to the insignificant number of night calls to be dealt with, and is generally prohibitive.

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* "The Post Office and Automatic Telephones," *Journal I.E.E.*, 1925, vol. 63, p. 617.

Economics.—The telephone engineer, like his confrères in many other branches of the electrical industry, is called upon to undergo much heart-searching and brain-twisting on the subject of the economics of his constructive work. He has to steer the best possible course between over-provision of plant for the future on the one hand and under-provision on the other, and I think he has some reason for the idea that in the case of telephone plant the course between Scylla and Charybdis is peculiarly narrow and hazardous. The telephone engineer's word "plant" seems indeed a specially appropriate term to apply to the material of a telephone system. It is always growing; always pushing out fresh tentacles in some directions and withdrawing them at other points. For every 100 new stations he joins up he finds, on the average, that about 30 have gone out of service and that partially useless lines are thrown back upon his hands. Conditions affecting development were not particularly troublesome in the early days when exchanges were small and the lines consisted of open wires strung upon poles or overhouse fixtures, which could be supplemented or rearranged at small cost, but modern conditions have sadly reduced the element of flexibility. Exchanges are now immovably established in large special buildings, and the many thousands of lines radiating from them are embedded in cables carried beneath streets and roadways that can only be opened at great expense and inconvenience. The exercise of the utmost possible foresight in determining the primary quantities and lay-out of plant in a telephone area, and all subsequent additions to it, has thus become a *sine qua non*. If the annual increase in the number of telephone users in a section of the area, and the probable trend of the prices of money and materials, are known with approximate accuracy, one can calculate the "economic periods" for which ducts and cables should be provided, that is to say, the quantities which should be laid at one time in order that the "ultimate" development of the area will be provided for by the minimum aggregate expenditure. The ultimate period is taken as 30 years ahead in the case of exchange plant, and 20 years ahead in the case of underground plant, and the calculations are made on the basis of the "present value" of the annual charges for interest, depreciation and maintenance, that would apply to the plant if constructed in quantities designed to meet the requirements of various intermediate periods. Detailed surveys which take all the known social and commercial factors of growing and changing localities into account have therefore to be made and systematically revised from time to time, and on these are based and maintained what are known as the fundamental lay-out plans applying to each area. These show the number, capacity and position of the exchanges needed to serve the area with the minimum mileage of costly copper conductors for subscribers' and junction lines, the local area to be covered by each exchange, and the rearrangement of exchange boundaries consequent upon the opening of each additional exchange, the routes to be taken by duct lines, and the numbers of ducts to be laid, etc.

The highly developed methods pursued in the determination of plant lay-out, in association with power distribution as well as with telephone distribution, were fully stated in the papers read before the Institution last session by Capt. Donaldson and Capt. Hines on the "Anticipation of Demand" and in the interesting general discussions which resulted.* The object aimed at is, of course, the substitution of scientific calculation for intelligent guesswork, and there is no question that the cost of elaborate and careful development study is richly repaid to such telephone administration as the Post Office, which sinks new capital to the amount of about 10 million £ annually in the provision of additional plant to meet its growing requirements, and which would certainly expend very large sums ineffectively if rule-of-thumb methods were depended on.

Telephone Development.—The number of telephones in use in Great Britain is far smaller than it ought to be in a great commercial nation such as this, and, unfortunately, the same remark applies to the amount of use made of the telephones actually in service. Village exchange lines cannot be expected to originate much traffic, but it is very disappointing to find that the total traffic originated at exchanges having 300 lines and upwards only amounts to an average of 5·3 calls per line per day, which is much below the average in many other countries, and it shows no tendency to rise. This cannot be attributed to an unsatisfactory grade of service, because the quality of the service given in this country has for several years been good and the call fee is low. Reluctance to hire a telephone, and to use it after it has been hired, may be a British characteristic, but I am quite sure that it is not an unchangeable characteristic. Much evidently remains to be done to bring home to the minds of our citizens the manifold business and social services which the telephone can render.

The position of this country among telephone users will not be improved merely by pouring more capital into the system. This would be putting the cart before the horse, and the additional interest and other annual charges thrown upon the accounts would soon convert the business into a losing one unless the public market for telephones and telephone service were at the same time correspondingly stimulated. It is only upon the estimated results of new salesmanship expedients that increased expenditure of capital can be judiciously regulated and the additional plant required be made available neither too soon nor too late. The system already carries and maintains the margin of spare plant required to meet continued development at the present rate of about $8\frac{1}{2}$ per cent, cumulatively, per annum. This rate of increase is in itself a healthy one and compares well with the progress which is being made in other countries, but it is not sufficient to enable Great Britain to retrieve its arrears of telephone development in a reasonable time.

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* *Journal I.E.E.*, 1929, vol. 67, p. 594.

The Post Office has adopted, and is continuing, various expedients to stimulate public interest in the telephone. Intensive personal canvassing, coupled with wide distribution of postcards and pamphlets, has recently been tried in a number of areas. It cannot be said, so far, that these efforts have achieved striking success, but the Post Office takes a hopeful view of the future and has faith that the public will increasingly find the telephone a necessity, both in business and in private life.

The Line.—A feature of communications engineering worthy of remark is the manner in which electrical considerations affecting the transmission line have advanced into prominence. Not very many years ago the indoor apparatus associated with telegraph and telephone systems was regarded as the complex subject, and as the main field for study and invention. Lines were looked upon as simple things, constructed on mechanical principles, and involving chiefly the consideration of strains and stresses, wind pressures, temperature variations of catenaries, and the like. One was expected to provide lines of sound physical design and construction, and then to make the best possible use of them by improving and refining the traffic-handling apparatus. The situation to-day is very different. Notwithstanding the wonderful development and performance of the apparatus of modern communication systems, it is overshadowed by the results of the attack which is now being made by research upon the properties with which the line, the transmitting medium and its adjuncts, may be endowed. All the weapons of the most advanced electrical and mathematical technique are being employed, and it may fairly be said that the contributions which the study of telephony has made to alternating-current transmission theory are of first-class importance to electrical science and practice in general. It is to the study of the ideal wave-transmission line, and to the efforts made to realize its qualities in practice, that we owe nation-wide telephony and the striking progress which has recently been made towards telephony of world-wide range.

Oliver Heaviside.—Our great pioneer in this matter, Oliver Heaviside, was unfortunately not endowed by nature with the faculty of exposition in a diluted form, or perhaps even with much spontaneous inclination to build bridges by which his less accomplished contemporaries could readily follow him to his conclusions and seize upon their practical applications. Recognition of the gifts of his genius to electrical science has come in full measure, largely within his lifetime but rather tragically late. Much of what was truly admiration he regarded as a somewhat unwelcome expression of sympathy. He was elected an Honorary Member of this Institution in 1908 and was the first recipient of its Faraday Medal in 1922, but I have often felt that if the contemporary appreciation of his work had been more adequate and friendly we might have had him amongst us for many years as an active and a jolly working member; if so, our loss has been great.

Loading.—Prof. Pupin has the honour of being the first to show how the harvest of Heaviside's theorems might be reaped by the practical engineer; and the great advance in the telephone art represented by the addition of inductive loading to long-line circuits will always be associated with his name, as well as with the names of Campbell and others who followed him very closely and with great effect.

Pupin showed that an approximation to the balance of line characteristics necessary for the transmission of complex electromagnetic waves without phase distortion ($R/L = G/C$) could be obtained in practice by inserting inductively wound loading coils at intervals which must provide not less than π coils in the shortest wavelength to be transmitted. In practice this is governed by the highest frequency of speech which it is necessary to transmit in order to preserve good tone and articulation, say 2 500 periods per sec. The inductance added by loading increases the electromagnetic inertia of a line and raises its " energy transfer ratio," thereby tending to preserve the amplitude of the transmitted waves and so reduce the attenuation characteristics of the line. In practice, loading-coils are generally inserted at very accurately spaced intervals of about 2 000 yards, and the inductance of the coils is so chosen that the loaded circuits will transmit all frequencies up to about 3 000 per sec. This upper limit is known as the " cut-off point " of the cable and should be about 30 per cent above the highest frequencies needed for good reproduction of speech. In an underground cable with typical loading, say with an inductance of about 155 mH per mile, the propagation speed will be about 16 000 km per sec., giving for the mean speech frequency of about 1 200 cycles a wavelength of about 13 300 metres. Heavier loading reduces the propagation speed and correspondingly reduces the number of coils per wavelength with a given spacing of coils; the cut-off point is correspondingly lowered. On the other hand, lightening the loading increases the propagation speed and raises the cut-off point; a movement in this direction has been occasioned, at some sacrifice in the matter of attenuation, by recent demands for the provision of circuits capable of carrying the higher frequencies—up to 8 000 or more per sec.—required for the effective transmission of music for broadcasting purposes, and of pictures.

The attenuation of open-wire lines can also be reduced by the addition of inductive loading. Since the propagation speed of electromagnetic waves on such lines approximates to the speed of light, the wavelength at any given frequency is correspondingly great, and it suffices to provide loading coils at intervals of 10 to 15 miles. Effective loading, however, calls for a high degree of stability in the leakance of the line, and this factor is one which necessarily varies considerably in the case of a wire carried on open insulators, especially if the climate is damp and variable. For this reason, and also for the reason that the policy of placing long trunk telephone-circuits in underground cables was adopted in this country as soon as loading methods matured, the loading of open-wire routes has never been resorted to here, and it is now being generally abandoned elsewhere.

So far as underground cables are concerned, the introduction of loading immediately increased the practicable range of telephone communication to 3 or 4 times its former limits. Its application is, however, both costly and troublesome. At intervals of about 2 000 yards an underground manhole chamber has to be substituted for a simple straight-through buried joint, in order to accommodate the sealed cast-iron pots in which the loading coils are fitted, and into and out of which the cables have to be led. Many hundreds of loading coils have frequently to be accommodated in a single chamber in which much intricate jointing and plumbing work has to be done under trying conditions.

One would rejoice to find it possible to supersede inductive loading by some less formidable means of reducing the attenuation and the various forms of distortion which appear in unloaded underground cables. Methods by which this may eventually be accomplished, by compensating devices at the ends of the cables, are appearing and coming into use, in the search for further improvements in the transmission line. Phase distortion due to the unequal speed of propagation of the various component frequencies making up the complex speech wave, which would be eliminated by perfect loading, can also be corrected by the introduction, at the terminals of the circuit, of artificial line networks in which inductance and capacity are so disposed that the propagation irregularities natural to the cable are reversed. The lower-frequency components which will arrive too soon, after passing over a cable in which the ratio of inductance to capacity is too small, may thus be retarded and stepped back into their original phase relationship with the higher frequencies which have travelled more slowly along the line.

Similarly the disproportionate attenuation to which the higher frequencies have been subjected in the cable may be corrected by terminal networks, so designed that the lower frequencies are over-attenuated and brought down to approximately their original proportions in the complex wave.

There remains the difficulty of compensating for attenuation as a whole, since the omission of loading coils and the introduction of such devices as those already mentioned—all of which fritter away the energy of the speech wave—will have increased the attenuation factor of the circuit to 8 or 10 times that of the loaded cable line.

It may be thought that the energy loss can readily be made good by the almost unlimited possibilities of amplification now at our disposal; but in practice the amount of amplification that can be applied at any point in a telephone circuit is severely limited by the necessity for avoiding crosstalk between one circuit and another. It is necessary to pack hundreds of pairs of conductors closely together within the lead sheath of a single cable, and the problem of avoiding crosstalk, even at the ordinary energy levels of telephony, by maintaining the greatest possible symmetry of position and uniformity of electrical characteristics of all conductors throughout the length of a cable between repeater stations, is one which calls for the greatest care and accuracy in manufacture. It has been necessary also to devise an elaborate system of testing the resistances and various cross-capacities of all the pairs in each cable length after the cable is drawn into ducts, in order that pairs having high and low characteristics in each length, and successive groups of lengths, may be selected and matched together in such a way that variations in the manufacturing lengths may be made to cancel each other out as far as possible in the completed cable.

All that can be done at the successive amplifying points in a long line is therefore to restore the energy to a level not much exceeding the energy output of the subscriber's telephone.

Any two adjacent circuits near the end of a telephone cable between repeater stations are liable to be carrying, respectively, the comparatively high energy of speech from the near end amplifier and the much attenuated energy of speech from the far end. In practice, a ratio between the sent and received power of about 40 to 1 is maintained on 2-wire circuits. If this ratio were much exceeded, either by adopting a higher level of output or by allowing the received energy to sink to a much lower level before amplification, the crosstalk from the near end would cause proportionately greater interference with the intelligibility of the speech received from the far end. Each repeater station along the line would contribute its quota of additional crosstalk, to be amplified by successive repeaters, and chaos would result. The present system by which amplifying devices are used merely to restore the normal minimum energy of received speech to the normal level of transmitted speech, by an amplification averaging about 40 to 1 at each point, enables repeater stations to be installed 50 miles or more apart. If unloaded cables were used, the stations would have to be so close together that their cost would far exceed the cost of loading the cables. The answer to the frequent question whether amplifying and distortion-correcting devices have sounded the death-knell of inductive loading is therefore decidedly in the negative, and it is clear that the art of cable manufacture will need to achieve another order of freedom from crosstalk, before an answer in the opposite sense can be given.

This is not intended to imply that telephone cable design and manufacture are in any sense open to the charge of being non-progressive. On the contrary, steady improvement is being made in the mechanical symmetry and electrical uniformity of the circuits and in the means of providing circuits for special purposes, as well as in the economics of production.

The Telephone Repeater.—Apart from conductors and cables, as such, the study of the transmission line must be credited with a wonderful range of inventions designed solely from the standpoint of improving it as a transducer, and included strictly within the limits of the line quadripole.

Facile princeps among these must be placed the telephone repeater, developed on the basis of De Forest's conversion of the Fleming valve into a triode amplifier and since improved in all directions by many inventors and engineers. For many years an effective repeater which would regenerate speech currents, and pass them forward automatically in the manner of our well-known telegraph repeaters, had been longed for by telephone men who were straining to extend the range of communication. Never did the seed of an invention fall upon soil better prepared to receive it and to promote its rapid growth, and never was a long-standing fundamental problem solved in a more complete and satisfying manner. It harnessed for the first time the simplest known element of nature, the flying electron, not, indeed, an agent independent of time and inertia, but one making a demand upon these conditions that, from our gross material standpoint, is almost infinitely small. Its practical applications in telephony were taken up at once with unbounded enthusiasm on all hands.

England was the only nation in which an appreciable proportion of trunk telephone circuits had been laid in underground cables before the advent of the valve, and the range of such communication was limited to a little over 200 miles. To reach the Liverpool and Manchester areas from London, loaded cables carrying wires having a weight of 300 lb. of copper to the mile were in use. In a very short time the lay-out of the trunk system was entirely replanned on the basis of using light-gauge cable conductors—20 lb. and 40 lb. to the mile—working through repeater stations, and an era of rapid trunk cable construction set in, which has since had its counterpart in all the major nations.

Each repeater on an ordinary 2-wire circuit is arranged for transmission in both directions, on the general principle of the differential telegraph line duplex, and this has necessitated the development of artificial line networks which simulate the characteristics of the actual line so closely that they are capable of balancing it throughout the whole effective range of speech frequencies.

Four-Wire Circuits.—The need for such balances at the line repeaters, and for other refinements which are difficult to apply on very long circuits, can be avoided by the use of 4 wires for each circuit, one pair carrying speech in one direction and the other carrying it in the reverse direction. This 4-wire system is now in general use on the longest classes of circuit throughout the world. It permits the use of higher degrees of amplification, since crosstalk can be minimized by placing the outgoing transmitting pairs and the incoming receiving pairs of the cable in two separate groups, and by protecting the receiving group by electromagnetic and electrostatic shielding against interference from the comparatively strong currents of the transmitting group. No doubt the amplification used, and consequently the distances between repeater stations, could be further increased by the more effective shielding which would result from placing the transmitting and receiving sides of the circuits in entirely separate cables. This would, however, involve extensive rearrangement and reconstruction of existing systems, and, moreover, I think it is reasonable to hope that further improvements in cable construction, and in the 2-wire system for circuits of equally light gauge, will eventually cause the 4-wire circuit to disappear or become a rarity. It is essentially a double-line circuit, only one half of which is in effective use at one time, so that its doubled weight of copper contributes nothing to the transmission efficiency of the line.

Electrical Echoes.—A phenomenon which gave a good deal of trouble in connection with the first attempts to provide very long telephone cable circuits was the occurrence of electrical echoes. If the time of transit of the speech waves from the transmitting to the receiving end and back again by reflection exceeds about $\frac{1}{16}$ sec., the effect in the ear of the speaker is very confusing and may be rather disastrous to the intelligibility of the conversation. The effect is, of course, equally marked in the case of 4-wire circuits, although on such circuits the possibilities of lighter loading, with consequent increase in the speed of wave propagation, extend the distance that can be covered before the return of the reflected waves is retarded beyond the permissible time. It was at one time thought that such echoes would set a practical limit of about 1 000 miles to the length of cable circuit that could be used for telephony. The difficulty was overcome by the invention of voice-operated echo suppressors applicable to the 4-wire circuit. These devices utilize a small derived portion of the speech current, passing on the active half of the double line, to energize delicate devices which temporarily block the inactive half against the return of reflected current. In the suppressors first devised by the Post Office the blockage was effected by over-priming the grids of the repeater valves in the inactive line to an extent which put them temporarily out of action. In another type of suppressor, sensitive relays actuated by amplified speech currents are employed to produce an actual disconnection, or a short-circuit, of the inactive line. Both types are in practical use, with satisfactory results.

The Post Office type of echo suppressor has been successfully applied to experimental 2-wire circuits, but other considerations at present limit such circuits to lengths on which the echo effect is not noticeable.

Reflections are, of course, produced only at points where changes in the electrical characteristics of the circuit are introduced, and the setting-up of echoes can be minimized by preserving the utmost possible uniformity throughout the length of the line. Echoes from terminal transformers and from other apparatus at the end of the line can similarly be reduced by reproducing as closely as possible, in the apparatus itself, the characteristic impedance of the line, so that the wave energy will be absorbed with minimum reflection. It is not possible in practice, however, to match the impedances of all parts of the system so perfectly as to secure the complete suppression of distortion due to reflection.

Repeater Refinements.—The use of the repeater on long circuits has now become universal throughout the telephone world. Among many refinements which have been developed in association with their use mention may be made of devices for ensuring the constant energy-level of the amplified speech, independently of the level of speech incoming to the amplifier.

In one such device the amplification is regulated by varying the impedance of a 3-electrode valve, the requisite smoothness of control being obtained from a condenser and resistance combination.

Thus low levels due to weak voices, or to faulty lines, may automatically be made good at the amplifiers, and unduly high levels may be toned down. These devices have reached their highest development in the terminal apparatus by which the transatlantic radio circuits are connected to the ordinary telephone circuits of England

and America, but they are also being applied in a simpler form to inland trunk circuits.

Another device which it has been found desirable to introduce provides for automatically regulating the amplification to compensate for the effects of changes of temperature. If the temperature of a line containing a chain of repeaters rises, the attenuation of each section of the line will be increased and the consequent percentage losses will be multiplied together by the repeaters, with fatal results on the volume of speech received at the ends of the line. To operate the correcting device a wire on the same poles as the working circuit, or in the same cable, is used as a "pilot wire." The variation with temperature in the resistance of the pilot wire is used to operate a regulator which controls the amplification factor of the repeaters. Long circuits of open wire, or in aerial cable, are particularly exposed to sudden changes of temperature. In Great Britain, where practically all the circuits equipped with repeaters are in underground cables and considerable variations in the temperature of the conductors occur only very slowly, it is not necessary to use such automatic devices for maintaining correct amplification.

Mechanical and Acoustic Analogies.—It is interesting to note that the study of the theory of electrical wave transmission, arising, to a great extent, out of the work of Heaviside, has done more than replace the former imperfect theories and place new mathematical tools in the hands of the telephone engineer and of the power engineer dealing with the propagation of high-voltage currents. The conception of electrical impedance—the vector sum of resistance and reactance components—includes factors which have wider relationships in nature, and which apply also to the transduction coefficients of more grossly material agencies, which, from this standpoint, may be regarded as the mechanical analogues of amperes and volts. A good deal of the knowledge acquired in the study of the problems of electrical networks has been found to be applicable, in analogous form, to mechanical and acoustic problems, and many of these are now being solved by methods and reasoning similar to those used in designing electrical circuits and by the use of the appropriate electrical formulæ. An interesting case in point is the work of the Bell Telephone Laboratories in the development of the modern high-quality gramophone. The problem in gramophone-recording was to intercept air vibrations and translate them into vibrations of the recording stylus; and similarly to translate the vibrations of the needle-point into air vibrations which should be a faithful reproduction of the original sounds. In the latter process we have a transmission system, containing the mechanical equivalents of capacitance, inductance and resistance, in much the same arrangement as in the loaded telephone line. To name a few of these elements, there is first the shunt "capacitance" of the needle-point; the series "reactance" of the mass of the needle-arm, and the shunt "capacitance" of its flexibility, associated with homologous properties of the spider and the diaphragm. Taking into account the properties of available materials and the requirements to be met, it was possible to design a reproducing system with much improved tone-range and uniformity of response.

Carrying the application of electrical theory into the field of air vibrations, it has been found possible to design acoustic filters which will suppress undesired frequencies while allowing others to pass. A promising field for these filters is in the ventilating ducts for sound-proof rooms.

The C.C.I.—I have already mentioned the presidential address delivered from this chair 7 years ago, in which Mr. Gill called attention to the progress made in long-distance telephony in the United States and described the possibilities and the results of developing international communications on this side of the Atlantic to a corresponding degree. His remarks attracted widespread attention, and acted with a kind of trigger effect upon the telephone engineers and administrations of war-riven Europe, releasing accumulated desires and plans for the resumption of mutually helpful relationships, and for the furtherance of business intercourse and social understanding by providing a higher order of facility for the direct interchange among nations of the spoken word. At that time there was very little international telephony. As I have already mentioned, Great Britain communicated only with Paris and Brussels and, through those cities, with a few of the other principal towns of Northern France and Belgium. Elsewhere in Europe telephonic relations were confined to communication between the chief towns of adjacent countries, by means of overhead lines.

Within a few months of Mr. Gill's address, and avowedly as a result of it, France took the first step by inviting representatives of the telephone administrations of Western Europe to a conference in Paris in the summer of 1923. At that meeting it was at once apparent that there existed a keen desire for concerted action. The technical and administrative position was surveyed and methods of co-operation were formulated. Programmes of works were drawn up, mainly in the shape of proposals for the building of overhead circuits to meet more or less obvious immediate needs, and the requirements of the future were roughly estimated. The engineering and operating practices of different nations were compared and machinery was set up for the study of a large number of important points which would have to be settled before the construction of an adequate and properly co-ordinated international telephone network could be proceeded with. Rules and specifications of a general character were drawn up in tentative form, defining the essential characteristics of cables, repeaters, switchboards, transmission apparatus, signalling methods, and testing and maintenance procedure which would have to be adhered to in the international service.

It may be remarked here that the need for plant and operating uniformity at all points in an international telephone system is a special feature of telephony which distinguishes it from other systems of communication. Letters or telegrams may be received at intermediate points and passed forward by any available method or route, but the operation of telephony demands that all parts of the system shall work uniformly together.

By the following year, 1924, it had been possible to secure the co-operation of all the belligerent nations of the Great War, and in April of that year a further meeting was held in Paris, attended by representatives of 19 countries—Austria, Belgium, Czecho-Slovakia, Denmark, Finland, France, Germany, Great Britain, Holland, Hungary, Italy, Lettonia, Luxembourg, Norway, Poland, Spain, Sweden, Switzerland and Yugo-Slavia. This Conference definitely constituted itself as a standing advisory Committee on international telephony ("Comité Consultatif International," referred to in brief as the "C.C.I.").

After some rather embarrassing flirtation with the League of Nations, in which I am bound to say that the Committee adopted a somewhat coy and reluctant attitude, it was, at the end of the year 1925, definitely adopted by its natural protector the International Telegraph Union, and it now forms a permanent part of the structure of that world-wide international association. Subsequent adhesions to the C.C.I. include the State Administrations of Albania, Dantzig, Esthonia, Lithuania, Mozambique, Portugal, Roumania, Russia and Persia; and by a recent decision regarding the definition of membership the Committee is now open to the adhesion of privately-owned telephone operating administrations. Under this provision Cuba and Mexico are now represented in its membership. The American Telephone and Telegraph Co., which has from the beginning helped the Committee in all possible ways most generously and effectively, has also been enabled by the new conditions of membership to join the Committee and thus add its great influence and prestige to its work in the cause of world telephony. We should warmly welcome also the appearance of Japan and of the British Dominions at the board. The surface of our globe now sets no limits to the range of the telephone, and the degree of progress made since the date of Mr. Gill's call to arms is, I think, something to warm his heart.

The International Advisory Committee carries on the details of its work by means of small commissions of assessors—"Commissions de Rapporteurs"—each consisting of a few experts selected to study and report upon a particular subject or problem assigned to them. It is one of the duties of these commissions to maintain full touch with the experts in private manufacturing industry and to see that their views are adequately represented in all discussions on the subject of technical plant. The main committee holds a plenary session annually, generally in Paris where its secretariat is located, but occasionally elsewhere. At these conferences the reports of the assessors are reviewed and recommendations are prepared and issued to all the constituent administrations. The committee does not issue mandatory regulations, nor has it any power to do so. Its function is confined to the giving of advice, which each administration is free to accept or reject. The system works smoothly and well. Recommendations passed at plenary conferences are justly regarded as the results of careful and disinterested study and are, almost without exception, accepted and given effect to so far as the ways and means of each administration will permit. I have had the privilege of attending, on behalf of this country, the plenary conferences of the committee from its beginnings, and I gladly testify to the fine spirit of co-operation and friendly concession which has been their characteristic throughout.

It will be recollected that Mr. Gill strongly favoured the entrusting of international telephony in Europe to a single company, or, in default of that, to a single organization set up by the existing administrations to carry on the business as a separate entity. No doubt either of these plans would, from the standpoint of efficient working, have been superior to the present system since, even with the best will in the world, co-operation is but a poor substitute for unified control. The opportunity of skimming the cream of Europe's telephone service would have appealed strongly to anyone to whom it might have been entrusted, but there never was the slightest chance that the existing telephone administrations would give it away. As a rule they look to the trunk system between busy centres, both national and international, to earn a little honest profit which helps to bear the burden of many unremunerative fringes of service which a national telephone administration is compelled to carry on in the interests of the public. It is also true that the political and economic situation in Europe does not readily lend itself to the setting up of independent international bodies whose activities would limit the sovereignity of its national services. The co-ordination of the international telephone system by a committee on which all the administrations are represented, on a basis of equality, was Mr. Gill's third alternative, and no doubt the one he loved the least, but it has proved to be the only one realizable in practice, and it cannot be said to have been barren of results.

The Transmission Unit.—There is, however, one much-debated matter in which the committee has entirely failed to reach a common agreement, i.e. the setting up of a unit in which to measure and express the attenuation accompanying the passage of an electromagnetic wave through any kind of transducer—open wires, cables, transformers, artificial networks, or any kind of apparatus combination. In its practical operation, the unit has merely to express numerically the ratio between the measured or calculated values of power, voltage or current at the extremities of the part considered, and when the question of approving a unit for world-wide use was first raised by Great Britain, one did not anticipate any appreciable difficulty in arriving at accord on the subject. In order to avoid the need for multiplying or dividing a series of ratios to arrive at additive or differential values, it is convenient that the unit should express, not the ratio itself, but its logarithm. One can then simply add together the units representing the attenuation of each element of a combination in order to obtain the attenuation of the whole in the same units. This was common ground, but the rock on which we split was that, in the view of America, Great Britain, and two or three of the Continental nations, "common" logarithms to the base 10 should be used and the measure should be that of *power*, while a majority in Europe desired to continue the use of "natural" logarithms, to the base e, and to apply the unit to the measurement of *current* or *voltage*. The latter attitude is supported by the convenient use of natural logarithms in the mathematical development of line-transmission theory, and the universally established Continental practice of expressing attenuation in terms of decrement of current, or, when phase differences are considered, in terms of the square root of the volt-amperes. Its advocates maintain that there is no need to frame a transmission unit on any other basis. The other side contends that the measurement of attenuation is more properly based directly upon power loss, which applies to the acoustic as well as to the electrical aspect of telephony, and that the use of common logarithms on the decimal base to express the unit has all the advantages which have led to their general adoption in other numerical calculations.

This is not the time or place to add to the discussion, which, in my opinion, has made mountains out of mole-hills and has wandered much too far into purely theoretical considerations. It will suffice to say that continental Europe and America each continue to use the system with which they have identified themselves. Great Britain, which has intimate telephone relations with both parties and which has from the first expressed its readiness, in the cause of uniformity, to adopt either unit, is thus compelled to use both systems in its international relations, but has joined America in the adoption of the decimal system for its internal purposes.

It has been agreed that the Continental unit shall be known as the "napier" (written "néper" on the Continent), as a compliment to the inventor of natural logarithms. One unit represents a ratio of current or voltage values $= e/1$; 2 units $= e^2/1$ and so on.

The basic unit of the decimal system has been called the "bel," in which abbreviated form it enshrines the name of Dr. Graham Bell and also, somewhat fantastically, recognizes the oft-recurring symbols e and βl, of transmission theory. One unit represents the power ration of 10 to 1; 2 units 100 to 1, etc.

The number of népers expressing the decrement of current or voltage, and the number of bels expressing the decrement of real or apparent power in any circuit, differ from each other by only about 15 per cent. Both units are so large that in everyday work it would be necessary to use fractional values.

Practical units of one-tenth the logarithm have, therefore, been introduced with the names "deci-néper" (e to the power of 0·1) and "decibel" (10 to the power of 0·1). These units have the advantage of avoiding to a great extent the writing of fractional values, since one unit represents just about the minimum change in attenuation that is recognizable by the human ear in a telephone receiver. In the literature of the decimal system the decibel (db) is now in general use, but I have so far seen no indication that the deci-néper is likely to displace the fractionally expressed néper on the Continent.

An unfortunate effect of the failure to agree is that much expensive measuring apparatus calibrated in accordance with each system continues to be constructed year by year. The material cost of unification, which would have been small when the first attempt to achieve it was made, thus increases as time goes on.

The Standard Reference System.—One of the tasks of the International Committee has been to define and construct a universal physical standard of reference in order to ensure the strictly equivalent calibration of all apparatus used for measuring the transmission efficiency of telephone transmitters, receivers, lines, and transmission plant in general. No universal standard, either relative or absolute, had previously existed.

The form of apparatus eventually chosen for the purpose was developed by the American Telephone and Telegraph Co., and the Committee has also to thank that company for having presented it with a complete installation of the apparatus, which is an exact duplicate of the reference standard set up in the company's laboratories in New York. The European installation is set up in Paris and is owned and operated by the C.C.I. It represents an absolute acousto-electric standard and is defined in terms of C.G.S. units, so that it could be reconstructed even if its physical representation were destroyed. The process of putting this basic reference standard in the hands of all telephone administrations and manufacturers, by means of working standards which will be periodically calibrated in the reference laboratory, is now being actively pushed forward, and it is anticipated that a higher standard of general efficiency will result from the elimination of the discrepancies which have hitherto existed in the standards of the various authorities.

Radio.—A vast new field was opened up by the production of Hertzian waves and their utilization for communication purposes. The literature of the subject is well represented in the *Journal* of our Institution. Radio telegraphy, in which the alternative emission or cessation of simple waves, or their alternative tuning and detuning, sufficed for signalling purposes, was speedily followed by radio telephony, in which the simple fundamental wave is used merely as a medium, or carrier, on which the complex speech wave can be impressed by modulation and subsequently separated out again and restored to its original character by demodulating processes at the receiving end.

The most impressive special services performed by radio to-day are those of the telegraph with ships at sea, which in the case of the Post Office station at Rugby is capable of reaching any properly equipped ship in any of the waters of the globe; the wonderful services of broadcasting throughout the world; and the transatlantic circuits between London and New York, by means of which all the millions of telephone users in America and in Europe are now linked together and provided with the means of verbal communication one with another at any time desired.

The classic occasion last year on which this Institution and its sister Institution in the United States held a joint meeting, at a time arranged and announced long in advance, will be fresh in the minds of our members; and its significance will be best appreciated by those of us who have had some experience of the chasing of far-distant radio stations, and of the exasperating way in which short and spasmodic periods of success are followed by relapse into the blank of failure.

The stability of the service between Europe and America depends primarily upon the "long wave" channel originally installed. This channel operates on a carrier wave of 5 000 metres and radiates energy averaging about 60 kW. There are also two short-wave channels each using waves of the order of 16, 24, and 30 metres and radiating about 5 kW; this radiated power will shortly be increased to about 10 kW. The provision of a further short-wave channel is now in hand, and endeavours are being made to obtain the availability of a frequency band in the crowded ether which will enable another long-wave channel to be established.

These radiated energies, both long-wave and short-wave, are very much more effective than similar amounts of energy used in ordinary broadcast practice.

In the case of the long wave it is possible to eliminate and suppress the bulk of the energy-consuming components of an ordinary radio-telephone wave, as used by all other radio-telephone stations, and to transmit only that part of the frequency spectrum essential to the reproduction of articulate speech. When a carrier wave is modulated by speech into a telephone transmitter each frequency component of the speech wave appears as two separate frequencies, one equal to the sum of the carrier and component frequencies, and the other equal to their difference. The complex speech wave thus sets up two frequency side-bands extending above and below the frequency of the carrier. Before the energy is amplified for radio transmission the carrier frequency itself, which is the main power element, is filtered out. One of the side-bands, and the non-essential portions of the other, are also filtered out. There remains for amplification and transmission only that portion of one side-band which, after treatment at the receiving end, will reproduce speech frequencies between 300 and 2 500 periods per sec. In this way the effectiveness of each kilowatt of radiated energy is increased about 6 times. By the use of highly directional receiving antennæ a great increase in the ratio of signal strength to noise admittance is secured, and an effective improvement factor of about 100 is introduced. A further improvement in efficiency is obtained by locating the receiving stations in regions which have been found to be comparatively free from "atmospherics." With this object the American receiving station has been established at Houlton (Maine), 600 miles from New York, and the British Station has been located at Cupar, Scotland, 450 miles from London. It has been calculated that a further improvement factor of about 50 was obtained by shifting the receiving station from New York to Houlton. In the case of the short-wave channels the carrier waves and both side-bands are at present radiated, but these channels have the advantage of directional transmission, as well as reception. It results in the energy used in all the London—New York circuits being many thousands of times more effective than equivalent energy radiated, on ordinary broadcasting principles, from one of those places for reception at the other.

Since the establishment of the London—New York system more than 25 000 successful conversations have been effected. The present traffic from all sources at each side averages about 45 calls per day, and the average duration of calls is about 6 minutes. The division of the traffic averages at this side:—

95 per cent from the United States
4 per cent from Canada
and 1 per cent from Cuba and Mexico.

At the other side they get:—

53 per cent from Great Britain
34 per cent from France
7½ per cent from Germany
and 5½ per cent from other European countries.

The behaviour of the circuits is continuously supervised and calls are classified as follows:—

Good—	When conditions are normal and conversation is easy.
Fair—	When additional time has to be allowed as compensation for interruptions.
Poor—	When conversation is difficult and double time, or more, has to be allowed as compensation.
Ineffective—	When the attempt to communicate intelligibly has to be abandoned.

As might be expected, conversations between America and Continental nations, which would be comparatively easy between correspondents speaking the same language, are occasionally rendered bad, or hopeless, by language difficulties.

The classification of calls for the past three months between Great Britain and the Eastern States of America was 85 per cent good and 15 per cent fair. To the Western States and Canada the proportions were 76 per cent good and 24 per cent fair. The whole of the traffic handled was classified as 80 per cent good, 19·7 per cent fair, 0·2 per cent poor and 0·1 per cent ineffective.

The charts on the wall (reproduced on page 12) show graphically the periods of good and bad service on long-wave and short-wave channels for a month, in winter and in summer. The black vertical lines denote good service at the hours of the day during which the channels were worked, marked as ordinates on the left, and the interruptions to these lines show interruptions of service. It will be seen that during the month of December the long-wave channel was 100 per cent commercial during most of the days, and that short uncommercial periods occurred on a few days.

The short-wave channel was subject to more frequent stoppages, but the combination of the two services ensured a practically 100 per cent service throughout the month.

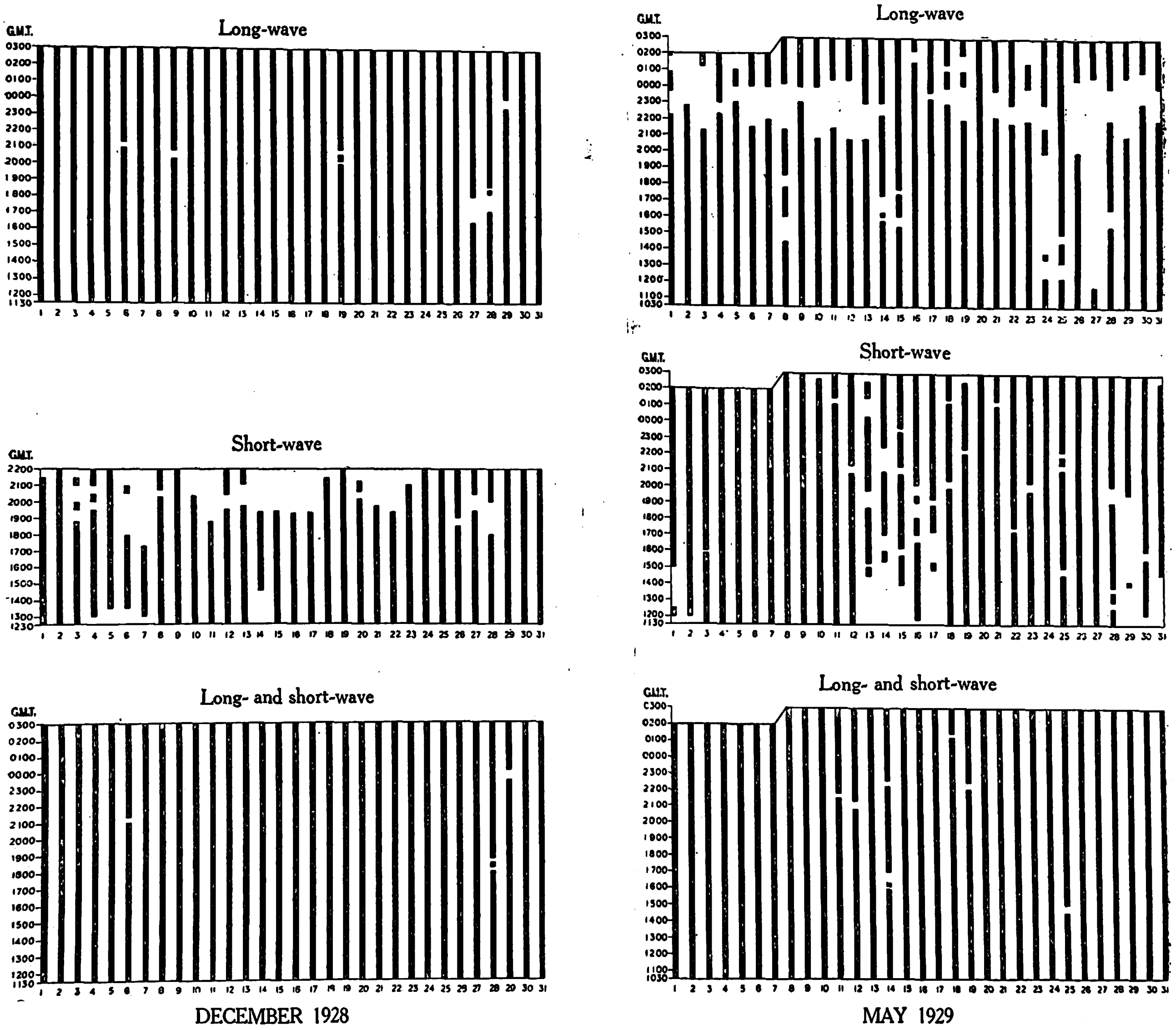
During the month of May, chosen because it shows somewhat abnormal interruption on the long-wave channel, this channel was subject to uncommercial periods, especially around the sunset period over the Atlantic, but it will be seen that the short-wave channel functioned well over that period as a complementary channel, and that the result of the combination of the two channels again ensured practically 100 per cent continuity of service at all times of the day during this month.

I should mention that the short-wave results shown are those of the first and least efficient channel installed. The second short-wave channel, brought into service in June last, has ensured full continuity of service at all times. When the third short-wave channel is provided at the end of this year there will be four channels available to take care of peak loads.

Although the general quality of the service may be regarded as satisfactory at the present early stage of transatlantic telephony, I think it may, with safety, be said that the possibilities of further developments in the art of linking radio circuits with telephone lines are such that the commercial data so far provided by the Anglo-

American service is very far from representing the ultimate grade of service which will be obtained from such circuits.

"*Privacy*" *in Radio Telephony.*—Since radio is necessarily to some extent a broadcast method of transmission, the transatlantic telephone has been subject to the disadvantage that the conversations passing over its radio link may be picked up and understood by other parties. Although such a possibility exists, however, it is not at all an easy matter for an unauthorized listener to "tap" its communications, and there is no reason to think that such tapping actually takes place.



Charts showing interruptions of New York—London telephone service in the months of December 1928 and May 1929.

The voice-actuated control devices employed on both the long-wave and short-wave channels now in operation have incidentally the effect that a receiving set on one side of the ocean can hear the messages transmitted from the other side only by listening directly to the radio station in the distant country. This, in general could only be done reliably by employing receiving systems approaching in cost and elaboration those employed in the commercial circuits. For practically all the time with the long-wave circuits and for the greater part of the time with the short-wave circuits an outside listener would therefore have to be contented with hearing only one side of the conversation, a condition which goes far towards removing any interest which he might have in overhearing a conversation.

The long-wave channels present special difficulties to would-be listeners because the frequencies transmitted represent only a portion of one of the side-bands, the carrier itself and all other modulation frequencies being suppressed. At the receiving point very accurate replacement of the carrier frequency and delicate filtering operations are necessary in order to reproduce the original speech.

Methods of imparting secrecy, or at least a high practical degree of privacy, to the systems have, however, been devised and much close attention is being given to their development.

In the existing short-wave channels, where both side-bands and the carrier are transmitted, directional propagation imparts a certain measure of privacy. It is possible also to vary the carrier frequency or to change the relations between the two side-bands, or between them and the carrier, in such a predetermined manner as to make it very difficult for the speech to be picked up and understood. Such methods have been tried out experimentally with promising results, and were for a time in actual commercial use in connection with a temporary radio-telephone service connecting the Island of Catalina on the Pacific coast of the United States with the Bell telephone system.

In the case of the long-wave channels it is possible to separate the spectrum of the transmitted partial side-band into strips and to invert and mix them in many arbitrary and successive combinations by complex heterodyning processes, which have to be fully known and carefully reversed at the receiving end. It is hoped that it will in this way prove practicable to transform the radio waves into an unintelligible jumble and to restore them, after reception, to their original shape for transmission over the land lines.

I do not wish to suggest that secrecy in radio telephony is yet in sight, in the sense that a competent outsider who is prepared to spend the necessary time and money in making arrangements to overhear conversations would never be successful, but I have little doubt that the system will ere long be equipped in such a way that a sustained and very elaborate attempt would be necessary in order to do so.

Contribution of Line Telephony to Transatlantic Radio Communication.—It is of interest to note that many of the special features of the transatlantic radio system, on which it depends for its commercial success, are devices intimately connected with, and in some cases borrowed from, the developments of line telephony.

Thus the single side-band system of transmission, used on the long-wave circuit, was developed originally in connection with the high-frequency multiplex system of telephony over land wires. It is no exaggeration to say that without this system commercial long-wave telephony across the Atlantic would be an impossibility.

The radio circuit is set up on the principle of a 4-wire telephone circuit connectable at both ends to 2-wire or 4-wire extensions, and it thus conforms to all the conditions associated with the linkage of land networks.

The voice-operated switching devices used on the radio circuit are fundamentally similar to the echo-suppressors evolved for use on long 4-wire land circuits, but much special development has been necessary to meet the far greater crosstalk and interference difficulties of the etheric path.

While it can be said that the radio-telephone system owes much to telephone development it, in its turn, is benefiting the development of line transmission because of its insistence upon the highest grade of design and construction in the land networks to which it has to be extended.

Transatlantic Telephone Cable.—Notwithstanding the high degree of stability which has been attained on the existing group of transatlantic radio-telephone channels, the system would gain greatly by the addition of a submarine cable channel to the facilities available. It has been felt that while such a cable would be so costly that, taken by itself, its provision would be financially impracticable, the expense could be justified in the case of a cable which formed part of a larger system, to which it would impart the valuable element of assured continuity of service and unchallengeable secrecy, as well as adding to the total traffic-carrying capacity of the system. The research laboratories of the American Telephone and Telegraph Co. had succeeded in producing remarkable improvements in the construction of ocean *telegraph* cables by the development of new metallic alloys for inductive loading, known as "permalloys." Its engineers were thereby encouraged to tackle the problem of the ocean telephone cable, with the result that last year the company announced that the Bell Telephone Laboratories had evolved a method of deep-sea telephone-cable construction which would be suitable for transatlantic operation. Work is now going forward actively on the development of a cable of this type for connection between London and New York, and it is possible that this circuit will be available for service as early as 1932. The new cable will yield only one additional telephone channel, but it will be a circuit of maximum reliability, free from the variations characteristic of radio circuits. It is probable that a superposed telegraph channel will also be obtainable.

The route of the cable is not yet settled in detail, but it is probable that the main transatlantic link will extend directly from Newfoundland to Ireland, a cable length of approximately 1 800 nautical miles. From Ireland the circuit will probably be carried through submarine cable to Scotland and thence by land cable to London, where it will terminate. It is expected that from Newfoundland the circuit will be carried through several sections of submarine cable to Nova Scotia and thence by land circuits through Nova Scotia, New Brunswick and the New England States to New York City, which will be the other terminal.

The new cable will be of the continuously loaded type. For the loading material it is intended to use one of a new series of alloys which are designated as "perminvars." These are composed of nickel, cobalt and iron, to which may be added small amounts of non-magnetic metals such as molybdenum. The so-called "perminvars" are characterized by high resistivity and by a wonderfully constant permeability over a wide range of magnetizing force.

The conductor will be insulated with a new dielectric material known as "paragutta." Submarine cables in the past have been insulated with gutta-percha or closely related materials, and in a few cases with rubber compounds. Paragutta makes use of similar raw materials and its mechanical properties are similar to those of gutta-percha, but the combination and treatment of its constituents endow it with superior electrical properties, approximately equal to those of tightly packed dry paper.

The attenuation represented by the main cable link between Newfoundland and Ireland will be immensely greater than that of any other telephone circuit which has yet been planned. It will, indeed, be such that the ratio of input to output power between the repeaters at its two ends will be about 10^{15}, or the equivalent of 150 decibels, for the high frequencies of the voice range; that is to say, the received power will be one thousand-million-millionth of the transmitted power. This decrement is, of course, far greater than that at which ocean telegraph cables are operated, and is indeed of about the same order as that experienced on the transatlantic radio circuits themselves.

The possibility of operating successfully through a line attenuation of this phenomenal magnitude depends upon two special features of the cable: first, the characteristics of perminvar, which permit the use of a level of transmitted power much in excess of that which can be used in an ordinary telephone cable; and second, the careful shielding of the cable ends, for many miles from each shore, against the possibility of even the slightest interference from other electrical circuits. The received power will be so extremely low that even the minute currents, or surges, caused by thermal agitation of the atoms of the conductor become an appreciable source of disturbance. It is anticipated, however, that the received speech currents will be successfully amplified and passed forward in good shape to the next section of the line.

The end repeaters will be single-way amplifiers and, in order to make 2-way conversation possible, voice-operated switching mechanisms will be employed to control the direction of transmission. Thus the two persons engaged in conversation will, by the mere act of speaking, alternately switch the transmitting amplifiers into action at each end as required and conversation will proceed in a perfectly natural manner.

Imperial Telephony.—The great success which has been achieved in the transatlantic radio-telephone service has led to investigations into the possibilities of opening telephone services with other distant systems, particularly with those of the British Dominions.

The first of these undertakings to take practical shape is communication with Australia. By the use of short waves an Anglo-Australian service of an experimental character has for some time been maintained via the Post Office radio stations at Rugby and Baldock, working to the corresponding transmitting and receiving stations near Sydney. It is hoped that a regular commercial service will be inaugurated very soon, and it is anticipated that this will shortly be followed by services to South Africa, India, New Zealand, etc. There is no doubt that direct exchange communication will also be established ere long with ships at sea and with other remote countries where radio telephony installations are being operated or installed.

Restricted Ultimate Field of Radio.—The demand for radio channels is continuously increasing, but the number of frequency bands available in the ether is strictly limited. It is probable that progressive increase in travelling by sea and air, and demands for the connection of moving craft with the world's telephone network, may in future limit the allocation of ether space to purposes for which no method of communication, other than radio, is practicable. In that case many of the services between fixed points for which radio is now employed may have to revert to the use of wires and cables.

Maximum Distance Conversations and Power Used.—As an illustration of the fact that the dimensions of the earth's surface now set no bounds to the range of telephony, it may be interesting to mention a long-distance test conversation carried out in association with the United States by two of my officers who visited Sweden last year in connection with the opening of communication between that country and America by means of the Anglo-American radio-telephone channels of the Post Office.

The chain of lines set up and spoken over on that occasion ran from Stockholm, via Berlin and Amsterdam, to London, and thence to New York by radio. From New York it was extended stage by stage via Chicago and San Francisco to Los Angeles, and back by another channel to New York, then once more to Chicago and back again to New York, with a final extension to the residence of one of the American Telephone and Telegraph Co.'s officials in New Jersey, from which a fair grade of conversation was exchanged with Stockholm.

The total length of the route traversed was about 14 000 miles, including approximately—

270 miles of open-wire line in Sweden;
200 miles in submarine cables across the Baltic and North Seas;
1 050 miles in underground cables in Germany, Holland and England, to London;
3 900 miles, London to New York, including the radio link of 3 200 miles and 700 miles in underground cables;
3 860 miles of open-wire line, worked by the high-frequency carrier system, and
4 850 miles in underground or aerial cables in the United States.

The aggregate length of copper conductor used on both sides of the Atlantic to carry this record long-line conversation would be about 40 000 miles.

The land-line equipment comprised 117 4-wire repeaters, 19 2-wire repeaters, 24 carrier-channel repeaters and 6 cord-circuit repeaters, in addition to 8 echo-suppressors and numerous other special devices. The total amplification of power included also that effected in the two radio transmitting stations, each of which has a power-amplification factor of about 100 millions, and at the two radio receiving stations which may be required to amplify the received power to any extent between 30 000 and 300 million times in order to compensate for the extremely variable ether channel at different times and seasons.

The power-amplification factor introduced at the radio transmitting and receiving stations—enabling the speech currents received over the land lines at the transmitter to be passed forward at the normal volume from the receiver to the land lines—will thus vary widely around a mean value of about 10^{16} (10 000 billions).

But the power loss made good by the repeaters on the wire-line portion of the circuit (11 000 miles) would be immensely greater. The transmission equivalent of the chains of circuits used would not be less than 2 400 decibels (240 bels) and was probably a good deal more. The relationship of power sent to power received over a circuit of 240 bels is a ratio of 1 to 10^{-240}.

It is permissible to think of the power which would be required to deliver currents of telephonic magnitude at the far end of such a circuit in the absence of repeaters. We start with an acoustic energy equal to about 10 microwatts delivered into the telephone transmitter by the voice of the speaker. The transmitter is itself an amplifier and delivers about 200 times this amount of energy into the line in electrical form—say 2 milliwatts. The receiver at the far end of the line will reproduce speech of minimum commercial volume with 1 microwatt. To deliver even 1 microwatt at the far end of a circuit of 240 bels without intermediate amplification, the initial energy must have the inconceivable value of 10^{231} kilowatts. I believe that the power radiated by the sun is of the order of 4×10^{29} kilowatts, from which it appears that the number of suns required to feed our circuit with the necessary power would be $0{\cdot}25 \times 10^{202}$. If we are inclined to accept Hubble's estimate that the maximum possible number of suns within the "world-line"—the limiting curve of space—is 2×10^{24} it follows that the whole radiant energy of nature would fall immensely short of meeting the requirements. We should need to multiply nature by 10^{177}—one might say "approximately"! It seems evident that the invention of the telephone repeater has tended to simplify certain problems!

The Photo-Electric Cell and its Applications.—The interesting phenomenon known as the "photo-electric effect"—the ejection of an electron from an atom by the absorption of a quantum of light-ray energy—which has assumed so deep a significance in fundamental physics, has also provided a new and extremely useful tool for the more materialistic purposes of the communications engineer. It may indeed be said that the invention of the photo-electric cell is comparable with that of the thermionic valve, in its power of achieving results which in its absence would have been beyond the range of possibility. Like the valve it has substituted the practically instantaneous response of the elementary processes of nature for grosser things. By its aid a pulsing beam of light, no matter how complex or how rapid its variations may be, can be made to produce an exact counterpart of its modulations in the form of an electromagnetic wave.

The photo-electric cell consists essentially of a light-sensitive element, usually an alkali metal such as potassium, used as a cathode from which electrons are ejected under the influence of light, and a separate electrode, maintained at a positive potential, which serves as an anode to collect the released electrons and conduct them into a circuit. The light-sensitive element is generally spread over the interior surface of a hermetically sealed glass bulb, leaving a clear window for the admission of the light. The anode is also contained within the bulb and has a grid-like structure so that, while allowing the light to pass freely, it will be favourably placed to catch and gather in the flying electrons. The interior of the bulb may be a vacuum, but the resultant current is considerably increased by the inclusion of an inert gas, such as argon or helium, at very low pressure in order to obtain the conducting effects of ionization of the gas molecules.

The electrical response of the cell varies in accordance with the wavelength of the incident light energy, being considerably greater to light near the high-frequency (violet) end of the spectrum than to the longer wavelengths, but, for light of constant character, it is directly proportional to the intensity of the beam.

Although the electrical energy obtainable from a photo-electric cell is necessarily very minute, it is sufficient to be successfully handled by modern methods of amplification, that is to say, it is well above the noise level introduced by the amplifiers themselves, provided that all possible screening precautions are carefully applied.

Time does not permit me to attempt any description of the methods by which this fascinating new tool is being used in the art of electrical communications. Within the past few years it has been utilized with great success in the development of apparatus for the telegraphic transmission of pictures, and of facsimiles of written messages and printed matter, both by wire and by radio.

It has brought practical television well on the horizon of coming events, and has also enabled the communications engineers of the Bell Co. to solve successfully the problem of combining the popular cinematograph with perfectly synchronized sound reproduction.

CONCLUSION.

In attempting to review the present position and course of electrical communications engineering within the compass of a short address, it is necessary to leave many aspects of the subject untouched.

I should have liked to say something about the interests of power and communication engineers in the avoidance of interferences between one system and the other, and of the widespread studies and discussions which are now going on with a view to devising means by which the lion and the lamb will be enabled to live together in peace and mutual satisfaction.

The general subject of submarine cables is also in a very interesting position, and the same applies to broadcasting—both by radio and by wire—and to the successful efforts which are being made to use simultaneously, for one purpose or another, every part of the frequency spectrum which wires and cables are capable of transmitting.

The automatic telephone system also presents many developments which are worthy of note, particularly in the direction of long-distance automatic switching and signalling, and in the design and utilization of really remarkable machines for automatically applying tests to the various parts of its intricate working plant, and facilitating its maintenance in proper condition.

There is much of interest, too, in the large programmes of line construction which are now being undertaken by telephone administrations all over the world, with a view to the building up of systems that will adequately meet the needs of the future, and be worthy to take their place in an efficient and reliable world system of electrical communication. The underground cable networks of Europe are becoming notably more impressive year by year, and they will be increasingly linked with the great systems of America, where the United States expects, within the next 5 years, to have the Southern States, and those of the Pacific and South Atlantic coasts, connected by all-cable circuits with the main cable network of the Eastern States and the States of the Middle West.

I feel, however, that I have already inflicted enough at one time upon this audience of general electrical engineers, and these and many other aspects of communications engineering may well be left to future opportunities, and, I hope, to many other and more competent exponents.

WIRELESS SECTION: CHAIRMAN'S ADDRESS

By Captain C. E. KENNEDY-PURVIS, R.N., Member.

(Address delivered 6th November, 1929.)

In this address I shall attempt to deal briefly with the progress of the art of wireless communication during the past two years.

One of the outstanding events is the fusion of wireless telegraph and cable interests by the merging of the communication side of the Marconi Co. with the Eastern Telegraph Co. Opinions as to the advisability of this are various, but the scheme has the approval of the Government and is now an accomplished fact. My own point of view is that this fusion is all to the good. Wireless telegraphy and cables are complementary to one another for long-distance point-to-point communication. It would have been little short of disaster for the cable services to have been completely superseded.

We are in an age of acute competition in communications, and every possible line must pull its pound. Cables have a distinct rôle in this, and after their long period of monopoly their owners are being forced by stress of circumstance to push on with developments and improve their technique. Some of these improvements may make the wireless world feel that cables are still a keen competitor.

We may now look forward to concerted development of Empire and world communications using both systems under one authority.

The Imperial and International Communication Co. has a link with the Governments of the United Kingdom, Dominions and Colonies through an advisory board of nominated members which has wide powers and can control the work of the company to a considerable extent, from the point of view of rates and service generally. There seems little doubt that there is a mass of traffic to be picked up if rates are made sufficiently low, and the cable and wireless technical staffs must so improve working and speed of traffic that rates can be cut and yet still pay. From the strategical point of view, cables are considered to be essential, and the merger saves these for future use in times of emergency or war.

The development of Empire and world communications by wireless telegraphy has shown satisfactory progress during the past two years. The original beam services to the British Dominions have continued to give an excellent and improved service, and the beam routes to South America and the United States are now well in their stride. Subsidiary lines by short wave to the smaller Colonies are being developed, and will develop much more quickly when the merger company has time to formulate its full proposals. Foreign nations are developing their own lines of world-wide communication, and competition among all nations to gather in traffic is acute.

While the use of short-wave working for long-distance traffic is advancing by leaps and bounds, I venture to put in a plea that the development of long-wave working should not be entirely abandoned. Congestion in the ether seems likely to be permanent; congestion will probably always be ahead of technique. As technique improves, additional lines will be started up and will overlap such improvement as may be effected from time to time.

It will be foolish to desert the lower frequencies without exploiting them also to the uttermost. In time of war, even if we are neutral, it may be found that short-wave working becomes exceedingly difficult; a nation at war will not care much for conventions, and those countries which have continued to use a long-wave service and their cables will have an advantage.

Radio telephony has made very great strides and has now reached the stage of being a sound commercial proposition. Commercial telephony over long distances was first made possible by the British Post Office in conjunction with the American Telegraph and Telephone Co., with the result that Great Britain is the centre for Europe of the North American transatlantic service. By the judicious use of long and short waves a 24-hours service is possible, and four separate channels are available.

Other countries have since advanced with more or less success, and some services now opened are Holland to Java; Germany to Siam and Buenos Aires; France to Buenos Aires; and Spain to the United States and Buenos Aires.

Experiments in multiplex transmissions whereby one carrier is made to do duty for one or more channels of telegraphy as well as telephony show signs of promise, but it is rather a question whether the wave-band occupied by such methods at present is not considerably wider than the sum of the wave-bands which would be used by an equal number of separate stations.

Cable companies are not lagging behind; a cable capable of telephony and high-speed telegraphy across the Atlantic is likely to be put into service before long.

Turning to broadcasting, the difficulties which arise between different nations as to their requirements are now in a fair way to be considered as settled, at least for a time. There are more than 150 broadcasting stations operating in Europe alone. It is easy to see that without very careful organization there must be serious interference over the whole of Europe. The recent agreement of 27 European nations to the Prague Plan for the allocation of wavelengths was a notable step in the right direction.

This Plan is the culmination of four years of work at the Union Internationale de Radiophonie. As early as 1924 it was realized that international agreement and co-operation were essential if the rapid increase of the number of European stations was not to result in a state of complete chaos. This was due to the fact that the majority operated on wavelengths below 500 m, and that, although the range of the ground wave may be limited, under certain conditions the range of the indirect wave may cause interference at a very much greater distance.

Two international plans preceded the Prague Plan—the Geneva Plan of 1926 and the Brussels Plan of 1928. These two plans were successful in so far that friendly agreements were come to by responsible authorities to operate their stations on certain wavelengths. They suffered from the disadvantage that they were not agreements between the Governments of the various nations, and there was therefore no method of securing adherence to them.

The Prague Plan was a great advance on its predecessors in that it is an agreement between Governments and can thus be enforced. Although the allocation of wavelengths has been much criticized it was obvious that some such plan was necessary, and there had to be a certain amount of give and take. Nations who were early in the field, e.g. Great Britain, France and Germany, suffered somewhat on the re-allocation of wavelengths, but this was in a good cause. The establishment of an international wavelength checking post at Brussels was also a step in the right direction.

One important point which will soon require settlement is the encroachment of long-wave broadcasting on to the wave-band allocated for use by aircraft.

In Great Britain, interest has been aroused amongst the public by the Regional Scheme under which the country is to be served by a series of twin high-power stations located at selected points outside certain cities. The recent opening of the new station at Brookman's Park marks the beginning of this scheme. The underlying principle is to give to every listener an alternative programme, whilst to many listeners with selective sets it will provide several alternative programmes. In addition it will give a maximum of field strength over the larger cities where local interference is caused by trams and other electrical machinery. It carries with it, however, one drawback, viz. a probable " wipe out " area close to the station from which it will be difficult to receive anything but the local transmission and in which the listener may experience difficulty in separating the two local programmes if the simpler types of receiving sets are used.

Communication with ships must always interest a country which depends on ships for its existence. Services to and from ships have steadily improved. High-speed working in the case of big ships of the western ocean trade, and short-wave working for very long-distance communication, have developed. Long-wave working for medium distances has also shown advance.

That bugbear to broadcast listeners—" spark "—is being gradually scotched by the introduction of interrupted-continuous-wave working at all Post Office coastal stations. It remains for other nations to follow suit. An interesting point in this connection is the use of different note frequencies by each British coastal station in order to avoid congestion of traffic, it being a fairly simple matter to over-read or under-read the signal required from the interfering signal.

Let us now consider the theoretical advances which have been made. A very considerable addition has been made to our knowledge of the theory of the propagation of waves, notably by research work carried out in England under the auspices of the Radio Research Board and by the Marconi Co.'s research staff. This work has been described in papers read before the Wireless Section, and the earlier theories of Eccles and Larmor regarding the mechanism of wave propagation have been largely confirmed by the experimental work of Appleton, Eckersley and Hollingworth. The work done has shown that, whilst normally the long waves are plane-polarized, an important change occurs in the medium waves of the higher frequencies which may have downcoming components the polarization of which differs from that for the surface wave. The long waves travel over the surface of the earth, whilst the higher-frequency waves in the medium band not only travel over the earth's surface but have indirect components which are free from the earth and are modified by the Heaviside layer. A combination of the surface and indirect components of the medium waves may produce very serious night errors in direction-finding, and fading due to the interference of these components also occurs.

As regards the short-wave band, very valuable evidence has been obtained on the fading of wireless signals. This has been dealt with very fully in a recent paper read before the Wireless Section. Experimental work indicates that the Heaviside layer is a complex structure of electron clouds or strata, and when a group of electromagnetic waves at the frequencies of the short-wave band enters the layer the following phenomena occur:—

(1) *Scattering of the radiation.* This is evidenced in a remarkable manner by the fact that, for the case of the Marconi short-wave beam transmitters working to

a receiving station, direction-finding observations taken at distances close to the transmitter and within the skip zone give the bearing of the place where the beam enters the Heaviside layer, which corresponds to the great-circle bearing of the receiving station.

(2) *Fading of signals.* This arises from the complexity of the layer and the fact that, in addition to their purely free irregular motions, the electrons may also have definite motions due to the magnetic field of the earth. A plane-polarized wave entering the layer must ultimately be resolved into at least two circularly polarized waves travelling with different velocities, whilst for the case of a group of waves such as go to make up a signal, different parts of the group will also have different velocities. The various fading effects may be considered to be due to:—

(i) *Rotation* of the plane of polarization of the combined result of these circularly polarized waves, due to slight changes in the magnetic field.

(ii) *Interferences.* There seems to be experimental evidence that the waves reaching a receiving station may have traversed paths of very different lengths. These can interfere with one another and thus produce fading. Some of these have suffered only a single reflection in the Heaviside layer, while others have suffered multiple reflections between the Heaviside layer and the earth. The term " reflection " is here used in a very general sense to indicate that the wave has been bent back to the earth by the Heaviside layer. Calculation shows that modulation of the transmitted waves should reduce fading from this cause, and recent tests indicate that this is actually the case.

(iii) *Scattering.* When scattering is present, further fading effects are thereby caused.

The methods employed in short-wave reception for mitigation of the effects of this signal fading include the use of spaced aerial arrays and long horizontal aerials of the Beverage type. In addition, circuits have been developed with a view to obtaining increase of sensitivity for weaker signals, e.g. the use of grid bias the value of which depends on the field intensity at the receiving aerial.

The research work and experimental observations which have been made on the Heaviside layer, and on which papers have also been read before the Wireless Section, have indicated that there are two or more regions where changes occur, the two main regions being at heights of the order of 100 and 250 km respectively.

The problems underlying this work have been very largely tackled by the employment of suitable signal intensity and direction-finding apparatus which has also been described before the Wireless Section, and this work has resulted especially in a very considerable development of aerials and apparatus suitable for short-wave direction-finding, these aerials being based mainly on the type originally proposed by Adcock, in which the receiving aerial system is so designed that it is unaffected by any horizontal component of electrical force.

As regards the possibility of taking direction-finding bearings on short waves, valuable evidence illustrating the limitations has been published. The direction-finding observations which have been made on distant and near stations have tended to confirm the general correctness of our ideas regarding the Heaviside layer and wave propagation therein. Summarizing the results from these observations the following broad conclusions are obtained:—

(1) It is reasonably possible to locate by direction-finding apparatus a very near-by transmitting station where the ground wave preponderates.

(2) If the distance is such that the point of observation is within or close to the edge of the skip distance then the whole of the effects are due to scattering and either little or nil bearing, or an enormous error, is observed.

(3) As regards the distant transmitting stations, (*a*) If the distance is so great that in general a single indirect ray only is being received, bearings are reasonably accurate. (*b*) Even at very great distances, however, though bearings definitely in error are not frequent, there are some occasions on which nil or indistinct bearings are obtained, owing doubtless to either (i) a multiplicity of waves following different paths, or (ii) interference arising from scattering.

Our knowledge of the echo effects produced at a receiving station on the shorter waves (which may give rise to mutilation of signals) has been increased, and records have been taken with the cathode-ray oscillograph showing the arrival of waves which have travelled several times around the earth's perimeter.

A very interesting phenomenon is the arrival of echoes after a very long interval of time, and intervals of 15 seconds have been observed by continental research workers.

Whilst some workers are of opinion that these echoes are due to special conditions in the Heaviside layer enabling the waves to pass many times around the earth, there is no adequate explanation at the present time of how the great attenuation that one would expect in such cases is overcome. An alternative explanation is that these waves have penetrated the earth's atmosphere and have been reflected back by swarms or bands of electrons in space. This view has been put forward by C. Störmer.

The echo phenomenon observed in short-wave reception has led to the development of directive aerial systems tending to reduce the mutilation which the echoes otherwise cause.

Taking next the development of the use of long and medium waves, the valve thermionic generator is continuously displacing the other and older systems of high-frequency generation. It is only on the longer waves that the high-frequency alternator and arc systems are still being employed for point-to-point services, and the tendency is to reduce the traffic hours of these long-wave systems by supplementary valve short-wave systems.

Advance has been made in the way of stabilizing emissions, which in these days of congestion is a necessity.

As regards broadcasting, an enormous amount of hard technical work has been necessary to produce the extremely good quality of the B.B.C. transmissions.

I have mentioned the Regional Scheme earlier in this address. From the technical point of view, perhaps the most interesting development which the regional scheme renders necessary is the placing of all the so-called relay stations on the same wavelength. This proposal has brought with it the great problem of obtaining isochronism of the carrier wave of all the stations, and the success of the scheme must depend largely on the solution of this problem. So far it has been attacked by the use of tuning forks as the fundamental standard from which the carrier waves are built up by frequency multiplication. Apart from the disadvantage of the complicated amplifier system for frequency step-up, this method appears to give the required degree of accuracy. The advance being made in the technique of quartz-crystal control may ultimately, however, offer an alternative solution.

Short-wave development has been very rapid, whilst the short-wave beam and similar services have been well maintained. The main development of short waves has been in regard to the great extension of the use of waves in the higher-frequency regions between 15 000 and 21 000 kilocycles per sec., which band of frequencies has been found effective for long-distance communication during daylight hours.

Still higher frequencies have been used with a certain amount of success but, in general, it has been found that the results obtainable at frequencies from 21 000 to 30 000 kilocycles per sec. are subject to very heavy fading. During the cruise of H.M.S. "Yarmouth" to the Far East, commencing December 1925, good communication was occasionally established with Horsea as far as Hong-Kong, using a frequency of 25 000 kilocycles per sec. The Marconi Co. have obtained results across the Atlantic, using a wave of 8·67 m (34 600 kilocycles per sec.).

In regard to the frequency band between 15 000 and 21 000 kilocycles per sec., the results obtained have shown that the hours of working vary considerably with the season, but the development of these waves has enabled communication to be obtained at long ranges over a very large proportion of the 24 hours by the judicious change of frequencies at various times of the year. The success obtained with this frequency band is due not only to improvements in transmitting circuits and valves, but also in considerable measure to the adoption of special forms of directive aerial systems which have been found very efficient for radiation at these frequencies.

Apart from the Franklin vertical arrays as used by the beam stations, the most generally used types for these frequencies are perhaps multiple arrays of horizontal or vertical dipoles, but some interesting systems have also been developed in France by Mesny and Chiveix in which the array comprises wires arranged to form either a double zigzag or a Grecian Key curtain, and for long-range working multiple arrays erected on low masts of height less than 150 ft. have given satisfactory results.

Commercially, as regards the type of aerial array for a given service, it seems to be a problem of balancing power input and its cost against the cost of masts.

The Marconi Co. have developed their beam system for operation on this higher-frequency band, and considerable work has also been done on the Continent. For example, a service with South America is maintained by Germany, and the Dutch Government has developed a very considerable communication service between Holland and Java, using frequencies of the order of 18 000 kilocycles per sec. for day work and 10 000 for night work, variations in frequency being made from time to time as found necessary owing to the seasonal changes.

During the European summer period, particularly about June, practically continuous communication is maintained throughout the 24 hours of the day using these higher frequencies only. In winter time the higher-frequency communication is limited to some 4 hours of the day, but the lower-frequency period can be carried on for approximately 12 hours. For the communication by Germany with South America, frequencies of the order of 16 500 and 11 500 kilocycles per sec. are employed.

The Admiralty have for some years been working a service to the East (Hong-Kong and Singapore) on 8 570 kilocycles per sec. This service has now been supplemented by a day wave service working on about 18 000 kilocycles per sec., and during June of this year a 24-hour service was maintained with Singapore on the latter frequency. During the winter months, however, the possible service is much reduced, but the daily hours of communication can then be augmented by the use of frequencies of the order of 13 000 kilocycles per sec.

Other interesting applications of short-wave working have been the use by the British Post Office of short waves of the order of 19 000 kilocycles per sec. for the transatlantic telephone system as an alternative to the long-wave transmission, and the short-wave broadcasting programme on 12 500 kilocycles per sec. which has been carried out from Chelmsford. In addition, in Holland a short-wave transmitter has been installed near Hilversum with the object of broadcasting direct to the Dutch East Indies on the daylight wave-band.

All the above developments refer to point-to-point or to broadcasting services, but there has been a very considerable development in the use of short waves for mobile services both for naval working and for the mercantile marine. As regards British naval services, practically all H.M. ships have been adapted for short-wave working.

Satisfactory results have been invariably obtained on the lower frequencies usually employed for the night services, but it is not so easy to obtain satisfactory results on the daylight wave-band and the difficulties are at present not entirely overcome. Although the use of short waves for mobile ship services is proving of great value, there is a certain limitation to its use, due chiefly to the zone where either interference is experienced between the surface and indirect radiation from the transmitter, or there is a definite gap between these components of the transmission.

This "skip zone" has been observed at sea on all frequencies above 6 000 kilocycles per sec. at varying distances below 1 000 miles. The lower-frequency band between 6 000 and 4 000 kilocycles per sec. has been found to be very much better in this respect, but it cannot be said that short waves will meet the requirement of a continuous service for ranges up to 1 000 miles at sea to the same degree of reliability as long waves.

Apparatus Development.

As regards the obtaining of H.T. power supply for transmitters, the high-tension d.c. generators for the Rugby long-wave high-power station have now been in operation for some years and have given very satisfactory results. The British Broadcasting Corporation are also using high-tension d.c. power, for example in their 5GB station, with satisfactory results.

The alternative systems of H.T. supply by means of single-phase or multi-phase rectifier systems are, however, in more general use for the medium-power transmitters, and especially is the use of double 3-phase rectification in favour. It has been claimed that the rectifier systems give greater security and reduced tendency to flash-over of valves. On the other hand, figures have been published showing a considerable economy resulting from the use of high-tension d.c. machines for fixed station transmitters.

For the high-power medium- and long-wave transmitters, the metal-glass valve with suitable cooling agents, such as distilled water or oil, has become well established; the silica radiation valve has also shown itself to be a very economical means of generating oscillatory power up to 10 and 20 kW, especially where the space is limited. Considerable experimental tests on metal-glass valves of increased anode rating have been carried out by the Post Office engineering staff at Rugby, but the development of higher-power standardized valve units capable of being used in parallel is proceeding more slowly than at one time appeared probable.

The development of the daylight wave-band of frequencies for short-wave service working on long ranges has increased considerably the technical problems connected with transmitting valves and circuits. The inherent capacity of the valves imposes a limit to the permissible inductance and, in practice, it is a matter of extreme difficulty to design stabilized transmitters for these very high frequencies. As regards the metal-glass valves, there is an increased danger of puncture of the glass envelope; this is usually guarded against by fitting an annular ring as an internal guard-ring device to screen the seal joint of the metal to the glass envelope.

In this connection it may be of interest to record that, as regards high-power valves used for Admiralty services on these frequencies, very considerable success has attended the use of the water-cooled silica valve the development of which has been described before the Wireless Section, and two of these valves are in regular operation handling from 20 to 30 kW for Admiralty services to the Far East on frequencies of the order of 18 000 kilocycles per sec.

The ability of the silica envelope to withstand very high voltages at frequencies as high as 30 000 kilocycles per sec., without danger of puncture, renders it peculiarly suitable for the generation of oscillatory power on these higher frequencies.

The increase in wireless telegraph services is bringing with it an ever-increasing tendency to greater stringency as regards frequency control of transmitters. The tuning-fork method of control has now been in use for some considerable time in this country, e.g. at the Rugby high-power long-wave station and at various stations of the British Broadcasting Corporation, and this has proved an excellent system of high constancy.

As regards short-wave transmitters, the very large number of stages which would be required for tuning-fork control of the short-wave band of frequencies is naturally a disadvantage and, for this reason, the short-wave transmitters are controlled in frequency either by well-designed short-wave master control circuits as used by the beam stations, or by the use of quartz crystals. The quartz crystals employed have usually a fundamental frequency of the order of 2 500–3 000 kilocycles per sec., and stabilized transmitters taking H.T. inputs of 30 to 50 kW at their final stage are in operation using frequencies up to the sixth harmonic of the quartz crystal.

The use of quartz may perhaps not give such a high constancy of frequency as that which is obtained from tuning-fork control and, owing to the number of modes of vibration, care has to be taken to ensure that maximum control is obtained on the correct frequency. It does, however, operate exceedingly satisfactorily when the amplifying circuits are properly tuned and neutrodyned, and is capable of giving a continuous-wave note of excellent quality even for the case of relatively poor regulation of the H.T. and filament power supplies for the transmitter, or when a.c. supplies are used for the filaments.

There is usually a change of frequency with temperature of the order of 30 parts in 1 million per degree C. with the use of quartz crystals, and for this reason thermostatic controls are used, but it has been claimed by certain experimentalists that careful selection of the quartz cuts may reduce this variation to the order of 2 parts in 1 million.

Turning to the development of receiving apparatus, there has been very marked advance in connection with the design of broadcasting receivers and their components, and the apparatus sold by the great majority of British firms is of excellent quality and most reliable in operation.

There has been a gradual change in the type of set offered to the listening public by the manufacturers, consequent on the introduction of two new valves to the market, i.e. the screened-grid valve and the pentode. The large amplification factor of the former and the large mutual conductance of the latter have made it possible to build up relatively cheap sets using only three valves and having a performance at least equal to that of the more ordinary types of sets employing four 3-electrode valves. From an operating point of view these sets gain in ease of handling, but they need careful construction and screening in order to function properly.

The moving-coil loud-speaker has also made great progress, and there has been a general development of power amplifying valves which has resulted in greater demands being made upon the high-tension supply of broadcast sets. This has led to improvements in dry batteries, but principally it has led to the development of highly successful battery eliminators.

Apart from receiver broadcasting developments, the chief technical development work has occurred in connection with the use of short waves, where a large number of problems have arisen for solution. Especially was it soon realized that for satisfactory short-wave reception the screening between the various parts of a receiver must be much more perfect, to be effective, than for the case of long waves, and that special precautions were necessary to prevent back-coupling from battery leads and what were formerly regarded as earthed leads.

The past two years have seen the commercial development of various remarkable types of screened-grid valves, and valves with amplification factors of over 1 000 are now available. At the same time these valves have a relatively small anode-grid capacity compared with that of the 3-electrode valve.

Despite the introduction of the many new and improved valves it is, however, fair to say that for frequencies above, say, 8 750 kilocycles per sec., only slow progress has been made in the development of a system of genuine high-frequency amplification, and for these higher frequencies the most successful methods of reception are still (i) the detector valve with reaction followed by note magnification (the quenched type of receiver may be regarded as a modification of an oscillating detector), and (ii) the super-heterodyne.

For work in the Navy both these methods have obvious disadvantages, since in their simplest forms they involve oscillations in the aerial with consequent interference between ships in close order receiving the same signal.

The use of detector valves in "push-pull," and special methods of feeding-in the heterodyne, do much to reduce the difficulty in the case of the super-heterodyne type of receiver.

In the case of the detector valve with reaction, however, removing the reaction from the aerial tends to reduce the efficiency of the receiver to a very great extent. It is in this connection that modern screened-grid valves have proved of great value, for it has been found possible by the use of one of these valves in front of the detector to make up to a great extent for the loss involved in removing the oscillating circuit from the aerial. This make-up can hardly, however, be regarded as true high-frequency amplification, since what amplification is obtained depends almost entirely on the fact that the anode circuit of the screened-grid valve is oscillatory, and the addition of further stages between the valve and the aerial in which reaction is not applied may even result in a loss of signal strength.

OTHER DEVELOPMENTS.

The extensive research work which has been done over a considerable period, in connection with the high-speed transmission of pictures and print by wireless telegraphy, has borne considerable fruit, and the Marconi Co. have applied this to the short-wave beam stations for services working between the United States and England. In the system which they have developed, a source of light, which is mechanically interrupted, explores the surface of the message forming the interior surface of a cylinder. The light scattered from the message surface is collected and arranged to fall on a photo-electric cell the output of which modulates the wireless transmitter. The output of the wireless receiver is applied to the electrodes of a Kerr cell, which controls the light intensity falling on sensitive paper. The necessary synchronization is obtained by separate tuning-fork control. Means for phase adjustment of the message cylinders at both transmitter and receiver ends are also provided.

The Fultograph system has also been developed for the broadcasting of pictures of current events, and the B.B.C. have a regular service of this system for pictures and for weather charts.

As regards the transmission of living pictures, broadcasts by the Baird Television Co., Ltd., are now being made for $\frac{1}{2}$ hour daily for 5 days a week, and in this connection it is interesting to note the development by them of synchronization between the transmitting and receiving apparatus by utilizing electromagnetic control obtained from the current forming the picture elements.

Another branch which is undergoing considerable development is that in connection with radio beacons for direction-finding at sea and for navigation in bad weather. In general, it is doubtless the best policy for ships to be fitted with suitable direction-finding receiving gear capable of giving accurately the position of fixed transmitting stations on land, and the tendency is for the ships fitted with direction-finding apparatus to increase in numbers. Not only can the observations of special shore station transmitters along a coast be taken, but in certain cases other shore stations may be observed to give cross-check bearings.

An alternative system which is undergoing trial is provided by the rotating beacon developed by the Royal Air Force, which employs a vertical closed-loop transmitter arranged to rotate about a vertical axis. The full intensity in any direction will depend on the position of the plane of the coil, the signal being a minimum when the plane of the loop is at right angles to the great-circle bearing. In this case no apparatus beyond a simple wireless receiver and an accurate stop-watch for the ship is necessary, and when the plane of the coil is perpendicular to the geographical meridian a special signal is sent out by the beacon and the observer on board ship starts his stop-watch. As the beacon rotates, the intensity of the received signal will vary and finally pass through a minimum value at which instant the plane of the loop is at right angles to the great-circle bearing. By observation of the time interval the bearing can be obtained by a simple calculation, since the beacon is revolved at a definite speed. These stations have a definite value not only for coastal ships and ships not fitted with direction-finding sets, but also for aircraft. An experimental beacon of this type has been erected at Orfordness and is giving excellent results.

In addition to the rotating beacon system, the Marconi Co. have developed a fixed aerial beacon system which sends out a recognized signal at convenient intervals to enable ships fitted with direction-finding apparatus to take bearings. They have also designed their system to operate in conjunction with synchronized signals from submarine signalling apparatus so that the ship can, from the observed time difference between the wireless and submarine signals, obtain the distance of the ship from the beacon transmitter as well as the bearing by the use of direction-finding receiving apparatus.

A further navigational development, which rather resembles the synchronous signal idea, is to transmit a radio-telephony signal through a microphone adjacent to the siren of a lightship or lighthouse. The operator first hears the siren in his head telephones and later the air-borne sound, the time interval giving the distance. This system is actually under trial on the Clyde.

WIRELESS TELEGRAPHY IN THE MERCHANT MARINE.

The Washington Convention of 1927 has had a good effect in forcing the gradual elimination of spark sets in ships. By this Convention no new spark set may be installed of over 300 watts after January 1930, and all existing spark sets must be reduced to 300 watts by 1940. The result of this is to cause shipowners to fit interrupted-continuous-wave and continuous-wave sets of modern design. The large ships now usually carry a set of about 2 kW capable of use on continuous waves over a wave range of 1 000–2 650 m and on interrupted continuous waves over a wave range of 600–800 m. Smaller ships are now being fitted with ½-kW interrupted-continuous-wave sets to cover the 600-m neighbourhood.

Short-wave sets are growing in popularity and are usually fitted to work off the long-wave rectifying panel. Communication over some part of the 24 hours is possible from any part of the world with either the Post Office short-wave station in this country or the United States, or both. A daylight wave of about 26 m and a night wave of 36 m are commonly used.

Certain services which are required in the big Atlantic passenger liners are of interest. One of these is the "brokerage" service. This implies an independent service which must be free from interference from, and must cause no interference with, the ordinary wireless telegraph traffic of the ship. This is not an easy problem to solve, but the difficulties have been overcome. Quotations are received normally on long waves from Tuckerton and New Brunswick, but transactions are carried out on a short-wave service which is entirely independent of the ship's main installation and is fitted in a separate office.

Direction-finding apparatus has been further developed, chiefly in the direction of reduction of space required for aerials and in increase of wave range. The number of ships fitted shows a very great increase.

ORGANIZATION TO LIMIT CONGESTION.

The remarks which I have made regarding the very large development of services on all bands of frequencies indicate how the overlapping of services is tending to increase the resultant interference. This has received a good deal of illumination at the recent meeting of the International Radio Technical Committee held at the Hague during September last, and I propose to quote a few of the agreed items. This Committee, known as the C.C.I.R., is intended to fill in the gap between main meetings of the International Radio Conference, of which the last was held at Washington in 1927.

The findings of the C.C.I.R. are not binding on any Governments but are intended to be advisory. Any recommendations it may make can only be brought into force at the next meeting of the International Conference. There will be a meeting at Madrid in 1932 of the Radio Conference, where matters which have been raised by the C.C.I.R. will come to the forefront.

The recent meeting at the Hague was attended by representatives from practically all nations, including Russia. The agenda of the meeting was confined strictly to 16 questions, which had been previously circulated. I propose to touch on certain of these questions which are of more general interest.

Question (2) raised the evergreen problem of how the power of a transmitter is to be measured. It is recommended that the power of the transmitter should be understood as meaning the power in the aerial itself; methods to carry out this measurement were included.

Question (3) dealt with the definitions of long and short waves. These definitions are, of course, quite arbitrary, but it is well that the different nationalities should understand what is meant by the various terms.

The definitions were fixed as follows:—

	kilocycles/sec.	m
Long waves	Below 100	Above 3 000
Medium waves	1 500 to 100	200 to 3 000
Intermediate waves ..	6 000 to 1 500	50 to 200
Short waves	30 000 to 6 000	10 to 50
Very short waves ..	Above 30 000	Below 10

Questions (5) and (6) dealt with wave-meters, standards of frequency, admissible tolerances and monitoring. It was decided that no absolute international standard of frequency is practicable at present. It is left to each nation to establish its own standard, and to arrange for comparisons with other countries.

Recommendations for tolerances for the various orders of wave-bands at different types of stations are made. The tolerance is defined as the maximum admissible departure from the nominal frequency notified to Berne and the mean frequency actually transmitted, the difference being due to (i) the error in wave-meter or control circuit; (ii) the error in adjustment at the station; and (iii) the "drift" during transmission.

No account is taken of the modulation. The tolerances agreed to at present for short waves are as follows; these are of the most interest:—

For waves of 6 000–23 000 *kilocycles per sec.*:—

Fixed stations	0·05 per cent
Land stations	0·1 per cent
Mobile stations	10 kilocycles per sec.
Fixed and land stations of 250 (or less) watts output ..	10 kilocycles per sec.

The tolerances for the future, at some date not given but as soon as technique allows, are respectively 0·01 per cent, 0·02 per cent, 5 kilocycles per sec., and 5 kilocycles per sec. These tolerances apply only to fixed and land stations whose waves are actually notified.

In the case of mobile stations the right to use any wave of the bands applicable was agreed to.

It was agreed that each nation should establish a national laboratory with a national frequency standard, each country to monitor frequencies of its own stations.

In this country the N.P.L. standard will be regarded as the normal standard, and the Post Office will do the necessary monitoring.

A "pious hope" was expressed that countries would hasten the abolition of spark, even before the date fixed by the Washington Convention.

Questions (7), (8) and (14) dealt with the channelling problem. The channelling scheme itself was not agreed to, but the Committee drew up certain recommendations necessary in order to prevent chaos in allocation of wavelengths. These briefly are:—

(1) In the reserved fixed service bands below 50 m, frequencies allotted in kilocycles should be divisible by 5. It was agreed that a separation of 5 kilocycles is not always sufficient at present but that actual practice shows a separation of 0·1 per cent to be practicable.

(2) Certain definite particulars should be forwarded when notifying waves. This was intended to stop premature wave-appropriation, but whether it will do so or not remains to be seen.

(3) Indicates the frequency band width (in cycles) occupied approximately by various forms of wireless transmission.

(4) Stresses the necessity of selective reception.

(5) Deals with the question of the use of short waves, of different orders for various distances. Final recommendations were:—

  (*a*) Waves between 50 and 13 m should be reserved for long distances, but these may be used for moderate distances from 2 hours after sunrise until 2 hours before sunset.

  (*b*) Waves between 50 and 85 m would be reserved for moderate distances.

  (*c*) Waves between 85 and 200 m would be used for the shorter distances.

These recommendations refer to point-to-point working only, and are only put forward as a general principle.

(6) Draws attention to the importance of stations which use the shared bands employing modern apparatus, having regard to the number of stations which are likely in the near future to operate in these bands.

Question (15) dealt with the limitation of power of broadcasting stations, and it was recommended that the power of European broadcasting stations using waves between 200 and 545 m be limited to 100 kW. Russia was excepted from this recommendation at her own request.

As regards stations using waves above 1 000 m, the liability of interference with air services was considered and certain articles of the Washington Convention were reiterated which forbid any increase of power of long-wave broadcasting stations if such increase should cause interference with existing services.

Some Problems of the Immediate Future.

One of the most interesting problems is to determine what application can be made of the band of higher hertzian frequencies of the order of 30 000 kilocycles per sec. and above. At the present time they are mainly employed for such purposes as rotating beacons for ship navigation and for short-distance communication, but further developments of aerial and reflector transmitting systems, together with receiving apparatus, may make them suitable for highly directional communication systems.

In regard to the receiving problem on these waves, it is important to emphasize the need for valve development in which the inter-electrode path is reduced to a minimum; for the time of flight of the electron at the higher values of these frequencies, such as those of the order of 300 000 kilocycles per sec., is comparable with the period of oscillation.

The work of the C.C.I.R. to which I have referred brings out the necessity of aiming at the highest possible degree of frequency stabilization and reduction of permissible tolerances to admit of an increased number of services without interference. In this connection the importance of developing suitable monitoring stations and apparatus for the checking and setting of transmitters to definite frequency values cannot be overestimated. It is interesting to note that at the present time the technique of frequency control of short-wave transmissions approximates to the accuracy with which the absolute value of the frequency can be measured.

The further development of receiver control, for example the method of "gain control" used at the present time for counteracting the effects of fading, is an urgent requirement for short-wave services. The development of the screened-grid types of valves having better effective screening might lead to considerable improvement as regards amplification and to better performance results on the shorter band of wavelengths.

Turning to the atmospheric interference problem, as regards long-wave reception the improvements of receivers with a view to reducing this have been small, and this interference is still an outstanding difficulty. Advantage has, however, been obtained indirectly by the use of the higher frequencies of the short-wave band, where the atmospheric interference problem is not so serious.

The development of single-unit thermionic valves for the generation of very high powers is not proceeding so fast as was at one time to be anticipated, and considerable development work is still required. As regards the receiving valve, it would appear that there is still room for improvement in connection with the reduction of microphonic noises.

METER AND INSTRUMENT SECTION: CHAIRMAN'S ADDRESS

By E. W. Hill, Member.

"ELECTRICITY METERS."

(*Address delivered* 1st *November,* 1929.)

I appreciate and acknowledge the great honour that this Section has conferred upon me in electing me its Chairman. I earnestly desire to do all in my power not only to maintain the dignity of the office I hold, but to make the activities of this Section interesting, useful, and of a nature to reflect credit on the Institution of which this Section is a constituent part. I am very pleased indeed to say that the Section is in a healthy and flourishing condition. We have had a very successful first session with a number of papers of considerable merit. In addition we have a full syllabus of important and interesting papers for this session, with an overflow into next session.

Memories, still vivid no doubt, of the late Meter Engineers' Technical Association even now linger among us, especially among those who helped in its inauguration and its subsequent development. After two years of remarkable progress that Association, which was plainly growing into the full efflorescence of its development, was called upon, by circumstances and by a call that could not be disregarded, to make the greatest sacrifice it could be called upon to make, namely its own extinction. It made that sacrifice, as you all know; it offered itself up for the common good, and became substantially the nucleus of this Section. That transformation, and its results, should be a source of pride for us. It is true that some regrets have been voiced. There are those who thought, and perhaps still think, that the junior members of the old Association are not participating in the benefits of this Section owing to the difficulty of absorbing them within the Institution membership. A project has even been mooted for forming a new association mainly for the benefit of juniors. The advocacy of this project has been able enough, but to my mind the pleadings, plausible though they be, are fundamentally unsound. Anyone, junior or otherwise, who gave support now to such proposals as those for a separate association, would be tending deliberately to deprive himself of the benefits that are available to him within this Section. The members of such an association would run the serious danger of becoming self-centred. One of the collateral advantages of membership of the Section for the juniors is the definite incentive to them to improve their technical knowledge for the sake of advancing their grades in the Institution; and in these days technical knowledge, as complete as it is possible to acquire it, is an almost indispensable condition for material advancement. Juniors will do well to ponder over this point. They will do well to have as high an aim as possible. The Institution provides at once the aim and the almost indispensable means of achieving it. It offers also unique opportunities for those who wish to seek contact with the best that is being thought and practised in the sphere of their professional interests. If these things involve for some the surmounting of difficulties, surely nothing is better as a discipline for the character.

Nobody, I imagine, will be surprised, in view of my personal predilections, and in view of the impossibility of covering the whole field of electrical measuring instruments, at my choice of the subject of my address, namely "Electricity Meters."

It is a curious reflection that electricity meters must have been allowed by default to be named on the paradoxical principle of *lucus a non lucendo*—the same principle that leads us to call "up"-lands "downs." Water meters measure water, and gas meters measure gas. Electricity meters, however, do not measure electricity. The elusive electrons can, it is true, be numbered, but the electricity meter does not do it—at least not expressly. What matters, and what is measured, is not alone the number or the quantity of electrons engaged, but something more important and fundamental, namely their activity while they execute the tasks imposed on them by man's ingenuity. Their activity is evaluated by the amount of work they accomplish, or by the amount of effort and expense incurred in urging them to do this work. In short, it is energy that is measured, and our science might well have been called "electric energetics." I would not of course labour this very obvious point did I not wish to direct attention to something beyond a mere defect in nomenclature. Our meters, as I have said, are required to measure energy. Energy, apart from the ultra-refinements introduced by the very latest ideas of modern physics, is, as far as engineers are concerned, a perfectly straightforward scalar quantity. It is an *amount*. It is not, one would think, an awkward thing to measure like a velocity or an acceleration, which are *rates* or derived quantities. That being so, we ought to be able to measure it accurately, or at least accurately enough to leave us free from introspective and continual preoccupation about possible lack of accuracy. We seem like invalids, constantly preoccupied about their lack of health. We are obsessed with this question of accuracy tolerances. We have had a society formed for the "promotion of accuracy in metering." We have had British Standard Specifications framed after much difficulty and labour and some contention. Manufacturers compete most keenly to provide meters more accurate than those of their rivals instead of being able to say "our meters are accurate with a negligible margin of tolerance."

In power station plant-tests it is well known that practically all the quantities requiring measurement on the input side can be measured with greater accuracy than the electrical energy output. Other kinds of electrical measurements can, even with commercial grade instruments, be made with great accuracy. Time measurements can be made, even with a very mediocre clock, to an exceedingly high degree of exactness. Even a foot rule can be used to measure with an accuracy of 1 part in 1 000. Other branches of science offer impressive examples of excessive accuracy. The astronomer can directly measure star parallaxes as small as 0·75 second of arc with certainty, which is the angular diameter of a halfpenny as seen at a distance of 4¼ miles; by photographic methods 0·01 second of arc can be measured. Heat radiation as feeble as that equivalent to the effect of a candle flame at a distance of 100 miles can be measured by sensitive bolometers. Naturally we must beware of confounding sensitivity with percentage accuracy. But the moral is obvious, and provokes the question: " Is there something fundamentally wrong with our methods of measuring electrical energy? " Should we in this respect submit ourselves to a course of self-examination, with confession and repentance to follow, and an amendment of our ways? What do we do now in measuring energy by our meters? Do we not conduct an operation which for indirectness is comparable with the following hypothetical but possible method of measuring a distance? Suppose that, instead of straightforwardly applying a measuring scale to determine the distance between A in London and B in Edinburgh, for example, we traversed the distance in a vehicle, the while making determinations of its velocity as it varied from time to time, and of the duration of the journey; and that we then performed a complicated integration of velocity/time, and in that way ascertained the length of the journey. That would be measuring a scalar quantity, distance, by determining derived quantities—rates of motion—and integrating with respect to time; exactly, in principle, what practically all electricity meters do. Can no way be found of substituting a direct form of attack for this indirect one?

Nearly all the outward manifestations of electronic activity—electrostatic, thermal, chemical, magnetic—have been laid under contribution for effecting electrical measurements. The magnetic manifestation is the one now almost exclusively used for energy measurements. Is it beyond all bounds of possibility to utilize new combinations of these, or even hitherto neglected ones such, for example, as gaseous conduction or radiation phenomena? I must, I fear, leave this in the form of an interrogation. But the posing of the difficulty may perchance stimulate some of the younger generation to apply themselves to seeking a solution, by casting aside all preconceived ideas which have for the last 40 years accumulated round the subject.

Even with our present methods, another way of escape from our accuracy difficulty seems open, or at least not definitely closed. In measuring electrical energy we do not, indeed dare not, allow our instruments to absorb the energy that is measured, in the way that some forms of mechanical absorption dynamometers do. The flying electrons are caught in our instruments, made to give an account of themselves, and then allowed to pass on to their proper business of lighting our lamps or turning our motors, etc. Of course, they do not get through that ordeal quite scot-free; they have to do a little work. Not much, it is true—they have to turn a disc against a little magnetic friction, and turn the wheels of a counting train. The actual mechanical work is absurdly small; so is the levy demanded for this purpose from the electron flow—that is, small in comparison with the amount actually measured. But the disproportion between these two small amounts, i.e. between the electrical input to, and the mechanical output from, the meter is simply amazing; it is something of the order of 50 000 to 1. This fact has never ceased to strike me with astonishment. Why cannot a meter, considered as a motor, converting electrical energy into mechanical energy, be more efficient than that? Of course, it is admittedly a very small motor and, as we know, small motors are in general less efficient than large motors. A kind of anti-relativity principle reigns in this domain. In respect of some concrete things there is a sense at least in which we can say that smallness and largeness are not purely relative. Indeed, I believe that even in these days it is not orthodox to say that *all* things are relative. There are absolute things, but they have to be sought deeply for. Apart from abstract ideas, however, it is not necessary to look far for certain kinds of absolute magnitudes. For example, aggregations of matter in the form of planets, under a certain size, cannot retain atmospheres. Larger aggregations, like the luminous stars, have an upper limit of size and are observed to be nearly all of about the same mass, owing to the gravitational concentration of nebulous matter which forms them being ultimately limited in amount by the disruptive tendency of the enormous internal torrent of radiation. Small communities could not easily sustain insurance schemes; there are too few to share the risk. Engineering appliances, like motors, transformers, engines, etc., have a limit of size—not well defined, it is true—below which it is hopeless to expect any approach to ideal 100 per cent efficiency. But it is a dismal thought that a meter can never be expected to have, as a motor, a better ratio of input to output than 50 000 to 1. It may be asked, " Why trouble? " Well, presumably a meter having higher mechanical working forces than at present would much better perform its functions as a meter, and our accuracy difficulties would tend to disappear in consequence. A curious consideration, however, emerges here. In presence of the eternal urge towards cheapness, manufacturers dare not make their meters much more efficient, in the sense I have just used the word, for the reason that higher efficiency means higher driving torque for the same watt loss; and higher torque necessitates stronger permanent magnets to damp down the disc movement. So that even a modest four-fold increase of efficiency would involve a positively prohibitive cost for the necessary permanent magnets. This is, indeed, not a fanciful notion. Manufacturers cannot afford to make ordinary meters, at prevailing prices, with torques much higher than they are now. May I suggest this as the reason why meters are not made far more accurate than they actually are?

But it is legitimate to ask whether we really want more accurate meters. It would take a very bold man to answer that question in the direct negative. And yet an unqualified affirmative might not altogether be justified. In this connection I would refer to a statement made by Mr. C. G. Morley New, in his address in 1927 as chairman of the Western Centre.* There is much food for thought in that passage.

I conceive the real function of supply meters to be to provide equitable and determinate means, rather than any arbitrary means (leading to approximations only), of fixing the relative amounts of individual consumers' contributions. But it is to be observed that, under the guise of two-part tariffs, arbitrary means are becoming more and more prevalent as part at least of the modern systems of charging. It is now common practice to charge the consumer that part of the cost of supply included under the heading of "fixed charges" upon the basis of an assessment, either on aggregate connected load, or rateable value of premises, or floor space, or something similar. Such charges by assessment cannot, at least at present, be adopted to the exclusion of all other factors, mainly for two reasons, viz. the risk of waste by negligent consumers, and the wide diversity of the capacities for consumption of energy of different consumers, ranging from small domestic demands of a fraction of a kilowatt to large industrial demands of hundreds or thousands of kilowatts. The latter class obviously, for equity's sake, exacts a tariff based on accurately ascertained facts and costs, and this involves among other things, as a *sine qua non*, extremely accurate metering. This raises a consideration of some importance. As regards both price and watt loss, manufacturers have, figuratively, in recent years been driven down a kind of asymptotic curve. Even this statement may be too sanguine, since an asymptote implies a limiting value, and I am not sure that there is yet one in sight for this process, except it be zero. However admirable this tendency may be from the user's standpoint, and admirable as it may be for its disciplinary effect upon the manufacturer in imposing upon him in respect of cost, increased efficiency of production, and in respect of low losses, increased economy in the use of material, it is a tendency, in my opinion, containing elements of danger, one reason, among others, being that it is an undiscriminating tendency embracing in its field all kinds of meters, large and small. I consider that a broad distinction should be drawn between small meters for which low prices and low losses are admittedly important features, and large meters for which these features sink into relative insignificance. The manufacturer should surely be allowed a little more margin, economic and technical, to enable him to supply a better, more accurate, meter, for really important supplies. Especially important is this consideration when we remember that so many large meters have demand indicator attachments upon the readings of which the transfer of large amounts of money depends. The mention of demand indicators leads me to remark how curious it is that the exigencies of the conditions governing electrical generation and supply, combined with the efforts of the tariff builders, have imposed upon engineers the necessity of providing for the automatic measurement of a quantity based upon so artificial a conception as that of average maximum demand. It is a conception which involves a necessity unparalleled in any system of measurement, other than electrical, of which I am aware. It seems to be the exclusive privilege of electrical engineers to have to determine that particular value of unvarying rate of flow of energy, through a meter, which in a given time interval would have produced, had it been flowing, exactly the same number of integrated units as was really produced by the actual experienced load, however fluctuating. Many problems, mainly of a mechanical nature, have presented themselves for solution in connection with maximum-demand measurement, and most of them are now satisfactorily solved. One problem, however, still remains unsolved, if we are content to allow the exception of thermal types of demand indicator. I refer to the fact that time switches, or equivalent apparatus, pick out successive time intervals for resetting demand-indicator mechanisms at arbitrarily allotted epochs, which may split the peak of the load curve instead of completely straddling it, in which eventuality the ideal maximum load period is not exactly accounted for. We still await a tripping apparatus endowed with prescience, capable of holding its hand as it were, and being ready to start a resetting period just when it can foresee the immediate incidence of a period which is going to embrace the true maximum load.

As though the artificiality of the maximum-demand conception were not enough, we have, superimposed upon it, the even more transcendental idea of kVA, and the problem of its measurement. On this particular subject I desire at the moment to do little more than pay a tribute to the work of those whose labours have crystallized out into some really beautiful examples of inventive skill designed for kVA measurement. We may, I think, legitimately feel proud of the capacity of meter engineers for tackling and solving any problems, be they never so perplexing, and for exhibiting inventive genius second to none.

The subject of kVA and its collateral, power factor, have raised problems not only of achievement but of exposition. The difficulty of explaining to non-technical people the nature of these quantities has stimulated many to offer from time to time very clever and illuminating analogies drawn from interests in life other than electrical, in order to expose what really underlies the ideas expressed by kVA and power factor. Useful as such analogies may be, yet direct technical explanations are preferable for technical people, and of such explanations those of a graphic character generally convey the underlying ideas more clearly than any other. I have here a very beautiful graphic model, devised by Mr. Dance of Birkenhead, whose kindness in allowing me to use it here I very gratefully acknowledge. This model shows the outlines, or silhouettes, of a.c. voltage, current, and resultant power curves; and also a related crank diagram. A complete sequence of relationships between the three elements, and the phase displacement of the two vectors, can be exhibited. It shows clearly how, at power factors other than unity, some of the energy is wastefully flung to and fro like a shuttlecock.

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* *Journal I.E.E.*, 1928, vol. 66, p. 27, col. 2, 1st complete paragraph.

It is quite unnecessary for me to dwell upon the theoretical aspect of this in this address. The importance of the theory, of course, is here quite subservient to the interest of the apparatus itself, which for demonstration purposes has great advantages over a set of laboriously prepared, and disconnected, diagrams on one hand, and on the other hand over the expensive and cumbersome cinematograph method, especially as the movement of this model can be arrested at any stage in order to allow any particularly interesting phase of the operation to be studied.

TABLE.

Progressive Reduction in Sizes and Weights of Induction Meters.

Approximate date	1890	1896	1905	1913	1929
Space occupied, cub. in.	900	300	165	135	75
Total weight, lb.	80	15·5	8	4·4	2·75
Weight of voltage element, lb. ..	14	3·7	1·2	0·7	0·44
Weight of current element, lb. ..	11·5	1·5	1·2	0·4	0·28
Weight of disc, oz.	2·1	4·7	1·1	0·9	0·8

Reverting to general aspects of the electricity supply meter business, the impressions derived from it by uninitiated observers might be quite deceptive. On the technical side, development may seem to flow in a very placid stream. Meters are now, it may seem, much as they ever were. Truly, there have apparently been no spectacular or revolutionary advances, as there have been in other branches (e.g. wireless). Yet there has been not only steady and definite progress on the technical side but enormous expansion in the way of new designs of meters for special purposes. As regards general development, one had only to glance back at the records of some 25 to 30 years to see, from the narrowest point of view, what phenomenal progress has been achieved. So we see the great advances that have been accomplished in economy of material and space (a condensed summary of which is given in the table above); in elegance of construction, and, hidden beneath and underlying all, great progress in subtleties of design.

As with the meters themselves, so with the outlook of meter engineers. Very different is it now from the days when the testing and maintenance of house service meters were their sole concerns; and, not less important, even their material prospects have improved. But of course, as a concomitant, and as a contrast too, the meter engineer has now, if he would be a man of really complete parts, to be equipped with a most comprehensive range of knowledge—he should know a great deal about mathematics, even about elliptic functions, for example, if he would understand all the profundities of the Aron meter theory; quaternions to enable him to perform vector analysis for the real understanding of the induction meter and other a.c. problems; chemistry to probe into the properties of the materials he uses and the peculiarities of such things as lubricating and insulating oils; metallurgy to understand his steels, permanent magnets and pivots; and general physics and electrotechnics to realize the full range of application of his meters to present and future problems. Above all, he should have a profound knowledge of mechanism, since in these days of prepayment meters and other complicated apparatus at least half his interests must be concentrated on mechanical and not electrical things. Whether or not such a paragon, completely fulfilling the above specification, could possibly exist I am not prepared to say. But all meter engineers, whatever their capacities, should rejoice that they live in an age when their problems are so much more interesting, even thrilling, than they used to be. Among others, still outstanding, there are the metering of super-tension supplies of 100 000 volts and over, avoiding the tremendous difficulties of potential transformers for such voltages; and the impending problem of metering high-tension d.c. supplies.

I have spoken a great deal about supply meters, but I have had no intention, of course, of identifying them as the sole items of interest under the heading of Meters and Instruments. Many other important things there are, e.g. transformers, relays, and general measuring instruments, which deserve the attention of our Section. For lack of time I must perforce leave them to other occasions. I have contented myself with a little discursive philosophizing on metering, pursued with some inside knowledge perhaps, but from a somewhat detached point of view. What lies in the future is no doubt a puzzling question. But as Sir Thomas Browne wrote long ago: " What song the Syrens sang, or what name Achilles assumed when he hid himself among women, although puzzling questions, are not beyond *all* conjecture." Neither is it beyond all conjecture what might be the outcome for the art of metering if electricity supply were to become so abundant that it could be charged for as water is now, without the use of meters; or if supply were to be distributed by some as yet unknown form of radiation through space, such as broadcasting. What would happen then? I can only echo the words put into the mouth of the Earl of Warwick by Shaw at the real point of termination of his play " St. Joan "— " I wonder."

WESTERN CENTRE: CHAIRMAN'S ADDRESS

By S. B. Haslam, Member.

(Abstract *of Address delivered at* Cardiff, *14th October*, 1929.)

The more recent Addresses submitted by the Chairmen of this Centre have dealt with the problems of the industry as raised by recent legislation, but it seems to me that the general trend of industry to groupings and amalgamations provides problems which are more vital and more deeply seated than any others. These problems affect the various branches of our industry in different ways. Those of the supply side have already been dealt with, and the work of the Central Electricity Board and the consequent establishment of what is known as the "grid" is a noteworthy example of grouping. What the result may be time alone will show, but nobody can deny that the scheme has received most efficient and loyal support even from those who were and are not in entire agreement, and while success will be assisted largely by the efforts of those concerned, failure, if any, can only be due to fundamental faults, not of design, but inherent to the general idea.

It may therefore be taken for granted that for the present the supply side of our industry, whether undertaken by municipal or private enterprise, is being tackled in a comprehensive manner; but otherwise the industry as a whole, and especially the manufacturing side, is seriously affected, and some drastic reorganizations will be necessary if we are to maintain our position compared with our foreign rivals.

It is with the economic aspect that I propose to deal, and to put before you some ideas regarding the commercial development of the industry as affected by conditions which have grown up since the War and are now in existence. Recent legislation has no doubt been adopted with the primary object of widening the use of electricity; and, assuming that this praiseworthy object is achieved, a greater demand for electrical products will be created in the home market, while foreign markets offer an ever-increasing field. It is difficult to decide as to the importance of the foreign market. Generally, it will be agreed that export business is not in itself remunerative to any manufacturer, but nevertheless it is of paramount importance in that the load factor of the factory can be considerably improved thereby with resulting benefits to the home market and to the manufacturer's own costs of production.

Figures taken over the last three years will show that in electrical plant the export business is divided almost equally between this country, the United States and Germany; but, unfortunately, whereas in 1926 our share was slightly greater than that of either of the others, the figures for 1928 show that both of our competitors have had a slightly larger share than we have. But if we take into account the Dominions and our Colonies, and remove from the total export figures the value of the electrical goods sent to other parts of the British Empire, it will be found that our share of the foreign trade compares very badly with those of our chief competitors.

In this connection an article recently published in the *Electrical Review* * is of interest. The article includes a table showing as percentages the world exports of electrical products, the figures for 1928 being as follows:—

Germany, 28·8 per cent.
United States, 24·0 per cent.
Great Britain, 20·2 per cent.

To students of the general industrial situation abroad as well as at home, the most noteworthy feature has been the wonderful revival of Germany in the past three or four years. The cause of that revival may be summed up in the one word "Rationalization." In this address I propose to submit my views on this subject, which may well be divided under three headings:—

(*a*) What is meant by rationalization?
(*b*) What results, if any, have been obtained by rationalization in productive industries generally?
(*c*) How can the knowledge gained in other industries be applied to our own? What results can be anticipated, and how can such results be used to the best advantage?

Dealing with the first point, the word itself has been described as "a new word, made in Germany, which stylists proclaim to be an abomination. Nobody has yet succeeded," the writer adds, "in saying shortly what it means, but that it means something of importance is not open to doubt."

There is no doubt that all industrial countries will be devoting much time and thought to rationalization during the next two or three years, and to enable the full significance of the word to be appreciated it is necessary that the origin and evolution of the process be clearly understood.

Many statements on the subject have been made and many definitions have been attempted, and it must be emphasized that no definitions made by people with any knowledge of the subject contain any suggestions that the maintenance of prices or the elimination of competition is part of the scheme.

The careful and comprehensive definition published by the World Economic Conference held in May 1927 may be taken as covering the subject as well as is possible in a few words. This definition is as follows: Rationalization is understood as "the methods of technique and organization designed to secure the minimum waste of either effort or material." It includes the scientific organization of labour, " standardization both of material and products, simplification of processes and improvements in the system of transport and marketing."

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* "The World's Electrical Exports," *Electrical Review*, 1929, vol. 105, p. 515.

Dealing with the results obtained by rationalization, it may generally be stated that the lead in this matter was taken by the Germans, not, as the many admirers of that country would have us believe, owing to superhuman foresight, collective daring and energy, but because financial conditions forced its development in that country before the necessity became so overwhelming in this country. In both countries every kind of scheme—financial amalgamation, central selling, market control, output regulation, and all the other shifts known to capital—have been taken up as the exigencies of the moment seemed to demand; and the demand in Germany may be said to have occurred at 5 minutes to 12, whereas ours became imperative at 5 minutes past 12.

The year 1924 may be taken as the year when general and financial conditions in Germany were at their worst, and, while it was in this year that rationalization was seriously considered and schemes were first put into operation, it was not until the following year that these ideas became generally adopted in all of Germany's main industries; and a brief comparison between the latest available figures for 1924 and 1928 will be interesting and illuminating.

In the coal industry the output per man per shift, including all workers above and below ground, increased by 38 per cent, i.e. from 16·8 cwt. to 23·2 cwt. During this time the actual output increased by more than 15 million tons, and the exports, excluding reparation deliveries, increased by 22 million tons.

During this period the average earnings per shift of the underground worker increased from 6s. 2½d. to 9s. 5½d. and of all workers from 5s. 5½d. to 8s. 2½d. General conditions of living also improved, and during 1927, with the cost of living about 50 per cent above the figure for 1913, the average earnings amounted to 53 per cent above pre-war level. At the same time it will be realized that their recovery did not come about without hardship, and the unemployment figures show how the first steps of rationalization cause unemployment owing to the necessary reductions of surplus workers; but also how, ultimately, these unemployed can be, and are, absorbed in other work which naturally follows in the wake of successful basic undertakings. The figures for the mining industry are as follows:—

In 1924 the total number of workers employed was 463 000. As the measures for the concentration of production, by the closing of inefficient or costly mines and seams, were put into operation there was a steady decline to 396 000 in December 1925, and to 355 000 in May 1926. In March 1927 the number of workers had risen to 418 000, leaving only some 45 000 unemployed; and more recent figures as regards total unemployment show that these have now been absorbed in other work.

The process of rationalization was also adopted in the iron and steel works. Of necessity this process is more complicated and full benefits have yet to be obtained, though remarkable progress has been made and notable results achieved. Production has increased, from 1924 to 1928, by 5 300 000 tons, or 68 per cent, in the case of pig iron, and by 6 500 000 tons, or 65 per cent, in the case of steel. As regards the workers employed final figures are not available, but at least 30 000 more workers were employed during 1928 than during 1924, so that the industry not only re-absorbed the surplus workers dismissed when the schemes were first put into operation, but also absorbed a considerable number who were redundant in some other industry. During this period, owing to improved methods, the daily output of steel per worker increased by 36 per cent. The financial aspect proved equally satisfactory, and the first full year's balance sheet of the main operating trust revealed a gross surplus of £14 000 000.

It must not be imagined that the burden of taxation, etc., is unduly light, as during the year in question the amounts paid for taxes were £3 000 000 and for social services £2 500 000. Wages did not rise to the same extent as in the coal mines, the average increase being 26 per cent. The question of hours worked is of interest, and many employers will maintain that in this lies the whole secret of the trade revival. The normal working week is from 48 to 54 hours, though the tendency is to reduce this and 46 per cent of the workers now work the 48-hour week as against 26 per cent in 1924.

Similar results attended rationalization in other directions, notably the electrical, chemical, artificial silk and textile industries, but the examples quoted may be taken as average and in no way showing inflated results. Any estimate of the general results of German rationalization must be tentative. It cannot be suggested that the state of the country is normal, but it cannot be denied that conditions show a very real and definite improvement as compared with those of 4 years ago. So marked is this improvement that it is worth while to attempt a tentative survey.

In 1924 wages were extremely low, and a 12-hour working day was not uncommon. Such conditions favoured communistic propaganda, and it is needless to say that very energetic efforts were made to exploit the sullen anger of the workmen, while at the same time the movement to establish the currency and re-establish the gold mark was sending prices bounding upwards. Gradually wages became adjusted to the rising prices, and though there was little unemployment the rate of individual productivity was low. This low output caused high costs of production and, coupled with short time, working costs rose to an impossible figure. The banks were charging 12 and even 14 per cent for loans, and credit was thus restricted to very narrow limits.

This, briefly, was the condition of German industry, and the only apparent alternative to collapse was rationalization.

The first outstanding result of putting rationalization into effect was a rapid increase in unemployment. In September 1925 the number " on the dole " was about 250 000; by the end of the year it was over a million, and by the end of February 1926 it had reached the 2-million mark.

Subject to comparatively small seasonal fluctuations, this figure has steadily decreased from that time, and in October 1927 it had fallen to under 400 000; and though the number of unemployed to-day is greater than this there is still a very substantial reduction. The main features of this recovery may be summarized as follows:—

(*a*) The rise in individual output following the closing of the less efficient mines and works, the concentration of full-time production in those best adapted for preservation and extension, and rapid progress in modernization of plant.

(*b*) The steady improvement in the physique and morale of the workers due to the rise in wages and standard of living.

(*c*) The elimination of duplicated activities and other forms of waste of labour and plant.

(*d*) The immense reduction in transport costs, due to the allocation of production to particular works for particular purposes and centralized control of the movement of raw materials and finished goods.

(*e*) The advance in full utilization and progress in general technical and scientific practice and further concentration of sales organizations.

While it is not possible at this period definitely to say that the improvements in the German industrial conditions are permanent, there is very substantial evidence that these improvements are founded on solid ground, and we may ask ourselves how the experience gained may be adapted to our own conditions.

Since this address was written, a White Paper has been published by the Department of Overseas Trade, dealing with the financial and economic conditions in Germany during the period 1928–9. This report shows very clearly that the prosperity of that country is general and continuing; rationalization is progressing rapidly, especially in the coal and coke trades.

During the period under review industrial activity has been slowed down considerably, owing partly to the loss of production attendant on re-equipment of works and rationalization, and partly to financial causes, such as the American demand for money and the high rates of bank interest. Yet, notwithstanding this, the savings of the German people continue to show an upward movement. The deposits with German savings banks at the end of 1928 amounted to £454 000 000. The increase during 1928 amounted to about £135 000 000. While the British iron and steel industries are labouring in deep water, the report tells us that, on the whole, the German iron and steel industries may be said to have overcome successfully a critical period.

German shipyards were better employed during this period; the engineering industry had a better year than in 1927.

German foreign trade showed "the remarkable increase of £70 860 000" in exports for 1928; this compares with a British increase of only £14 000 000 in the same year.

"The strain to which German economic life has been subjected during the first five months of 1929," states the report, "serves to emphasize the fundamental stability and soundness which it has developed since 1924."

Quoting once again the article in the *Electrical Review* previously referred to, "the greatest support of the English industry is stated by the report to be found in the Dominions and Colonies, which take about two-thirds of the total exports. For the rest the British exports are said to have made no progress since 1925, and from 1926 have even fallen as a percentage of the world total. At the same time German imports into Great Britain have increased from 104 million marks in 1925 to 126 million in 1928, or over one-third of the exports, the reason cited being declining competitive capacity owing to the lack of rationalization."

It must be realized that fundamentally the Englishman is not temperamentally suited to the conditions of rationalization: he is by nature and upbringing an individualist. It is very doubtful whether any country is psychologically so well fitted to the system as Germany. This is a definite weakness requiring careful consideration when applying these modern industrial conditions in this country, and many people will maintain that conditions which may change the general character of our race cannot possibly cause any permanent improvement. Undoubtedly the age of amalgamation and specialization is upon us. The result of amalgamation among our large industrial concerns, and the formation of combines each with one huge head office and one centralized organization, is to create a general tendency to split up the organizations into sub-divisions, each dealing with a particular portion of the industry.

The effect of this is "mechanization," and the human element becomes reduced to a minimum. The old order with the capable all-round business man taking charge of the whole business is rapidly giving place to the new, and the young departmental head specializing in his own particular branch is coming to the fore. Unfortunately, too often he has not the advantage of a general all-round training, and therein weakness lies. It is fairly easy to obtain and train a routine worker for one or two of the various departments in an industry, but it becomes increasingly difficult to find the all-round expert for the control of all departments.

Economists will maintain that prosperity in the future will depend on standardization and specialization of both industry and labour. Both undoubtedly tend towards the cheapening of a commodity and a higher efficiency in organization, but they also lead to a much larger number of purely routine workers and a shortage of all-round experienced leaders. Standardization and specialization must come, but the ultimate measure of success will depend largely upon whether this weakness of modern organization can be overcome; otherwise our industries will in the future be dependent on an army of specialists who will know very little themselves of the actual internal organizations of their own concern.

The system which has proved so successful in Germany is being put into practice in this country in most of our industries. The chemical combine is perhaps the most noteworthy example, but other industries are adopting the same principles in varying degree. Time alone can show what the results will be, but it is to be hoped that those who control and direct the combines will realize that the object to be aimed at is economy and, therefore, lower prices coupled with higher wages and better working conditions.

Undoubtedly, one of the immediate and most important questions which will arise will be that of finding, or rather recovering, the markets for our goods. If rationalization, complete or in a modified form, when put into operation in this country produces results similar to those obtained in Germany, increased production will result. This country cannot absorb such an increase and, therefore, markets in the Dominions and Colonies and abroad must be found and, when found, retained. Political activities will undoubtedly have considerable bearing on this problem, but when all is said and done the two chief factors will be the salesman and the publicity man.

Twelve months ago Sir Malcolm Robertson, British Ambassador to Argentina, said that we must look to salesmanship for the spread of British trade abroad, and for the recovery of our old position in the world's markets.

Again, in February, the Prince of Wales, speaking at the dinner held in connection with the British Industries Fair, stated that given the necessary modern equipment and methods the British workman could hold his own with anybody in the world. He went on to ask whether the salesmanship of this country was up to the standard of the workmanship of the men. It appeared to him that there must be something utterly wrong if a British community abroad anxious to buy British goods were unable to do so.

It is my very definite opinion that it is to the salesman that our industries must look if our old-time preeminence in engineering development is to be recovered. In making this statement I want it to be clearly understood that I am referring chiefly to the foreign markets, which as I have previously stated become more and more of vital importance.

It is an exploded doctrine that orders will come to the manufacturer; the man sent out to get these orders must be carefully selected. He must be a skilled trained engineer with a good and definite personality. He must be able to examine and advise on the work to be done; to calculate and guarantee the time of performance; to set up and start the plant when delivered, and finally, by actual demonstration, if necessary, to prove that his statements and advice were correct. In other words, only the best trained and equipped men should be selected.

There is in this country a very false idea that there is something undignified in the selling of specialized products, but I hope and believe that this idea is slowly and surely becoming eradicated, and that the younger generation will realize the importance of this branch. No matter how good may be the manufacturer and his products or how efficient the user, connection must be established, and I would suggest to all senior engineers and executives that they can do this country a lasting service by encouraging the young salesman. Of course, the manufacturers must do their part and send out only those men who know their job and who will not waste valuable time. When, in addition to the qualifications above mentioned, it is realized that for foreign business the salesman, or, as I prefer to call him, the commercial engineer, must know at least two foreign languages and speak and write them fluently, and must also study the manners and customs of the country in which he operates, it will be realized that his is no easy task and, therefore, is all the more worthy of encouragement. Sir Edward Crowe, Controller-General of the Department of Overseas Trade, at the last British Industries Fair emphasized how necessary it is to know various points of etiquette in foreign countries. In some you are considered an uneducated boor if you make a call in an overcoat; in others you must put on a glove to shake hands; in China the number 250 is never used if it can be avoided, and one firm making a 250-cm^3 motor cycle increased their sales enormously by calling it a 249-cm^3 model.

The subject of salesmanship is much too large to be more than touched on in this address, but I have indicated some of the lines on which the choice and training of the commercial engineer should proceed. To these must be added the quality or virtue of tact. Buyers and users of plant have their own prejudices and ideas, and these must be met and overcome without losing the confidence and goodwill of the buyer in question.

Lastly, the commercial engineer must be able to express himself well on paper. He must remember that the manufacturers thousands of miles away can only act on his reports, and he must put himself in the place of the man at the works reading these reports and enable him to grasp what is wanted in the way of design and estimate. On the other hand the manufacturer must place implicit confidence in these reports, and must remember that the man on the spot knows the local conditions, and should these conditions call for re-design he must be prepared to re-design if he wants his share of this business.

And now we come to the problem of advertising. Of late years advertising has become a profession in itself and the sums spent yearly on advertisement are enormous. Whether they are justifiable or not is a moot point. In my opinion, one of the benefits to be derived from amalgamations will be the restriction of these advertisements, and the sums thus saved will prove of inestimable value, whether put back into the industry for research and development, or given to the public by way of reduced prices. Of course, these remarks do not apply when dealing with foreign trade, as in that case foreign competition has to be met. For the home markets the propaganda work carried out by the British Electrical Development Association can be relied upon to do what is necessary to increase the number of users of electricity, and it is my serious suggestion that greater support of this Association by manufacturers and supply authorities will give good results, and at the same time materially reduce the individual advertising allocations of the subscribers. As regards foreign trade, different conditions have to be met and very special efforts made to keep British goods before the buyers.

Much could be written on this subject, which is worth very careful consideration. Many firms go to endless trouble to see that all wastage in production is eliminated, and yet place unlimited trust and large sums of money in the hands of an advertising firm without giving sufficient thought to whether the programme is likely to be remunerative.

It may be pointed out that this address, though delivered before a body of electrical engineers, does not deal specifically with that industry; but I submit that as far as South Wales is concerned, and to a slightly smaller degree the whole country, the electrical industry is dependent on our basic industries of coal, iron and steel and that, therefore, any remarks concerning the one will also apply to the other.

To sum up in a few words the commercial future of our industry as I see it, reorganization on rational lines is necessary, not only on the production but on the distributing and operating sides. Old-fashioned methods must go, and a new vision must materialize. Wherever possible, co-operative production must be put into operation and weak links cut out or strengthened, as costs can and will be reduced thereby.

There will always be the danger of amalgamations genuinely formed for better and cheaper production becoming debased into price-maintenance cartels, and this danger must not be overlooked. Trusts and monopolies have never yet benefited mankind, and it is to be hoped that our profession—the one above all others operating for the general good—may never be free from honest competition.

Another danger lies in the suppression of individual thought and effort. Those in authority must guard against this, as it is just that individual touch which distinguishes British goods all over the world.

The standard of commercial engineering must be raised and recognized, and both manufacturers and users must realize that it is only by co-operation that the industry can survive the great trade struggle between this country and its foreign rivals which is now commencing. The next few years will witness competition from abroad the like of which has never yet been seen. We need not fear this competition as regards quality: there are no goods to equal ours. We can meet this competition in price if only we realize what we have to do and set about it. We can regain the markets of the world if we abandon our somewhat insular methods and appreciate that the man who pays the piper has a right to call the tune. Let us therefore realize that in our industry each has a job to do—a niche to fill—and that each can help, not only the industry, but his fellow man if we will forget self and, with larger vision, regard himself as a small unit of the greatest industrial profession the world has ever known.

SOUTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By G. R. J. PARKINSON, Member.

"ELECTRIC POWER SUPPLY."

(*Address delivered at* BIRMINGHAM, 16*th October*, 1929.)

During the last 45 years the advance in electrical knowledge and the application of electricity to so many purposes have resulted in engineers being compelled to specialize in some particular branch, and the concentration of their studies and research in that particular direction has necessarily left them with an indifferent knowledge of the intricacies of other equally important branches of their profession. Now this Institution caters for every class of electrical engineer, but as the whole of my experience has been gained in the electric supply industry I trust that those members who have followed other branches of our profession will forgive me if I confine my remarks to the only section on which I can speak with any authority.

The public supply of electricity was commenced about 1880. In 1882 the first Electric Lighting Act was passed, and, as the name of the Act implies, little importance was attached to the possibility of supplying electricity for any other purpose than illumination. At this time the financial return from electricity supply was of a very speculative character, and consequently the pioneer work of developing the electricity supply service was left solely in the hands of private companies, although provision was made in the Act that where a company was authorized to supply electricity, the local authority in whose area the supply was authorized had the right to buy out the company at the end of 21 years. This period was far too short: Electric supply was in its infancy, and progress was very slow until 1888, when a new Act was passed, amending the tenure of private companies by increasing to 42 years the period after which local authorities could purchase.

From this time onwards progress was more rapid. Many new companies were formed and, confidence in the industry being established, most of our cities and large towns applied for Provisional Orders under municipal control and, with the exception of London, the company undertakings were confined to the smaller towns. In all cases, however, the authorities for the individual towns were quite independent, and were only authorized to give a supply within the boundaries of their respective city, town or urban district.

Even at that date it was recognized that many of the supply areas were much too small to be operated on the most economical lines, and about 1898 a number of companies were formed, with statutory powers, to supply electricity throughout the comparatively large areas of one, two or three counties. These companies were mainly confined to supplying power to factories, and bulk supply to smaller authorized distributors, and were prohibited from supplying lighting except under separate Provisional Orders, and not in competition with existing authorized distributors. This latter provision stultified one of the main objects of the power companies, as it still left the country saddled with a large number of small isolated supply undertakings with small and inefficient generating stations. The 1919 Act was passed with the object of removing this disadvantage. The country was provisionally divided into about 20 Electricity Districts, and it was anticipated that a Joint Electricity Authority would be formed in each district, to consolidate under one ownership and one management the generation of electricity for the whole of the district. The Act also provided for the setting up of a Board of Electricity Commissioners who, in addition to taking over the duties previously carried out by a department of the Board of Trade, should be responsible for co-ordinating and judicially supervising the development of the electric supply industry. Unfortunately this Act, with the further provision of the 1922 Act, did not fulfil the expectations of its sponsors, primarily because the districts were not compelled to form Joint Electricity Authorities, and in 1926 a new Act was passed, still with the object of improving the methods of generation, by concentrating and interlinking, and thus providing a cheap and abundant supply throughout the country but on entirely new principles. Under this Act a further Board was set up, known as the Central Electricity Board, an executive body which was made responsible for co-ordinating the generation and main transmission of electricity throughout the whole country, without actually owning the generating stations. The Board will select a number of the largest and most economical stations and link these together by means of 132 000-volt transmission lines, thus forming a system of national busbars serving the whole country. The selected stations will be operated to the instructions of the Central Board, in such a manner as to generate the full requirements of the country at the highest possible efficiency, and considerable savings can be made by closing down hundreds of small inefficient stations, by running the most efficient stations at high load factor and utilizing the less efficient stations for peak loads only.

As previously mentioned, the first supplies of electricity were used almost exclusively for lighting purposes. The generators were rope-driven sets, with reciprocating steam engines as the prime movers. When I went to Portsmouth in 1894 the generating station had just been opened, and was considered one of the most up-to-date in the country. Electricity was generated at 2 000 volts by means of flywheel alternators and horizontal Corliss-valve engines. The alternators were of 212 kW capacity each, and we also had a small Parsons turbo-alternator of 75 kW. At that time records and performance tests were of the crudest, and integrating watt-hour meters were of doubtful accuracy, but from some of my old notes I find that the actual consumption was about 12 lb. of slack per unit sold. I have no record of the annual load factor, but it was probably about 8 per cent.

At this time, although most engineers realized that high load factor was the key to low cost per unit, very few had the courage to offer electricity at a sufficiently low figure to induce manufacturers to adopt electric driving in their factories; moreover, electric motors, especially alternating-current motors, left much room for improvement. It was not until 1898 that the idea of using electricity for industrial power purposes became popular. By this time considerable improvements had been made in induction motors, and experiments on the Continent had proved the advantages of polyphase transmission and distribution, but although a number of power companies started operations about this date it was some years before electricity was adopted to any extent for factory driving. It was extremely difficult to convince manufacturers that electricity could compete in cost with either steam or gas. Take this district, for instance: a fair quality of engine slack could be purchased at about 4s. per ton, delivered in barges alongside the works. Stokers' and engine-drivers' wages were about 5d. an hour for a 60-hour week, and, notwithstanding the many advantages of electric driving compared with steam, it was difficult to show an actual saving in cost and it was necessary to offer electricity at a very low rate in order to displace an existing engine. Nevertheless, electricity gradually won its way. By 1914 electricity was slowly but surely replacing all other forms of power in existing factories, and was installed almost as a matter of course in new works. During the War the demand for elecricity for driving machinery, electro-metallurgy and electro-chemistry was far beyond the capacity of the existing supply undertakings, and during the 5 war years it was impossible to install generating plant at a sufficiently rapid rate to meet the demand. We all suffered from the slump in 1921 after the feverish excitement of over-production and false prosperity in 1919-20, but since then electric supply undertakings throughout the country have experienced a steady and ever-increasing demand.

I have sketched very briefly the history of the electric supply industry in order to give an idea of the progress that has been made and the importance of the business, and I shall now refer to its bearing on our national economy.

Our very existence as a nation depends upon our ability to export manufactures in competition with the rest of the world. Not only must our manufactures be of such quality and kind as to satisfy our clients, but they must be offered at a competitive price. We are handicapped by heavy rates and taxes; the hours of work and rates of wages paid to our workpeople are in many cases higher than those of other competing nations, and our only chance of keeping abreast of our competitors is by reducing the cost of production. The question of rates and taxes we must leave to our politicians. Reduction of wages is out of the question, for the present wages are barely sufficient to maintain a reasonable standard of living. We must therefore look to the improvement of methods and the reduction of the cost of the utilities, the most important of these being heat, light and power. These have to be derived from some natural source. In many countries an inexhaustible supply is available from the rivers and can be obtained without draining the potential capital resources of the country. Unfortunately, we have only a very limited amount of water power available in this country, and until a commercial proposition for the utilization of the tides is available we have to depend almost entirely upon coal. In this respect we are blessed with very extensive coal deposits, and it is to this source that we must look for our supplies of heat, light and power. It should be remembered, however, that the supplies are not inexhaustible. We are, to an extent, living on our capital, and it is our duty to posterity to see that we utilize our national resources with reasonable economy.

Starting, then, with coal as our source, we have to provide the three utilities heat, light and power—utilities which are required by every member of the population, in the cottage, the mansion, the shop and the factory, and electricity is the ideal medium for obtaining these utilities from the raw coal and conveying them to the individual consumer. I shall refer later to other methods of domestic heating, but whether this is done entirely by electricity, or partly by other means, I feel that electric supply undertakings should be in a position to meet all requirements for heat, light and power.

Now as to the development of public electric supply. Referring to the Board of Trade Reports on the census of production, it will be found that in 1924 roughly 50 per cent of the power required in factories was obtained from electricity, and of this one-half was purchased from public supply authorities, and one-half generated privately, so that only one-quarter of the power requirements was met by public supply authorities, and we can look for a potential demand, for this purpose alone, four times as great as the output in 1924, independent of extensions and new developments. Railway electrification is another potential demand: whether or not our main lines are electrified, there is no doubt that we shall have large extensions in suburban line electrification. Then again, in electro-chemistry and electro-metallurgy we may look for considerable development. It is possible at the present time to convert iron ore into steel in an electric furnace, and although the process is not a commercial success at the moment it is not improbable that an improved furnace, working on a continuous cycle, and obtaining a supply at high load factor from a modern selected station, may be able to compete successfully with the blast furnace and convertor.

Lastly, there is the domestic consumer (and with the domestic consumer I include shops and offices) with a demand for heat, light and power equal to one-third of the requirements of the country for all purposes. Domestic electrification is a somewhat contentious question, even among electrical engineers. I am not convinced that the all-electric house is the ideal, from a national economy point of view. I would divide domestic electrification into two sections:—

(1) Including lighting, occasional heating, cooking, ironing, washing, ventilating, vacuum-cleaning, refrigerating, etc.
(2) The general heating of houses, and hot-water supply.

In the first section electricity not only offers enormous advantages from the point of view of convenience, cleanliness, health and labour-saving, but it can be supplied at a cost which compares favourably with other methods. The second section is, however, in a different category. Under the best conditions the thermal efficiency in the production of electricity is only about 18 per cent when reckoned at the consumer's terminals. Coke and coalite can be burnt in a closed stove, for heating the house and the hot water, at a thermal efficiency of at least 50 per cent; moreover, general heating is required for only 5 or six months out of the 12, and the universal adoption of electricity for general heating would have a serious effect on the load factor of our generating stations and prevent that reduction in cost which we are all anticipating as the demand for electricity extends. On the other hand, if electricity were confined to the first section the occasional heating in the summer months, when general heating is not in use, would tend to equalize the summer and winter demands and thus improve the load factor. I am, of course, speaking in general terms: there are no doubt many instances where both general heating and water heating, particularly if combined with thermal storage, can be, and have been, installed with most satisfactory results.

I have referred to the fact that in 1894 it was not uncommon for a generating station to burn 10 to 12 lb. of coal per unit sold, or, say, 8 to 10 lb. per unit generated. Since that date, engineers have so improved the design and operation of generating stations that, together with the larger demand and improved load factor, in the most up-to-date stations it is possible to reduce the consumption to less than 1½ lb. per unit generated. It does not appear probable that we shall be able to reduce this very much further without introducing such complications as would counterbalance the reduction, and I think we must look in the future for further economies by extracting and selling by-products. There are a number of processes now in use for the extraction of gas, oil and tar from coal, and leaving a coke residue known as coalite, which makes an excellent smokeless fuel, and such a process can be conveniently combined with the generation of electricity. The low-temperature carbonization of coal is essentially a continuous process, and a supply undertaking could run such a process at 100 per cent load factor, burning the whole output of gas and coalite on full load and storing the excess of coalite during light loads, the excess being sold to consumers for the general heating of their houses, just in the same way as the gas undertakings sell coke. The oil and tar recovered should more than repay the cost of carbonization. Naturally, the quality of coal available, whether suitable for carbonization or not, and the relative cost of other fuel available in the district, would require very careful consideration, but I feel that an electric supply undertaking should be in a position to meet all the requirements of the public in supplying heat, light and power, and a combined system of carbonization and electric generation offers an ideal method, both from a national and a personal economy point of view.

Few people realize the vast quantity of coal burnt in open grates. In 1927, 180 million tons of coal were consumed in this country, and of this total 40 million tons were used by domestic consumers. We, as electrical engineers, claim that not only is this coal used most uneconomically, but that most of our smoke, dirt and fog is due to the open grate. It is true that the general use of coalite would not dispose of the inefficiency of the open grate, although it would make a big improvement in the smoky atmosphere of our towns and cities; but the public should be educated to make more use of the closed stove, combined with central heating and hot-water supply. I was discussing this question recently with an engineer in Switzerland. Owing to the large amount of water power available in Switzerland, from a national economy point of view it would be to the advantage of the Swiss to use electricity for every purpose, but this engineer told me that, notwithstanding their intensive electrical developments, they could not supply electricity for general heating purposes at a price comparable with the cost of coal, and in most of their hotels and large buildings they used coal or coke for central heating, and electricity for lighting and all auxiliary purposes.

You have all heard of the experiments carried out by the Newcastle Electric Supply Co. for the carbonization of coal in connection with the generation of electricity. Their Chairman stated recently that their experimental plant had proved the commercial possibility of this combination, and I understand that they are now making considerable extensions to their carbonizing plant. At the present time there is keen competition between gas and electric supply undertakings, a competition which has been of undoubted advantage to the public and has led to most of the improvements in both electric and gas lighting. On the other hand, it is not economical to have two systems of distributing heat, light and power, involving double sets of distribution mains and services, and administrative charges, and, further, the healthy competition has often developed into rampant antagonism. It may be that some day we shall see the gas and electric supply undertakings working together—the gas department taking responsibility for the carbonization and leaving the electric department to generate and distribute electricity and coalite to meet all the requirements of the public for heat, light and power.

IRISH CENTRE (DUBLIN): CHAIRMAN'S ADDRESS

By T. J. MONAGHAN, B.Sc.(Eng.), Member.

"THE PROGRESS ACCOUNT."

(Address delivered at DUBLIN, *17th October,* 1929.)

The task I have set myself to-night is to examine a few of the current entries, debit and credit, in the ledger of progress.

First let us decide what we mean by the word "progress." If it were possible to obtain the considered views of the educated public as to the principal benefits conferred upon the world at large by the scientific advances of the past one hundred years, there can, I think, be little doubt that the consensus of opinion would be very much as follows:—

(1) Vastly improved methods in medicine and in surgery.
(2) Rapid transport by road, rail, sea and air.
(3) Enormously improved communications by the aid of telegraphy and telephony, including wireless.
(4) A general improvement in the standard of living.

Examining this agreed list, we find that almost all these developments are really concerned with loosening the fetters of space and time, that are, or rather that seem to be, imposed upon mankind in this material world.

The improvements in medical science have added something more than a decade to our expectation of life as compared with that of our grandfathers', and have, furthermore, by the potent aid of antiseptics and anæsthetics, substituted hours of mere discomfort for the days of agony endured by earlier generations of patients.

Modern transport enables man to spend most of his time where he wishes to be, rather than, as hitherto, in covering the space separating him from the place of his desires. Modern communications enable him to disregard to a very considerable extent the limitations of both space and time, and to exchange ideas easily and quickly with his brethren wherever they may be.

By the somewhat vague description "an improved standard of living" we mean such things as the release from drudgery in workshop and in home rendered possible by that most useful servant electricity, such things, too, as the health and comfort given by ventilation, refrigeration, heating, etc.—products of an electrical age.

Now all these tremendous advantages have increased very considerably the possible "efficiency of living," which expression I would define as the ratio of the time spent in doing the things we want to do, to the total time at our disposal. This higher efficiency of living has created for the world, in the aggregate, many years of that very precious commodity, time. These benefits have not, however, been won without toil and trouble, and in order to get some appreciation of what has been involved in reaching our present state of development, let us glance at its history.

The birth of each of the major advances in applied science has been due, I think, to inspired dreamers, practical visionaries, forward-looking men who were not satisfied with things as they found them and hence were always seeking to push on into the land of new ideas. It is such men as these who, in the lifetimes of many of us, were so foolish as to believe that aeroplanes and transatlantic telephony would one day be normal public facilities though the solid citizen knew such things to be but wild dreams and vain imaginings. Fortunately, such visionaries have usually been able to infect with their enthusiasm a few holders of the purse strings, but, unfortunately, it has usually happened that the scientist has lost his time and hope, and the capitalist his money, without reaching the goal of their desires.

But the way to progress has extorted a heavier toll than time, hope and money, for many of the seekers after knowledge have been willing to gamble with their lives. Doctors have allowed themselves to be inoculated with fevers and other dread diseases, in order that treatments and antidotes might be tested under carefully supervised conditions; the earlier workers with X-rays have continued to labour for the benefit of humanity while suffering the agonies of X-ray dermatitis, which has killed them at last; and in more mundane matters, such as the development of the motor-car and the aeroplane, there have been many venturesome spirits willing to stake their skill and luck against the forces of nature, in an effort to extend man's dominion. In the development stage, then, we find many instances of individuals who consciously staked their lives in an effort to prove a particular hypothesis, perhaps that a certain serum will cure a fever, perhaps that a certain car can travel at more than 300 miles per hour. Thus have the amenities of scientific progress been won for the benefit of the world at large, and we may well pause to pay our tribute of respectful gratitude to those who have struggled so hard and staked so much on our behalf.

The fruits of progress that we are considering have passed beyond the development stage, and through the next stages of experimental and of restricted private use, and are now available to, and utilized by, the general public on an ordinary commercial basis. Successful commercial enterprises have to be at least self-supporting, that is they must be offered to the public at a price that the public believes to be fair and reasonable for the services rendered and is therefore prepared to pay.

In talking of price we usually mean cost as expressed in terms of the cash or commodities that we exchange for the wanted article, but I desire to emphasize that in the real price of these modern amenities there is an element much more important than cash, namely, human life. I spoke a little earlier of the deliberate staking of life by individuals in their efforts to wrest her secrets from Nature, but here we are dealing with, not a voluntary, but an imposed risk, borne by the public at large. In a dim sort of way the public recognize that most practical advances of science are accompanied by an element of danger; thus high-speed travel introduces risks not present in low-speed locomotion, the danger of electric shock could not arise in an unelectrified community, and aeroplanes could not crash if they could not fly. The mass of mankind recognize and accept these risks, in a vague and uninformed way, but there is a limit to the risk that the public will take. For example there is, at the moment, a mass searching of heart going on throughout the world as to whether the toll of life and limb being exacted by motor-car accidents is not altogether too high, and the public are, I think, prepared to acquiesce in restrictions on their present degree of liberty in an effort to reduce the present very high accident rate.

We should really consider then, in each case, the two elements of cost—cash and risk—before deciding whether a thing is cheap or dear, and it often happens that the cash element can be reduced if one is prepared to increase the risk.

Turning now to the particular commodity in which we are all interested, namely, electricity, let us consider the risks, actual and relative, attendant upon its use. There have been many arguments upon such matters as wiring rules, standards of construction and so on, that I, for one, have found somewhat unreal, because of the difficulty of measuring the amount of protection gained or the extent of the risk run. In an effort to throw some light on the matter, I have collected from various official sources some authoritative figures to which we can, with, I believe, considerable advantage, devote some attention.

Table 1 gives for various countries and different years particulars of the number of deaths from various accidental causes. The figures are not so bewildering and disconnected as they may seem to be at first sight; they assume some sort of order after a little scrutiny.

Let us consider first the figures for England and Wales for 1924. The figure for fatal accidents per 100 000 of the population gives us some sort of idea of the general risk level in the community, for comparison with that in the same country year by year and with the corresponding figures for other countries.

It will be seen that falls account for more deaths than any other single cause, though the figures for motor vehicles approach them closely. Accidents on railways are about 25 per cent of the motor-vehicle rate. The figure for accidental absorption of poisonous or irrespirable gas is of interest for comparison with the electrical shock rates. The other figures I have selected, excessive heat and cold, lightning, cricket and football, give us some idea of the extent of little-appreciated risks.

A brief study of the table as a whole will show that there are no very large jumps in any of what we may call the man-made causes from year to year (excessive heat, which is outside human control, showing, I think, the widest variations). There is, however, evidence of marked trends even over the short series of years I have shown in the table.

The United States is apparently prepared to live more dangerously than Great Britain, the ratio for all accidents being about 2 to 1, but in the domain in which we are specially interested, viz. electric shock, the rate in the United States, as compared with that in this country, is about 10 to 1. The American rate for gas deaths, is considerably more than 10 times the English rate.

Canada comes intermediate between Great Britain and the United States for electrical accidents and gas accidents.

It will be noticed that there is a tendency for the accident rate in England and Wales to rise in the years under review, and a little inspection shows this to be due chiefly to motor accidents. In England and Wales in 1924 there were more falls than motor accidents, falls still lead, but by a lesser margin, in 1925, but in 1926 motor accidents exceed falls and continue to advance in 1927.

In the case of the United States figures we see that, for the years under review, motor accidents have been more numerous than falls and are becoming more numerous each year, and the rate of accidents per 100 000 of the population is considerably greater than in England. A very considerable number of accidents due to falls and to motor vehicles is evidenced for each country in the table for each year.

It will, I think, surprise most people to find that in England and Wales one is more likely to meet a sudden end by falling downstairs than in a railway accident; in the United States, however, the risk rates for these causes are reversed.

The number of deaths in England due to excessive heat came as a surprise to me, and it is interesting to note that the figures for this cause of death for England and Wales and the United States move in sympathy over the years shown. Thus, taking 1924 as a datum, there is a marked rise in both countries in 1925 and both show a fall in 1926. I expected, but did not find, some correlation between deaths due to lightning and those due to excessive heat.

These comparisons are, I think, all of interest, but their real value for our purpose to-night is to enable us to see in correct perspective the entry with which we are particularly concerned—deaths from accidental electric shocks.

Taking England and Wales first, for which my figures are most complete, it will be seen that the deaths due to falls out of bed are more numerous than those due to electric shock, and that, year in, year out, excessive heat and cold each levy a toll comparable with, and usually greater than, that levied by electric shock.

I would direct attention to the figures which show that accidents at football and cricket are responsible for about half as many deaths as electricity. Study of the table will suggest many other interesting comparisons that need not be detailed here.

Before we attempt to draw any rules for guidance from these figures, let us see whether we can analyse

TABLE 1.

	1924		1925			1926			1927	
	England and Wales	U.S.A.*	England and Wales	U.S.A.*	Canada (excluding Quebec)	England and Wales	U.S.A.*	Canada (including Quebec)	England and Wales	Holland
Population (approximate)	38 750 000	99 200 000	38 900 000	103 100 000	6 740 000	39 100 000	105 200 000	9 400 000	39 290 000	7 630 000
Fatal accidents (all causes)	13 239	75 745	13 968	80 774	3 775	13 895	82 715	5 063	15 007	2 070
Fatal accidents per 100 000 of population (approximate)	34	76	36	78	56	36	79	54	38	27
Falls: Total	2 766	12 955	2 935	13 846	394	3 044	14 681	678	3 195	354
Downstairs	563	1 506	620	1 707	—	657	1 979	—	673	—
Out of bed	57	—	63	—	—	63	—	—	62	—
Motor vehicles †	2 453	15 528	2 827	17 571	425	3 293	18 871	606	3 707	553
Railways	578	6 430	527	6 778	228	419	7 026	434	466	
Accidental absorption of irrespirable or poisonous gas	133	2 525	163	2 439	58	213	2 836	80	195	—
Excessive cold	40	335	56	239	53	54	256	44	62	3
Excessive heat	30	409	121	1 355	72	92	646	32	15	3
Accidental electric shocks (excluding mines)	38	977	42	955	34	44	1 037	53	48	16
Lightning	15	334	17	442	19	11	364	13	5	23
Football and cricket	18	—	19	—	—	29	—	—	25	—

* Registration area. † Includes cars, vans, lorries, cabs, omnibuses and cycles, but excludes collisions with railway trains and street cars.

TABLE 2.

Year	Country	Accidental deaths from electric shock			Age at death											
		Total	In work-shops and factories	Balance	Under 5	5–9	10–14	15–19	20–24	25–34	35–44	45–54	55–64	65–74	Over 75	Unknown
1925	Great Britain (excluding mines)	46*	24	22	—	3	2	5	9	14	7	4	2	—	—	—
1926	Great Britain (excluding mines)	47†	17	30	1	5	9	5	5	13	5	2	1	1	—	—
1925	U.S.A. (registration area)	995	—	—	6	11	52	92	165	325	202	87	42	11	1	1
1926	U.S.A. (registration area)	1 037	—	—	10	17	43	99	201	319	198	78	50	16	2	4
1925	Canada (excluding Quebec)	34	—	—	—	—	4	2	3	13	9	3	—	—	—	—
1926	Canada (including Quebec)	53	—	—	—	—	2	4	10	21	9	7	—	—	—	—

* England and Wales, 42; Scotland, 4. † England and Wales, 44; Scotland, 3.

them still further. It would be of considerable interest if we could separate the industrial accidents from the totals, but with the means and time at my disposal I have been able to do this only for Great Britain. The manner in which the various official statistics are published renders it easier to use figures for the whole of Britain for this purpose, rather than those for England and Wales alone as has been done in Table 1. In Table 2 is given, then, some analysis of the electrical accidents.

The percentage of industrial accidents is perhaps not so high as we should have expected. The information as to incidence by ages suggests some interesting reflections, and will be further invoked in evidence later on. It will be seen that quite young children figure in each country's return year by year. It has been suggested to me that possibly the uninformed use of electrically-operated toys has something to do with this, and personally I have a suspicion that unguarded wall plugs may also be a factor. The climbing age is in evidence, I think, in the 10–14 and probably in the 15–19 groups. The majority of the accidents occur to people in the prime of life, though the United States figures show that some quite elderly people are involved. The vast majority of the accidents occur to men.

An examination of these figures suggests the thought that the electrical accident rate in any country probably depends upon two main factors. The first is the general mental outlook of the people, i.e. the price they are prepared to pay for progress, or, in other words, the extent to which the conservative or the adventurous type predominates amongst the population, particularly in the ranks of those responsible for the compilation of electrical codes of rules. The second main cause that we should expect to influence the rate is the extent of user of electricity. Possibly, too, local climatic conditions may be of moment, but it is very difficult to get evidence of this.

Table 3 gives the consumption per head and the risk rates for various countries. This will repay examination.

TABLE 3.

Country	Accidental deaths from electric shock per 100 000 of population	Electrical consumption per head per annum
		kWh
U.S.A.	1	1 100
Canada	0·4	1 500
Great Britain ..	0·1	220
Holland	0·2	160

We have now surveyed a limited field, admittedly in a hasty way, but we can, I think, now draw some general conclusions of interest and value. First, there is a very marked difference in the incidence of electrical risks upon different peoples, and, secondly, the risk does not necessarily increase in proportion to the rate of use of electrical energy.

If one had the time and opportunity to collect for each country information as to the proportions of industrial and non-industrial accidents, and to analyse the causes of both types of accident, and if this information were studied in the light of the constructional rules and methods in force in the various countries, it would no doubt be possible to account for the differences in risk rates in different countries in a more or less satisfactory way. Valuable as such a detailed and comprehensive analysis would be, my purpose to-night has been sufficiently served if I have established clearly that the rates of electrical risk differ widely in different countries, and that in none of them is there as yet any sign of general public protest that the risk rate is too high.

I have already pointed out that, up to a point, the people as a whole are satisfied to leave the setting of standards of risk to their expert advisers. Thus we electrical engineers are confronted by the difficult task of trying to strike a true balance between the two elements of cost of electrical applications—cash and hazard.

I would submit, for example, that the electrical accident rates of 1 per 100 000 of the population of the United States, and of 0·1 per 100 000 of Great Britain, are difficult to reconcile; either one is much too high or —and I say this with considerable trepidation—possibly the other could be suffered to increase. Whether we like it or not, it is our duty as the advisers of the general public to form, and to act upon, a definite opinion as to the magnitude of the risk rate that can be regarded as reasonable.

Here I must take great care to prevent any misunderstanding of my arguments. Let me say, then, as clearly and as positively as I can, that I deplore as much as anyone the avoidable loss of a single life. But I am trying to deal with the world we live in, and the fact remains that avoidable loss of life is continually taking place. Mankind in the mass does not hesitate to accept risks to life and limb if there is enough to be gained by the venture. If the cult of "Safety First" is pushed to the limit we may manage to exist a little longer on the average, but we shall certainly lose much that tends to make life worth living.

We often hear the sentiment expressed that human life is of infinite value, above and beyond all monetary price, but though I shall be talking later in terms of money I am not trying to strike a balance with life in one scale pan and gold in the other. Looked at in the proper way, the problem is an effort to balance correctly human life against human life, years of one individual's existence lost, set against a gain in life value for tens of thousands of people, a gain brought about by improved conditions.

I am not advocating that we should incur more risks in electrical applications; I am trying to survey the ground to see what justification, if any, the electrical engineers (who are morally responsible) have for increasing the hazards of the general public, offering, as recompense for the greater risks, improved and cheapened facilities.

This is an issue that we electrical engineers must face. How can we begin? It will readily be agreed that in attempting an investigation such as this we must go on statistical lines. Individual cases, except as grist to the mill that grinds out the average we are seeking, must either be forgotten or met with the reminder that we are looking for the greatest good of the greatest number and are prepared in our search to appear callous if only we can be clear.

In order to be able to put our findings to practical uses, however, we must make a conversion into money, because the hard facts of the case are, that acceptance of increased risks enables us to cheapen construction costs.

The first step in the investigation, then, is to try to express our time losses and gains in terms of money. Let us suppose that we ask an actuary, a member of that profession accustomed to dealing with human probabilities in the mass from a monetary point of view, "What value do you place on human life?" The answer, I imagine, would be something like this: "The estimated value of a particular human being at a given time is the difference between the present value of his probable future earnings and that of the cost of his future personal needs; in a nutshell, the probable surplus available after he keeps himself."

I attempted to collect some information as to the average earnings in Great Britain, but I was not very successful. I found from the Income Tax reports that the average income of those people who make returns in Great Britain was about £500 per annum, but this figure does not include wage-earners whose gross income does not reach the exemption limit. My very rough attempt to include all wage-earners gives a figure of about £250 per annum for all incomes. Later I found a reference to an estimate by distinguished economists that the average income per head in Great Britain for 1924–5 was £84. At any rate these figures give us a clue to the order of the magnitudes concerned.

If, by any means, we can form an idea as to the probable accident rate due to a particular change of conditions, we are in a position to form an estimate of the cash cost of the risk, for we have evidence in Table 2 as to the probable age of the victims, actuarial tables will give to a close degree of accuracy their expectation of life, and we may safely assume that they will probably be men and earners. I do not wish to labour the point, and I have perhaps sufficiently indicated that it is possible to estimate, it may be very roughly, the actuarial cost of electrical accidents.

To crystallize our ideas, let us assume that a fatal accident occurs to a man earning £250 per annum, whose expectation of life is such that his actuarial cash value is £5 000. Now there is a vast difference between the absolute and irrevocable loss of a life, and the gain in the amenities of other lives, and it is necessary to make some provision in our inquiries for this outstandingly important fact. In many engineering calculations we use a factor of safety, a factor that increases as our ignorance of the real values of the quantities involved increases, and that increases also according as risk to human life is involved in the issue. In attempting to balance loss of life against increased amenities we must introduce a factor of recognition of the vast differences between the two things. I have called this factor, tentatively, the "vitality compensation factor."

Much more detailed examination than has been possible to-night would be required before I dare attempt to assess its magnitude—it may be 20 or 50 or 100—but to show how it would operate, suppose it to be 50. Then for constructional estimate purposes the cash value of our man of actuarial cash value £5 000 is 50 × £5 000 = £250 000. I know this sounds very materialistic, but let me remind you that overhead high-tension lines are being erected all over the world to-day because they are cheaper than underground cables, and we all know that with open lines fatalities which are impossible with cables are bound to happen.

I have only one more point to touch upon. The question arises: "Assuming that an increase in electrical risks can be faced, in what way do we propose to relax our precautions?" Well, I imagine that most electrical accidents are due to one or more of the following causes: Bad design of equipment; bad workmanship; ignorance; carelessness; recklessness; forgetfulness.

Real risk to the ordinary user of electrical facilities should be removed as much as possible by attention to design and workmanship, but it is at least debatable whether we are not going further than we should in protecting people against the consequences of their own recklessness or avoidable ignorance.

There is too, perhaps, a tendency to guard against extremely remote contingencies, against risks that arise only with two or more simultaneous failures of plant or personnel, each failure highly improbable in itself. Unfortunately we can only find out whether the seemingly remote contingencies really are remote by accepting, at least for a time, indeterminate risks.

With that I close my plea for a critical examination of electrical risks. I do not pretend to have done more than indicate a line of thought that may be worth following up, but I do feel that it is essential that we electrical engineers should, in this matter of risks, as in other matters, know what road we are on, how fast we are travelling, and why.

NORTH-EASTERN CENTRE: CHAIRMAN'S ADDRESS

By B. A. ROBINSON, Member.

"THE NEED OF MEASUREMENT."

(*Address delivered at* NEWCASTLE, 21*st October*, 1929.)

One important function of this Institution is to afford opportunities for the experience and knowledge of the electrical profession to be gathered together. The results can then be considered from many aspects before being consolidated and made available for posterity. This is especially necessary in any branch of knowledge where the growth is rapid. It follows that the majority of our meetings and discussions are concerned with technical questions whereby attention is concentrated and directed for the time being on to a certain field of view of small limits. It is not undesirable that your Chairman's address each session should tend to be the reverse and that it should deal with a wider survey, although necessarily briefly.

Whatever may be our outlook on the ultimate meaning of life, it will generally be agreed that we find ourselves in what appears to be a boundless treasure house containing a profusion of treasure, romance, riches and surprises in the most wonderful and bewildering array. In this treasure house we appear to be vital, all-important units, although we are only visitors for the time being. At the same time, although we are fully aware of our separate existence as individuals, we know also that we each form only one unit of a vast confluence of ever-moving units which are changing more or less constantly. On reviewing our knowledge of the history of past ages, we are sensible of the development of a faculty for the appreciation of the treasures and wonders around us. The growth of this faculty has not been uniform. At some periods it has been slow, indeed almost stagnant; at others it has been more rapid, and it is so rapid at present that it is difficult to appreciate its full extent, even without considering details. This cognition, not only of vast treasures, but also of minute elements, is what we call the work of science.

It is the function of the engineer to recognize the practical applications of the discoveries made by the workers in pure science and to utilize these to further the well-being of the community. He has to understand and use to the best advantage the materials which Nature has provided, and he has to develop the various forms of energy which are available.

The development of rubber will occur to everyone as an example of the use of material. It is only about 150 years ago that rubber was first obtainable in commerce, and then only in an insignificant quantity. To-day it is adapted to innumerable uses under various forms. On the other hand, we cannot forget Michael Faraday's fascinating experiments in 1831 when he moved magnet to coil, or coil to magnet. In some respects these seem simple to us now, but when we see the outcome in our modern transformers and alternators we find that they are epoch-making. Again, in 1865, exactly 200 years after young Isaac Newton made some of his brilliant mathematical discoveries, we find Clerk Maxwell using the outcome of those same mathematics to make known the original conception of electromagnetic waves. Compare that mental picture with the universal utility of modern radio communication.

The nation which possesses an active, able and far-seeing body of engineers is well equipped for the battle of life. In thus thinking of the universe in relation to ourselves, we must remember that we are a privileged section of the great family of man. It is our function, privilege and duty to develop the capacity of the whole of mankind to appreciate, to use and, we hope, to benefit by, the bountiful gifts of nature discovered around us.

Mention must be made of the indispensable co-operation and concurrent effort of those working in research and those turning the results of research into practice. This team work inevitably results in further problems to be faced. We find ourselves reciprocating, as it were—some frequently, and others at more leisured intervals—between searching into the unknown, and improving and making more valuable that which is known.

Both to the worker in pure science and to the engineer two qualities are essential, firstly, that of adventure, and secondly, that of dogged determination. These must be maintained in order that a consistent, truthful conclusion may be arrived at, in spite of difficulties, conflicting factors and much disappointment.

We, as engineers, do not lay nearly enough emphasis on the necessity for a courageous spirit of adventure in our work in order to develop still greater enthusiasm in the younger men who will carry on the work at which we have so imperfectly laboured. The driving powers of these qualities are very well illustrated in the life of Faraday. His biographers state that "a new fact seemed to charge him with an energy that gleamed from his eyes and quivered through his limbs and, as by induction, charged, for the time being, those in his presence with the same vigour of interest." When first he saw experiments on the action of a magnet on electric discharges in vacuum tubes, Faraday actually danced around and cried "Oh, to live always in it." A friend once met him in the midst of a tremendous storm at Eastbourne, rubbing his hands with delight because he had been so fortunate as to see lightning strike a church tower.

Faraday's spirit of enthusiasm and adventure led him to investigate any phenomena, regardless of his own welfare. It is not generally known that, in spite of his far-reaching and epoch-making researches in physical science, he found time, in 1818, to carry out experiments on himself on the effect of inhaling ether vapours, thus doing early and important work on anæsthetics. His overwhelming energy was not spasmodic. "It was a lifelong strife to seek and say that which he thought was true, and to do that which he thought was kind." We also should be adventurers with imaginative, constructive minds, using unceasing and careful observation. We seek a clear and honest interpretation of the many bewildering manifestations around us in order to make available for others the powers of Nature. We keep our survey before us and, as we carry out our work, we compare notes of that which we call experience. In so doing we find that our individual knowledge has much in common. We are involved in a process, not only of discovery and development but also of comparison. Henry Cavendish in 1773 conceived the idea that various electrical conductors possessed different degrees of conduction—the early conception of electrical resistance. His method of comparison was to pass the discharge of a condenser through such a length of the material as would give a "shock" which felt the same in each case. The "shock absorber" was his devoted and faithful servant Richard.

The fact that there are many degrees of appreciation was apparent to the early workers long before the advent of so-called modern science. The gradual progress of clearly defined knowledge resulted in the birth of a process of comparison with recognized, determinate quantities. The origin of the British standard of length—the imperial yard—was the length of the arm of King Henry I. In those days, actually, not so long ago, there was no need of fiducial points, or of a temperature coefficient.

From crude beginnings the necessity for comparison has resulted in the building up of a technology of universal importance in its applications. Moreover, its evolution has been extremely rapid of late years. This applies, not only with regard to its ramifications, but also in its advancement from simplicity to comparative complexity. Hence it is a department of science which now is left strictly to specialists.

Here it is opportune to note the difference between comparison and measurement. An illustration may make this clear. We can compare a statue of Haig with the treasured memory of a great British soldier and gentleman. The mental picture may even be assisted by highly accurate arts such as photography or speech-recording. Only a comparison can be made, however, and, as recent events have shown, that comparison may be a matter of considerable difference of opinion. There is no possibility of measurement. On the other hand, observers with quite different outlooks as regards beauty would agree to within extremely small limits when the weight of bronze in the statue is compared with an equal weight of discs bearing the King's image and superscription. The latter is true measurement.

Music affords us with another example. There is a precision of a high order of measurement in its fundamentals, exemplified in the frequency ratios of the musical scale or the relation of pitch to a basis of 256 or 261 vibrations per second for "middle C." Even the temperature correction for tuning forks has been determined to many decimal places. As the theory is reviewed there are the accurate time-differences of quavers, crotchets and minims. The science of measurement is then abandoned although, ultimately, we come to a modulated succession of sounds which harmonize and please a trained ear, that is, if it is music. Measurement does not differentiate between concord and discord, nor between some so-called music and that designated "a noise," as evidenced by the new Act of Parliament. We cannot conceive of any attempt to measure the tune of so-called "jazz" or Tschaikovsky's "1812" overture. This fundamental difference between comparison and measurement is often overlooked, even by those with long scientific training, in their desire to obtain further knowledge of the problems with which they are confronted.

True measurement may be defined as comparisons made under strict scientific laws. Thus we claim to measure quantities connected with materials which we cannot see, feel, smell, hear or taste, or the power to do work, with an accuracy fully equal to that with which we compare the length of a table with that of a foot rule.

Hydrogen is a gas used in huge quantities in industrial processes of to-day. The assumption is now made that an immense outer envelope of this gas surrounds our own planet. It is thought that our atmosphere, consisting chiefly of nitrogen and oxygen, merges into one of pure nitrogen and then nitrogen to hydrogen and, finally, pure hydrogen. Anyhow, hydrogen in its normal state possesses no property which affects our senses. In fairly large quantities it can readily be detected by chemical methods, but the chemist has great difficulty in arriving at a fairly accurate estimate of its purity when dealing with small quantities or weak dilutions. On the other hand, an accuracy of 1 part in 1 000 can easily and quickly be measured by the purely electrical method of noting its thermal conductivity.

When we come to the perception of colour, shape, taste or beauty, we cannot measure in terms of C.G.S. units. We can only compare in terms of human experience—the greatest gift we possess, but one which, as far as we know, does not conform to scientific laws.

All measurement is a system of comparison. Some measurements are simple, especially when an approximate comparison only is required. Take, for example, the quantities of milk, coal and general foodstuffs delivered each day to our homes. Others are complicated in nature and difficult to obtain to a high degree of precision. The methods of comparison can be divided into two classes; firstly, those made to determine the ratio as compared with some fundamental principle, or against a recognized unit. These are called standard measurements, and secondly, those made in vast numbers, especially in industrial processes, to give information of certain empirical conditions. Examples are the grading of cast iron by the appearance of fracture, and the hardness of steel. The first are usually known as absolute measurements, and the second as empirical measurements. From certain points of view, especially that of accuracy, these terms are misleading; empirical measurements are often more accurate than some standard or absolute ones.

The measurement of temperature is one of the most common standard measurements. It is difficult to think of any industrial process in which the measurement of temperature is not involved at some period. It is, however, a peculiar measurement as it is one which conveys no idea of magnitude from a material point of view. It corresponds to the attempt to form a mental picture of electrical energy when one knows only a figure called voltage. Most people, however, unconsciously connect other totally different factors when speaking of temperatures.

The standard of measurement is the difference of temperature of any quantity of pure water when under a pressure of exactly 1 atmosphere between the points of conversion into a solid and into a gas respectively. This interval of temperature between the conversions into ice and steam is called the fundamental interval. Measurements to this fundamental can be made with considerable accuracy over only a small range of temperature. Up to about 500° C. the uncertainty is about 0·1 deg. C.; at 1 000° C. it is 2 deg. C. The melting point of platinum at about 1 750° C. can only be given to within 10–15 deg. C. Coming to temperatures of the melting point of tungsten and that of the electric arc, which represent the highest terrestrial temperatures, we cannot justify our measurements of 3 300° C. and 3 500° C. to nearer than at least 50–60 deg. C. It must be remembered that these figures are obtained with the best precision instruments used under laboratory conditions.

When we are concerned with measurements of temperature outside our own planet, the accuracy of measurement can be compared with the firing of a rocket to the moon. The rocket, with its trail of light, will probably go in the right direction if properly aimed, but how far it goes we cannot say with any precision.

The last 50 years have witnessed a great advance in the science of measurement, due to three outstanding factors:—

(1) The application of genius and of scientific principles to the design of measuring apparatus.

(2) The increase in the number and variety of materials, possessing widely different physical properties, available to the designer.

(3) Precision methods of manufacture, allowing reproduction of a desired shape to within small limits of tolerance, comparatively quickly and at fairly low cost.

The modern development of instruments has allowed knowledge to be consolidated on a much higher level, far beyond the wildest hopes of anticipation of the workers up to the middle of the nineteenth century.

Precision instruments have been the means of opening up immense stores of new information, some of which has been seized upon quickly by the engineers and passed on for the general use of humanity. New instruments can be compared with expeditions of exploration—they give not only greater outlook of vision but also, what is equally important, new combinations of facts.

It does not always follow that the discovery of a hitherto unknown principle and the application of that principle to everyday use can be embodied in a measuring instrument. In fact, the disappointment is often great.

To state that the thermionic valve has revolutionized radio communication is to express the fact mildly. This valve in its many forms is a highly sensitive device with several different functions of use. As a measuring instrument its application, contrary to the expectations of the general community, is extremely limited. This is due to the fact that, in its present form, the thermionic valve embodies several variables in its operation and at the moment it is difficult to separate these factors with sufficient accuracy to enable the valve to be used as a measuring instrument.

The photo-electric cell is another example. An accurate connecting link between the intensity of light and the conduction of electricity has long been desired. The highly exhausted globe with its metallic conductor in front of, but not shielding, a light, sensitive surface, appeared to fulfil this wish. The cells have many applications, but to the specialist in measurement the problem is still an unfulfilled expectation. At the same time, considerable use is being made of this device in applications where only comparison is possible at the moment. We all know something of the problem of smoke abatement; the photo-electric cell is helping towards its solution. Another application is in densely populated areas like London and New York where the wane of natural illumination, due to various causes, is signalled to those responsible for artificial illumination, who can then take the appropriate steps.

The development of coloured materials has reached such a stage that it is difficult even for well-trained eyes to differentiate between different shades of colour. In these cases the photo-electric cell enables comparisons to be made with a standard tint. Similar uses are found in the grading of photographic plates and the comparison of light intensities, especially in meteorological and astronomical work. Conversely, an instrument designed for a limited purpose may with little modification be adapted to give accurate information of far-reaching consequence. A seismograph is an instrument especially designed to record minute impulses imparted to the earth's surface by various terrestrial changes and upheavals. At first sight it would appear that such an instrument would be of little use in the development of oil ultimately to be used to drive our aircraft and motor-cars, or even to set electricity in motion through the agency of oil-fired boilers. Crude oil often is found under a well-defined physical structure of the earth known as a "salt dome." The seismetric method of surveying is based on the fact that sound travels through air at an approximate speed of 1 100 ft. per sec.; through ordinary surface formations at about 6 000 ft. per sec.; and through the highly elastic salt domes at about 16 000 ft. per sec. Hence if a small charge of a few ounces of an explosive buried, say, 7 to 10 ft. deep, is exploded, a compressive wave will travel outwards in all directions. A simple seismograph will record the movement due to the wave. The instrument is fitted with an oscillograph so that, by means of a wireless wave, the actual time of the explosion also is recorded. The time of arrival of the seismic wave is recorded on the seismograph later. If from the record it is deduced that the velocity of the wave is of the order of 6 000 ft. per sec., then it may be inferred that no salt dome exists between the points of measurement. If the velocity measured is greater than 6 000 ft. per sec. there is reason to suppose that a dome may be present or that there is some fundamental difference in the structure of the lower rocks. By employing several seismographs placed in different directions, and also at different distances in the same direction, it is possible to deduce the presence and, roughly, the shape and location of the edge of a salt dome. This illustration of geophysical surveying also draws attention to two important factors of the need of measurement. One has already been mentioned, namely that of exploration and the finding of new combinations of facts. The second now claims our attention.

In dealing with measurements of electrical phenomena it is especially necessary to revise our outlook continuously, particularly as regards our fundamental assumptions, in order that the knowledge deduced from such measurements may be comparable with the general trend of perception in the science.

We cannot, as far as we know at present, actually measure electricity in any shape or form. At the best we can only obtain information of a relationship of the phenomena it produces under certain conditions. These phenomena always include energy in extremely rapid motion. Electricity at rest is not measurable—it is zero with us. At the same time our own faculty of perception—our mind—is only of use when it is in a state of activity, apparently an activity of great rapidity of change. A mind at rest is a blank to us; that is, it is meaningless. Hence, in dealing with electrical manifestations it appears essential that both that which is to be measured, and the perceiver, should be in a rapid state of change. Imagine a number of cameras all focused in the same direction but freely and rapidly moving at random to each other. If they are pointed at a fixed or slowly moving object, and if the shutters are simultaneously released, it is not a difficult matter to assemble the resultant photographs to give a more or less true perspective picture of the single object. If the same collection of moving cameras is now sighted on to a large number of rapidly moving objects—for simplicity a number of balls—it is extremely difficult, if not impossible, to piece the resultant photographs together to give an even approximately true picture at the instant of exposure.

This point of view may appear to be converging too much towards pure science as distinct from practical engineering, but it is necessary for us to realize these limitations if we are to form correct mental pictures of the relationships we wish to establish, especially in connection with space, time and motion. It also helps us to understand the outlook of the modern development of electrical measurement. We are not satisfied with the simple stationary lantern-slides of our boyhood; the demand is for a wide outlook—the moving, "living" pictures Let me give two examples. One of the problems of the extended development and distribution of large quantities of electrical energy at high potential is that of rapid control and interruption. To test the breaking capacity of a switch it is not in any way sufficient to put an ammeter or wattmeter in series with it. It is necessary to measure, at the same instant of time, the changes in a considerable number of phenomena in order to form even an approximately correct mental picture of what actually takes place at the period of operation. One practical result of such knowledge obviously is that still more reliable and efficient switchgear can be built—what might be termed "pedigree switchgear." Similarly with modern alternator testing. In the early days in a test house it was considered to be good practice to use an ammeter, voltmeter and tachometer at the same time, and many anxious moments were spent in trying to get the three elusive pointers consistently steady at the same time in order to log three pointer readings. Pointer readings they were and, as a result, we thought we knew something of the idiosyncrasies of alternator design. To-day a short-circuit test demands all the skill of the instrument maker, combined with the mature experience of the engineer. In spite of the large number of measurements now made, the demand is for more records, with less delay in obtaining such records, and the more accurate synchronism of the measurements.

It is the perception of these necessities which has been largely instrumental in the establishment of national, co-operative, and individual research departments, which already have done, and are doing, work of great importance. Unfortunately this fact is not appreciated by a large number of manufacturers or by the "man in the street" who ultimately obtains the benefits of their labours.

The application of the above-mentioned principles to instrument construction has enabled precision methods to be adopted in increasing numbers in our workshops. The instrument of the laboratory rapidly becomes the workshop tool. The difficult physical conditions under which the measurements are required to be made often necessitate substantial modifications in design. It is necessary to convert the high-precision laboratory instrument, having adaptability for many uses and entailing skilled manipulation, to an instrument in which the accuracy is of a less high standard of precision but which will withstand the difficult conditions of the workshop, requires the minimum of attention and gives readings which can be readily interpreted by the workman. The same argument holds good when we apply laboratory methods to the necessities of everyday life. An example of this is the measurement of electrical energy, with its different components of current, voltage and phase, by means of the reliable, compact and cheap supply meter now fitted in consumers' houses. Two large industries are growing with tremendous rapidity, both of which are of immense importance to the community, inasmuch as one affects the production of food and the other provides essential clothing. These industries, namely the fixation of nitrogen from the atmosphere and the production of artificial silk from vegetable fibre, would be impossible from a commercial point of view were it not for the immense knowledge and control given by the use of instruments. In the synthetic ammonia industry the first essential is to have pure hydrogen and nitrogen. After this it is necessary to control the gas reactions, which vary considerably from one process to another. Not only are there the complicated questions of purity, high pressures and temperatures, but accurate mixtures of gases have to be maintained to produce the requisite reactions and to guard against explosion. In the manufacture of artificial silk, various solvents are essential, such as acetone and carbon bisulphide, the use of which would be highly dangerous, rendering the process impossible if the information which only instruments can give were not available.

The commercial importance of measurement is apparent in another form. The fashion and the passion of the present age is the demand for what, from the purely physical measurement point of view, is designated efficiency—the demi-god at whose throne many engineers appear to worship. It is measured by the ratio of useful work attained to the energy expended, the latter, however, from the purely materialistic point of view. It is admitted that efficiency is essential to enable most processes to be carried out for a purely financial end. There is a danger, however, that no allowance is made for the physical and mental energy expended by the personnel. In the past, human life was reckoned cheaply in terms of ignoble toil, then called slavery. The tendency to day is to sacrifice human life to speed and noise; that is, unedifying mental slavery which is hardly conducive to increased happiness.

Within recent years there has been an increasing demand for the use of instruments to effect automatic, or at least semi-automatic, control. Important strides have already been made and consistently reliable results obtained. The engineering problems involved are of a distinctive character. The laws of economics demand units of large size, transforming large quantities of energy, in order to obtain so-called efficiency. The alterations necessary to control appreciable amounts of energy likewise necessitate the expenditure of moderately large amounts of power. Conversely, the control instrument has available only a very small amount of power to operate any other device, with the result that generally several relay stages, each possessing necessary characteristics, have to be interposed between the point of measurement and the actual control gear.

Our ideal of being able to provide electrical energy, with all the advantages which this entails, at a moderate cost to the major portion of this nation is being realized to some extent by the installation of the grid system or systems. An essential factor in the scheme is the provision of automatic control of distribution. The solution of this problem not only entails accurate measurements but is dependent on operations being carried out in a correct sequence and with certain prescribed time-intervals. The fact that instruments can be utilized to control consistently such complicated operations reflects considerable credit both on the physicist and the engineer. In some respects a more advanced stage in the development of control has been reached by the growth of automatic telephone systems whereby the transmission of information, and therefore the general mental intercourse of mankind, has been accelerated. It was brought to my notice recently that, in an hotel in Barcelona, a telephone is provided in each bedroom, with an accompanying notice in several languages stating that, by its use, communication could be established with any telephone user in Great Britain, France, Germany, Italy and Spain.

In connection with a number of industrial processes, there is a necessity to effect automatic control of only one physical condition at a time. The first essential is to effect uniform local conditions rather than to attempt to obtain accuracy to the fundamental standards. It is agreed that in most cases there will be a constant relationship between these empirical conditions and an absolute measurement, but it is rarely necessary to deduce this factor. In order to secure a uniform product one must have uniform conditions of treatment. Thus the heat treatment of materials to within the close limits obtained to-day would be impossible were it not for the skilled application of temperature-measuring equipment coupled with automatic control gear. In industrial furnaces heated by gas, oil or electricity, there is no difficulty in controlling the temperature to within less than 1 per cent up to temperatures of 1 400° C. In special applications appreciably better control can be effected; for example, it is possible to maintain astronomical instruments under practically constant temperature conditions all the year round.

It may not be generally known that fruit from abroad can only reach us in the perfection to which we are accustomed, by the automatic control of the carbon dioxide content of the atmosphere in which it is stored. In the case of tobacco it is a question of the control of humidity. In a similar way other physical conditions can be controlled. An important but indirect outcome of these methods is the large saving in energy effected, and this helps to reduce the cost of production.

Although the widespread use of instruments as workshop tools, and the ideals of automatic control have produced, and are increasingly producing, enormous material and economic advantages to mankind, there is a distinct loss from another point of view. It is a loss which is difficult to estimate or, at present, to realize fully. The mechanical control of production has a tendency to cause the human beings employed to become simply parts of the machine. Workmen are thought of as mere units to be drawn from the pool of so-called "labour." It is the knell of passing craftsmanship. The loss of craftsmanship means the loss of the beauty of human experience expressed in material form.

We must keep ever before us the broad visions of our relationship with our fellow men, what we owe to them and what they expect from us. We must take care that we do not so closely concentrate our vision that in reality we become only a part of the machines for which we are responsible. We must not be parts of the instruments we use nor must our minds be the real charts. Some words written by Sir Isaac Newton shortly before his death are still true. He wrote " I seem to have been only a boy playing on the sea-shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."

We find the good in life because we search, and because we train ourselves to overcome difficulties. We gain experience, ungrudgingly pass it on and render it available for others. Each one possesses a measure of craftsmanship to some extent different in outlook, in power of execution and in application. Collectively, however, we do our best and offer it for the benefit of mankind.

If the spirit of Faraday with all his kindness and sincerity and, above all, his enthusiasm and wide vision, is in each member of this Institution then we may take courage, we shall not lose our vision and we shall go on in the adventure and the conquest of the secrets of Nature.

NORTH-WESTERN CENTRE: CHAIRMAN'S ADDRESS

By T. E. HERBERT, Member.

"INLAND TELEGRAPHS."

(*Address delivered at* MANCHESTER, *22nd October*, 1929.)

When the Society of Telegraph Engineers was founded in 1871, the telegraph was the only practical application of electricity. In course of time, however, interest turned towards electric lighting and power and the present more general and all-embracing title of the Institution was adopted. To-day, the advances in telegraphy and telephony have rendered these subjects particularly interesting and it is, I think, correct to say that recent developments have been of a radical nature unparalleled in any other branch of electrical engineering.

The telegraph and telephone systems of any country should be regarded as a whole rather than as separate services working in "watertight compartments." In Germany the whole of the telegraph line-plant had disappeared by the end of the War and the system had perforce to be re-established by utilizing circuits in telephone cables. I have chosen the subject of inland telegraphs for my address and have deliberately excluded from my review the Continental telegraph circuits because these services are self-supporting and show a definite profit. It will, however, be useful first to give a very brief outline of the development in telephone engineering so far as line plant is concerned.

The advent of the paper-core cable made it possible economically to provide large numbers of wires, to say nothing of the better transmission secured. For telephone subscribers' circuits the largest cable which has been made for drawing into a 3¼-in. duct contains 3 636 wires. The work of Heaviside and Pupin gave us the loaded cable. This advance brought with it new problems and it became necessary, after the cable was laid, to measure the capacity unbalances of the circuits, length by length of cable. The technique of these operations was devised and developed by the Post Office Engineering Department.

Quite recently a definite advance has been made in telephone cable design. In the star quad cable the 4 wires of each core are twisted together in one operation and so occupy the 4 corners of a square. This formation was adopted in the first London–Birmingham cable laid in 1899 but, owing to the instability of the make-up due to the loosely-wrapped pairs, there was very considerable inductive interference between the circuits. In the new cable practically the whole of the insulation consists of paper, and no attempt has been made to provide large air-spaces. Stiffening of the paper tubes has resulted in accurate and permanent centralization therein of the conductors, whilst a central string upon which the covered conductors are bedded ensures symmetry of the cores. This extremely important feature of centralization of the conductors within the paper tubes may be secured either by the use of specially creased or corrugated surfaced-paper wrappings, or by a spiral whipping of string directly adjacent to the conductor, over which the insulating paper is tightly wrapped. The cable is, therefore, extremely compact and uniform in its behaviour. For example, a 254-pair (127 quads) cable can now be drawn into a 3¼-in. conduit, as compared with the former standard 160-pair multiple twin cable.

Until the advent of the thermionic valve the telephone repeater was not a practical possibility, and consequently the distance over which speech could take place was very definitely limited. With its aid we can now speak all over the continent of Europe and, by the use of wireless, across the Atlantic.

A telephone cable bridging the Atlantic, with a repeater station at the Azores, is projected. Another suggested cable is from Cadiz to Pernambuco with repeater stations at Teneriffe, Cape Verde, and Fernando Noronha. One of these cables will have paper-insulated conductors with a double lead sheath. The main trunk telephone system of this country is now of a most extensive character and is almost wholly underground.

Whilst these developments have been taking place in telephony, corresponding advances have taken place in telegraphy. The first submarine cable was laid between Dover and Calais in 1850, and in general it may be said that a stranded copper conductor insulated with gutta-percha and mechanically protected by iron-wire armouring was the standard form of cable until the application of loading. The discovery of the remarkable magnetic properties of the nickel-iron alloys —permalloy, and its British equivalent mumetal— revolutionized the submarine cable. The stranded copper conductor is lapped with this alloy and its inductance is thereby increased to such a value that the speed of working is multiplied by 6 to 8 as compared with the unloaded cable. The effect of this was to render all previous long submarine telegraph cables obsolete.

The inland telegraphs were bought from the private companies concerned in 1870, and it is now recognized that the purchase price, £11 000 000, was too high, being only 12 per cent less than the amount paid to the National Telephone Co. in 1912 for the vastly larger plant of their telephone system. This purchase price does not, however, explain the loss on our inland telegraphs to-day. At the time of transfer, special rates were inaugurated by which additional copies of Press messages were transmitted at 2d. per copy. This rate applied to copies of messages sent to different towns and was not confined to additional copies in the same place, where the extra copies could be manifolded. Hence a night Press message of 100 words could be sent to 20 different towns at a cost of 4s. 2d. (1s. + 19 copies at 2d. per copy).

On the other hand the improved facilities for news distribution were definitely in the interests of the general public. Indeed, no modern newspaper could exist without the aid of present-day methods of electrical communication, and newspaper development was in no small measure rendered possible by the cheap Press message. This advantage was shared by the community at large, and it would therefore be arguable that the special concession has been justified.

There is to-day no justification for any such subsidy of the public Press—in fact, all the great newspapers have private wires of their own in order to avoid the delay inseparable from transmission of messages between the Post Office and newspaper offices. In other words, the greater celerity amply justifies the very heavy charges which this policy entails.

Some economy could, and no doubt will, be effected in the case of newspapers having suitable apparatus by switching the transmitting office through to the newspaper office when there is any considerable volume of traffic to be dealt with. At present many long Press messages are transmitted from the main office to the local papers by passing the received perforated tape through the transmitter on a circuit connecting the main office and the newspaper.

Let us now take a glance at the position in 1870, when the Post Office telegraphs were established. At that time no other means of electrical communication existed, and methods of transit were very slow compared with present-day facilities. Telephones have now passed from the state of an aid to business to that of a social and commercial necessity. Railway services are frequent and more or less rapid, and with the electrification of the railways still further acceleration will result. Motor vehicles of all kinds serve to make communication between distant places more and more rapid. Thus it will be appreciated that if a telegram is to take less time between its initiation and its receipt than any method of mechanical transport, such as train or motor car, the telegraph service of to-day must be vastly quicker than was necessary in 1870. It should not be overlooked that the inland telegraph system is the medium by which foreign messages are distributed to the recipients throughout the country, and thus it performs a most valuable function for the community.

Referring once again to the position in 1870, for a message of 20 words the companies charged 1s. for distances up to 100 miles, 1s. 6d. up to 200 miles, 2s. over 200 miles in Great Britain, and from 3s. to 6s. for transmission to Ireland. In addition there were charges for delivery beyond a limited radius. These charges were, at the time of the transfer, reduced to 1s. per message, and the telegraphs were rapidly extended so that, instead of some 500 railway stations, there were 1 800 stations and about 1 000 post offices from which telegrams could be sent. By 1914 the number of offices had been increased to 14 222.

The telegraphs were not developed on purely commercial lines, but as a national service, the aim being to bring every centre of population within the range of communication, regardless of the question as to whether it would pay. Commercial methods would, of course, have resulted in concentration on profitable business alone, and would have left our villages in a continued state of isolation.

A record of the total traffic in millions of messages year by year is given in Table 1.

TABLE 1.

Year.	Total messages	Inland messages
	millions	millions
1869	6½	—
1870 *	8½	—
1871	10	—
1872	12	—
1884 †	33	—
1887	50	40
1900	93	76
1910	87	71
1914	87	70
1915 ‡	91	72
1916	84	65
1917	73	54
1918	76	55
1919	85	63
1920 §	94	74
1921	80	63
1922	85	59
1923	71	53
1924	69	51
1925	67	49
1926	65	48
1927	62	47
1928	61	46
1929	59	44

* Transfer to State control.
† 6d. telegrams introduced in 1885.
‡ 9d. telegrams introduced in November 1915.
§ 1s. telegrams introduced in September 1920.

The revenue from the telegraph service has never been sufficient to pay interest on the capital. Of this loss the Press messages represent £225 000 per annum. By 1881 the balance of receipts over expenditure had nearly reached the interest due on the stock. This position was, however, profoundly modified by the introduction of the 6d. telegram in 1885; this reform was carried out deliberately by Parliament in spite of the losses that it was known would occur. Table 2 gives some particulars of these losses.

In 1913, of the total communications (telegrams plus telephone calls) 64 per cent were sent by telegraph, whereas in 1926 the figure was only 36 per cent of the total. On the other hand, in America 150 million telegraph messages were sent over the Western Union system alone during the year, this being 2½ times the number handled 10 years ago. This shows the vast difference between England and the United States in the use of telegraphic facilities. The explanation is, however, quite obvious—this is a small country and the distances are short. If the telegraph is to be quicker than other means of conveying a message the time available from initiation to receipt is much less here than in America, where the distances are vastly greater. The greater time available for telegraphs brings with it differential charges based on distances and also on celerity. The advantage of levelling up the load curve needs no explanation.

The day when every house has its telephone and its motor-car has not yet dawned, even in America, much less in England, and therefore it cannot be assumed that every message can be sent direct by the sender to the recipient, but it is reasonable to suppose that the number which can be sent in this way will tend to increase. A telephone message occupies an individual pair of wires for the whole time that the conversation takes place, whereas several messages can be sent simultaneously on a single telegraph wire by the Baudot multiplex or on a loop by voice-frequency telegraphs. The present tendency is, however, towards the use of sub-audio telegraphs worked on telephone trunk-circuits, or alternatively superposed on such circuits with thermionic-valve reception of the signals. For example, a 4-wire core gives 3 telephone circuits (2 physical and 1 phantom), and over the centre of the phantom a telegraph circuit can be worked without affecting the telephones. At the telephone repeater-stations all that is necessary is to connect across the centre points of the phantom superposing transformers; consequently the plant costs are only a fraction of the similar costs for telephone trunk-lines. There is, however, this fundamental difference, that a telegram has to be signalled by hand, whereas the work of a telephone operator is confined to making and severing the required connections. Hence it is only over very long distances that the telegram becomes the cheaper method of conveying messages. In the case of an Atlantic submarine cable the position is reversed, and the operating cost in human labour is small in comparison with the plant costs. More human energy is employed in the transmission of a telegram than in setting up a telephone call, and on receipt the message has generally to be delivered by hand. In the case of country villages the general use of the telephone by the villagers presents some difficulties, since few of them are connected. Possibly some method of making use of garages for telegraph purposes may be evolved, but it is true to say that the telegraphs in villages are to-day still serving the purpose for which they were originally designed. Incidentally it may be explained that many of these telegrams are transmitted over telephone circuits to the nearest large telegraph transmitting centre and vice versa.

TABLE 2.

Year	Loss
1904	£958 000
1910	£853 000
1924	£1 271 000
1925	£1 645 000 *
1926	£1 299 000
1927	£1 349 000
1928	£1 381 000

* This figure includes £300 000 paid for War services.

Let us now take a brief survey of the apparatus developments. At the end of last century, the main-line telegraphs were worked by sounder, and minor circuits by Wheatstone A B C, single-needle, or double-plate sounder. The Press work was all carried on Wheatstone circuits, generally worked at about 300 words per minute. The Wheatstone A B C was used to work to villages where there was little traffic. Its principal advantage lay in the fact that little or no skill was required to operate it. It was, however, very costly to maintain, and with the advent of rural telephone circuits its use became more and more restricted, and to-day it has entirely disappeared. The needle instrument persisted somewhat longer, since it was capable of dealing with a fair amount of traffic and did not necessitate the highly skilled training demanded by the Morse sounder. It, too, has almost disappeared and is now probably used only by some of the railway companies on their private-wire systems.

The Wheatstone automatic system originally consisted of 3-key perforators, a transmitter and a receiver. The message to be sent is recorded in the form of perforations on a tape; the speed at which this record can be made is about 20 to 25 words per minute. The tape is then passed through the transmitter, which automatically sends out morse signals in accordance with the perforations, at a speed of from 150 to 400 words per minute. At the far end of the line the signals are recorded in morse on a tape by a Wheatstone receiver. If 10 men each perforate at the rate of 25 words per minute and these slips are periodically collected and successively passed through a transmitter running at, say, 300 words per minute, then we have the equivalent of 10 men at each end working direct to each other, but on 1 wire instead of on 10. On the other hand, a man is required to collect the slips and to feed the transmitter, while at the receiving end another man is occupied in distributing the slips for writing up by hand. Hence it will be evident that Wheatstone automatic working is costly in labour but saves line plant. On the other hand, where the same message has to be sent to several towns—and this is characteristic of much Press work—one perforated slip may be passed through several transmitters, and thus several separate manual signalling operations are avoided.

The Wheatstone system was given a fresh lease of life by the design of new machines. Keyboard perforators raised the speed at which the tape could be perforated. Then the Creed receiving perforator replaced the Wheatstone receiver. Instead of dots and dashes inked on a tape, the message was received in the form of a perforated tape identical with the transmitting tape. This received tape can be used to send the message to other stations, or, by passing it through a Creed printer, the message may be typed in roman characters either on a tape or in column form.

While these developments have been taking place, all the great newspapers have arranged to rent lines to

London from the Post Office and to provide their own staff and apparatus. In this way some saving of time is effected, but it has, of course, reduced very greatly the amount of Press work dealt with by the Post Office.

Lieut.-Colonel A. C. Booth, of the Post Office Engineering Department, duplexed the Baudot. This system gives from 2 to 6 channels in each direction over a single wire. In its original form, messages were transmitted by depressing 5 keys in various combinations for each letter. This gives 31 working combinations, and by a device resembling the figure shift on an ordinary typewriter the number of characters is doubled. At the receiving end the message is printed on a tape in roman characters. Here, again, the system becomes expensive on account of the amount of highly skilled attention required. The latest development of this plan consists in providing a typewriter-keyboard perforator for sending the signals from the perforated tape. The advantage gained lies in the higher speed of operation and the absence of the necessity to send out the signals letter by letter in accordance with a time-beat. Moreover, modern receivers enable a speed of 60 words per minute to be attained, as compared with about 30 to 35 with the original Baudot.

We now come to the position to-day. It is quite clear that the Wheatstone automatic system must disappear altogether and it seems equally probable that multiplex systems will also have a very restricted field of utility in this country. In fact morse, whether manual or automatic, is doomed, chiefly on account of its inefficiency in the use of human effort. Here it may be well to remark that the losses on telegraphs would not disappear even if all the plant costs were entirely eliminated, and so the future line of development in so small a country as this will not consist in plant-saving devices such as multiplex, voice-frequency or automatic systems, but in the adoption of methods which obtain equal results with the minimum expenditure of human effort. The deduction from this would appear to be that heavy expenditure on plant is amply justified wherever labour savings can be effected.

At the moment the replacement of all forms of apparatus by start-stop telegraphs is beginning. These instruments derive their name from the fact that a starting impulse precedes the 5 currents composing the code, and the machine is stopped by a current at the end. The machine has a typewriter keyboard and prints the message on a tape in roman characters. The teleprinter 3A, adopted by the Post Office Engineering Department, is the invention and design of Mr. F. G. Creed, of Croydon. It is driven by a small electric motor and depends for its action principally on a battery of cams, the electrical portion consisting only of contact springs for sending and a single electromagnet for reception. It is interesting to notice that telegraphy is very largely mechanical in character, whereas in telephony the mechanisms used are of the simplest nature.

The teleprinter works at about 60 words per minute as compared with 20 to 25 for a Morse sounder, but even this is inadequate to wipe out the loss on telegraphs. The manual re-transmission of messages is necessarily a costly process and it is evident that this must be avoided to the utmost extent. In the early days of telegraphs experiments were made in telegraph switching, but these were abandoned. A comparatively elaborate system existed in Belgium some 30 years ago, and the metropolitan intercommunication system devised by Col. Sir T. F. Purves in 1900, by which sub-offices in London were interconnected at a switchboard to send their messages direct to each other, has only recently been taken out.

In this case the Morse sounder was used, but owing to the decline in messages across London, due probably to the more intensive development of telephones, the system ultimately failed to justify its continuance. It is interesting to note that the first exchange was not a telephone exchange, but a telegraph exchange at Newcastle, working prior to 1870 with Wheatstone A B C apparatus. In 1884 it was converted to telephones.

This brings us to the final stage, in which it is pertinent to consider what is likely to be the line of future development. I suppose it is generally unsafe to attempt prophecy: nevertheless I will venture to describe what I imagine will be the function of telegraphs some 20 or 30 years hence.

In the first place, the business community will have discovered that speeding up their methods will enable more business to be done with much less effort. There will, moreover, be such legislation in vogue as will prevent the recurrence of frequent financial upheavals, and people will thus be enabled to concentrate on useful work. Much more attention will then be available for concentration on doing the job in the simplest, quickest and most direct way.

Every business office will be equipped with a teleprinter and, by means of a dial form of automatic switching, communications will be sent direct to the recipient. All businesses where the office staff possesses even one typist will have the machine installed. In the case of very small firms, possibly, the telephone connection may be used for the dual purpose, or perhaps several small firms may share a single telegraph wire. The messages will be received on a form of receiving perforator in the main telegraph office of the town to which the recipient is connected, and in this way the message will be stored and automatically sent to the recipient as soon as his circuit is free. Several machines may be "lined up" on a rotary line-switch with messages for a single subscriber and will discharge their messages in sequence. This plan will enable the messages to be dealt with in a strictly routine manner. The telephone will, on the other hand, be used where discussion is essential, and all trivial inquiries addressed to important executives personally will be eliminated. Much time is wasted by inquiries addressed to particular people known personally to the caller for detail information which the executive has to obtain in a hurry while the telephone call is proceeding.

A service of the type I have sketched will need a large number of circuits, but these are already available, since it has been demonstrated that telegraphs can be worked at sub-audio frequency on telephone trunks without appreciable deterioration of the latter. When this source fails, voice-frequency systems, or even multiplex systems, controlled by precision vibrators as regards the division of line time, will certainly meet requirements.

There remains the problem of the delivery of messages. For the purely private message where the recipient is not on the telephone—and the percentage of such messages to the total messages would tend to decrease—there seems no alternative to delivery by messenger. If, however, the system as a whole can be made remunerative this does not seem a very serious matter.

The advantages of the plan I have outlined consist in transferring the human labour to the subscriber, but this does not represent any serious addition to his necessities, since the message can be telegraphed with no more labour than that involved in typing the corresponding letter.

That the development I have postulated is by no means improbable or visionary is exemplified by the following extract from the *Wall Street Journal*, 27th July, 1929:—

"*Bell System's New Invention.*

" Typewriter-Telephone Service eventually may compete
" with Telegraph. Device seen in Demand.

> " The Bell System has developed a telephone typewriter which provides equipment and circuits, and gives a service which permits subscribers to handle their own messages, telephone or telegraph, in their own way. Telephone typewriter instruments have to a large degree the flexibility of telephone instruments, and can be interconnected through suitable switchboards in the same manner. It is, therefore, quite feasible to provide a large number of subscribers in their business offices with these instruments, and to furnish wire interconnections between these subscribers as they may indicate their desires. The service need not be confined to a single city, but any subscriber in New York may be connected to any subscriber similarly equipped in some other city, the time required to complete this connection being of the same order as that required to complete a telephone connection between the same two points.
>
> " A service of this character is analogous to present telephone service in that the subscriber would, in general, provide his own telephone typewriter operator and on the completion of the desired connection to the called subscriber would handle his messages in any way that he saw fit.
>
> " An experimental service of this character has been established between switchboards and stations installed in telephone company offices in New York, Boston and Chicago and some adjacent cities. When placing a call, the subscriber merely switches on the power at his station, which is analogous to lifting the receiver from the hook. This operation lights the line lamp at the telephone switchboard and the operator responds by connecting his telephone typewriting instrument to the calling subscriber's line and writing the letters, for example 'NY OPR.' The calling subscriber types the station connection desired and awaits response from the called subscriber or from the operator if the connection cannot be completed.
>
> " It is obvious that the American Telephone and Telegraph Co. could become a competitor of the telegraph companies at will, but so far the company has concentrated its efforts entirely on the telephone and has contented itself with leasing its facilities for telegraph purposes. A new phase now enters the situation in the shape of the new telephone typewriter exchange service which is being developed by the American Telephone and Telegraph Co. which may become a factor in the telegraph field.
>
> " The Bell System engineers are perfecting the switchboard device and there is some experimentation yet to be completed, but it would appear that this form of typewriter telephone development is going to become a potent factor in the communications field in the not far distant future."

It only remains to add that salesmanship and adequate publicity are clearly essential to the early realization of such a scheme. The engineering details would present no insuperable difficulties, but it may be interesting to point out a few other possibilities. Firstly any telegraph message sent by telephone, either from a telephone subscriber, a telephone kiosk or from a village post office or railway station, would be typed as it was received at the main telegraph office and would thus be transmitted to its destination; or the typewriter might have a perforating attachment to enable the message to be stored in the form of a perforated tape and so transmitted automatically when a circuit became available.

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MERSEY AND NORTH WALES (LIVERPOOL) CENTRE: CHAIRMAN'S ADDRESS

By Professor E. W. Marchant, D.Sc., Member.

"SCIENCE AND ELECTRICAL ENGINEERING."

(*Address delivered at* Liverpool, 21*st October*, 1929.)

In a year which is so near to the centenary of the discovery by Faraday of the way in which an electric current can be generated by the movement of a magnet near to a coil of wire, it may not be inappropriate to survey the progress of electrical engineering which has resulted from scientific discoveries. In this address it is impossible to deal with more than a fraction of the important experiments that have been made in electrical engineering, and the degree of importance of those mentioned below is varied.[*] The last century divides itself into a number of periods, each of diminishing length, in which some great discovery has led to further progress and the development of new industries.

Electromagnetism.

The earliest experiment of importance in electromagnetism is that of Oersted, who was the first to discover the effect of an electric current on a magnet. A very interesting account of his work[†] has recently been published. The currents available at that time were very small, and the deflection that Oersted produced on a compass needle placed near to a conductor carrying current was almost imperceptible.

It is interesting to record that Oersted's first experiment, in Copenhagen, which was announced in July 1820, was made in what is now Telephone House, the headquarters of the Copenhagen Telephone Co.; and the exact point at which the observation was made has now been located. The house itself was partly residence and partly the scene of his lectures. On the day of his discovery, at the close of his lecture, he asked his class whether they would like to observe what might happen when an electric current flowed through a wire placed near to a compass needle. The class remained and witnessed the result, i.e. a deflection of the compass needle when an electric current flowed in a neighbouring wire placed in proper relation to the needle. The movement was so small that Oersted at first attributed it to capricious disturbances. He was perplexed by the movement of the pole in a direction at right angles to the direction of flow of the current in the wire. Why was not the line of movement the same as that of the originating current? Later he returned to the investigation and obtained definite results. Who can estimate the importance of this observation? It opened the way at once to a method of signalling different from that which had previously been possible, and gave to research an impulse as far-reaching as it was momentous. Sir John Herschel, at the meeting of the British Association in 1846, speaking of Oersted's discoveries, said: "The electric telegraph and other wonders of modern science were but natural effervescences from the surface of this second discovery which Oersted liberated, but which was yet to burst with all its mighty force upon the world."

Oersted and Faraday met for the first time in 1823. Each of the two philosophers followed closely the account of the other's researches. The first man in America to emphasize the importance of Oersted's discovery was Joseph Henry, and by 1841 Oersted's name was as well known in America as in Europe. Oersted had a considerable regard for Charles Wheatstone, the professor of physics at King's College, though it took 17 years for Wheatstone to apply Oersted's "beautiful discovery" to the practical electrical telegraph. By 1837 the telegraph was installed on one part of the line between London and Bristol over a length of 14 miles. Wheatstone, writing to Oersted from King's College, London, speaks of "the way in which I have applied your beautiful discovery for the purpose of transmitting instantaneously both visibly and audibly to great distances."

The next epoch in the history of electrical development began when Faraday discovered how to produce an electric current by means of a magnet. So many descriptions of this experiment have been made that it seemed worth while to construct some coils which exactly complied with Faraday's specification.

Faraday first tried experiments on mutual induction; that is, he wound two sets of coils on a paper tube, connected one to a battery and the other to a galvanometer, and noticed that when the current through one was switched on or off an induced current passed through the galvanometer. The next step was to place an iron core inside the coil, and he noticed that the effect was greatly increased thereby. The great discovery was made when he connected all these coils in series and, using two magnets each 24 inches long, placed the north pole of one in contact with the south pole of the other, and the other north and south poles in contact with the ends of the iron bar passing through his coils; and he found that if one magnet was brought into contact with the iron bar a current was induced in the coils and passed through the galvanometer. It was then a simple step to the discovery that a current was induced when a magnet was thrust into the coil. Such was the series of experiments, as described in the *Proceedings of the Royal Society*, which Faraday performed in 1831, and which have meant so much to the progress of the material side of human civilization. Nowadays the experiments seem so simple that every schoolboy knows about them, and it is difficult to realize their tremendous importance when they were made. It is worth while to try to do so, however, because it enables one to visualize the possibility of developments of almost equal magnitude arising from apparently insignificant discoveries.

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[*] In 1927 Sir Ambrose Fleming gave a course of lectures before the University of London which have been published in book form, under the title "The Interaction of Pure Scientific Research and Electrical Engineering Practice," and contains a description of a large number of researches having bearing on electrical engineering practice.

[†] *Electrical Communication*, 1928, vol. 6, p. 181.

There is, of course, a very big step between Faraday's experiment and the 160 000-kW alternators that are being built to-day. There are many men, such as Gramme, Pacinotti, Siemens, Wilde, John Hopkinson and Parsons, whose work as engineers has brought the generator of electrical energy to its present efficiency and size. Although I do not wish to minimize the services of these and many other eminent engineers, it is well to remember that the whole technique of the production of electrical energy could be altered if some means other than the steam boiler, turbine and alternator were discovered which would enable a larger fraction of the energy stored in coal to be transformed directly and economically into electrical energy. All scientific work of a fundamental nature should be encouraged for it is possible that entirely new methods of controlling the electrons, which we now know constitute an electric current, may be discovered. Our knowledge of the fundamental nature of matter has undergone a profound change since Faraday made his great experiment, and it does not seem beyond the realm of scientific possibility that there may be devised some methods of setting electrons in motion other than those with which we are familiar. Already physicists have accomplished things which we should have regarded as incredible 30 years ago, and astronomers have told us that in the interior of the stars matter must be completely broken up into a mass of atomic nuclei and free electrons. Whether engineers will ever be able to reduce matter to such a condition it is not for me to say, but no avenue by which more effective use may be made of our sources of energy should be left unexplored.

Although electrical engineers are concerned primarily with the practical application of physical science, it is well to remember that most of the fundamental physical discoveries were the result of purely scientific investigation directed towards no practical end. A member of the audience at one of Faraday's lectures on electromagnetic induction once asked, " Yes, but what is the use of it?" Faraday replied, as many another wise man has replied, by asking another question: " What is the use of a new-born baby?" As a matter of experience nearly all discoveries in pure science, however useless they may appear to be, find their practical application sooner or later.

CABLE TELEGRAPHY.

Another branch of electrical engineering which had its beginning in a more or less academic scientific discussion is cable telegraphy. The idea of telegraphic communication across the Atlantic was one which had appealed to many electrical engineers, and it was in 1856 that the money was raised which enabled the first cable to be laid, but the theory of cable transmission was not at that time clearly understood. In the early experiments a telegraphist named Whitehouse was in charge, and he thought that the proper method of improving the working was to raise the voltage on the cable, and actually used no less than 2 000 volts in the hope that signals might come through quickly to the receiving end. His method, of course, was wrong, and caused breakdown of the cable insulation. Prof. William Thomson, later Lord Kelvin, who held a relatively subordinate position in the undertaking, went out on the cable ship " Agamemnon " as electrician of the company. He had studied the conditions and realized that the problem of the transmission of an electric current through a cable was similar to the problem of the transmission of heat through a conducting rod or plate. The electrical resistance of the cable was analogous to the thermal resistance of the rod, and the capacity of the cable could be compared with its thermal capacity for heat. He and Prof. Gabriel Stokes worked out the complete theory of transmission along a cable by analogy with the problem of transmission of heat through a plate, which had been investigated by Fourier, and showed what were the factors which determined the speed of transmission. After Kelvin's delicate siphon recorder had been constructed cable telegraphy became a practical proposition, and a great step had been made in practical electrical engineering.

While the cable was being made, Kelvin recognized the necessity for obtaining pure copper in order to reduce its resistance as much as possible. He specified, for the first time, copper of " high conductivity." In order to ensure that the material should be of the right quality he set up at the factory an apparatus for testing it, and founded the first works testing laboratory.

TELEPHONY.

We have celebrated recently the work of Alexander Graham Bell. His serious study of electricity was undertaken with a view to understanding and repeating the experiments of Helmholtz in the artificial production of vowel tones. He set out with the idea of making a speaking machine which would reproduce human speech by the vibration of a series of tuning-forks or flat reeds. The sender of his first transmitter was a steel reed which was kept in vibration by a mechanism similar to that of the electric bell. When the currents from this apparatus were transmitted along a line they set in strong vibration a reed placed opposite to a magnet through the coils of which these currents passed, provided the periods of the reeds at the two ends of the line were the same. His original idea of a transmitter was a harp-like machine with a number of reeds that were set in vibration by the voice and produced currents corresponding to their natural frequency, which, being connected electrically to a series of similar reeds on the receiver, would set them in vibration and so reproduce the spoken word.

It would take too long to describe the steps by which Bell ultimately succeeded in devising the telephone. The discovery that a reed, when set in vibration opposite a magnet, gave rise to currents sufficiently powerful to cause another reed placed opposite another magnet, and tuned to the same pitch, to be set in vigorous vibration, was accidental; and from that the step to the thin iron diaphragm with which we are now familiar was relatively easy.

The discovery of the telephone, however, is an interesting illustration of research begun for purely scientific purposes, followed by the observation of an unexpected phenomenon, and then the gradual development of the idea to a practical result. Who can say what Bell's discovery has meant to the world? When telephony was attempted over distances of more than a few miles the distortion of the speech became so bad that the telephone was practically useless. Heaviside came to the rescue, and in a series of mathematical papers showed how these difficulties could be overcome by the use of inductance.

The mathematical equations for the transmission of telephone messages along a loaded cable are similar to those for the transmission of sound in the sound-box of a gramophone, and the solution that was given by Heaviside for the electrical problem has been of the utmost value to the designers of gramophone sound-boxes.

Electrical engineers can therefore take to themselves some credit for the progress that has been made in the recording and reproduction of sound.

Nowadays we are so familiar with telephony that we perhaps fail to realize the change it has made in our lives. One man can now do an amount of administrative work which would have been impossible without it, and the saving of time and trouble to the ordinary man is incalculable. Now that transatlantic telephony is an everyday event, one can begin to see what an influence the telephone is likely to have on the language of the future. It may tend, perhaps, to counteract some of the excessive nationalism which has been such a depressing feature of European politics since the War.

HIGH-FREQUENCY CURRENTS AND WIRELESS TELEGRAPHY.

I have referred * quite recently to the developments that arose from Lord Kelvin's paper on "The Production of High-Frequency Currents by the Discharge of a Condenser through an Inductive Coil." That paper was really the starting point of wireless telegraphy. I remember, too, a paper † on the direct-current arc, which was read by the late Mr. Duddell before this Institution, in which he showed how it was possible to produce electrical oscillations in an ordinary carbon arc by shunting it with a condenser and a coil. At that time it seemed a very interesting experiment with very little practical application; but it was found by Poulsen that if the arc burnt in an atmosphere of hydrogen and in a strong magnetic field, the frequency of the oscillations which it produced could be raised to values which might be applied in wireless telegraphy, and its utility became apparent. At the time of the War the Poulsen arc, as it is now generally called, was the best means known of producing continuous high-frequency oscillations. Nowadays it has, of course, been replaced by the valve.

One of the first papers on the valve was read before the Royal Society by a Past President of this Institution, the late Sir William Preece. In a paper * published in 1885 he described some experiments that had been made on what is known as the "Edison effect." Edison had found that, under certain conditions, a blue glow appeared inside some of the glow lamps made in his laboratory, and in order to discover the cause of this he inserted inside the globe a plate completely disconnected from the filament. He found that if a galvanometer was connected between the metal plate and the positive end of the filament, a considerable current flowed through it when the blue glow appeared inside the bulb. Preece brought back from America some of these lamps with metal plates inside the bulbs, and performed a number of experiments with them in his laboratory. At the end of his paper he stated that "this Edison effect is due to the formation of an arc between the carbon filament and the metal plate, and this arc is due to the projection of the carbon particles in right lines across the vacuum space." We know now that this explanation is incorrect, and soon afterwards Sir Ambrose (then Professor) Fleming began that important series of researches which led to the development of what is now known as the "Fleming valve." He showed what was really happening inside the bulb containing the heated filament and the metal plate. He laid the foundation on which the future development of the valve was built, and it was he, of course, who first showed that the valve would act as a valve, i.e. would allow current to pass through it in one direction only, even when it was supplied with very high-frequency currents.

There is a good deal to be said for what Lord Rayleigh called "wild catting" in experimental research. The introduction of the third electrode by Lee de Forest was made in this way. It is evident that he had very little understanding of the action of the 3-electrode valve when he first made one. The use of the third electrode was one of the greatest steps in the development of the technique of the thermionic valve, since it was after the insertion of this electrode that it became possible to use the valve as an amplifier and generator of electric waves.

The discovery of the fact that the resistance of selenium is reduced when this element is exposed to light was first applied by Shelford Bidwell in an attempt to transmit pictures, and the photo-electric properties of potassium and potassium-sodium alloys were studied by Elster and Geitel. At a soirée of the Royal Society over 20 years ago, a demonstration was given by Sir Ambrose Fleming of a sodium-potassium photo-electric cell which gave an e.m.f. of nearly 0·5 volt and a current of 5 microamperes. The advantage of the cell as compared with selenium is that it is very nearly instantaneous in its action and gives its current almost immediately a beam of light falls on it. The practical possibilities of these results were obvious, but it has taken nearly 20 years for the "talkie" to emerge, for

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* *Journal I.E.E.*, 1927, vol. 65, p. 977.
† *Ibid.*, 1901, vol. 30, p. 232.

* *Proceedings of the Royal Society*, 1885, vol. 38, p. 219.

it was only after the methods of amplification made possible by the valve had been perfected that the production of the currents from these cells became useful in practice. The "talkie" film makes use of the properties of the photo-electric cell. A trace on the film varies the intensity of a beam of light passing through it, and so produces the current which, when amplified, is sufficiently powerful to operate a loud-speaker. At the present time a number of engineers are engaged on the maintenance of "talkie" equipment, though it is perhaps too much to say that this has led to another new industry.

Television also may become practicable in course of time. That is another application of the same experiment.

Perhaps the most interesting observations made within recent months in wireless telegraphy have been those by Stormer and Hals on wireless echoes of long delay. Stormer has noticed that in some cases an echo of a short-wave signal, with a wavelength of about 30 metres, appeared to return to the sending station as long as 3 minutes after it had been sent out. Many observations of this kind have been made, the time interval ranging from several seconds up to over 4 minutes. A very interesting paper by Pedersen has recently been published,* in which he has discussed the possible explanations of this result. He has shown that it cannot be explained by a signal travelling round and round the earth continuously, for the attenuation of the wave would be too great; neither can it be explained by a lowered group velocity in the space above the Heaviside layer. The theory which meets the facts most successfully is that the wave penetrates the Heaviside layer, impinges on an electrical stream of charged particles emitted by the sun, and is in some way reflected back again to the earth. It is estimated that the length of path necessary to account for the delay in the echoes must be over 75 million kilometres, so that the signal must have traversed nearly a quarter of the distance to the sun before returning once more. The theory is borne out by the fact that these echoes are heard only at times of magnetic storms, when it is known that sun spots are actively sending out streams of charged electrons. The results are of considerable interest from a scientific point of view. If confirmed, they would appear to be the first records of signals sent out from the earth which have penetrated the upper regions of the atmosphere and returned again.

Electrical Engineering Materials.

Such are some of the fundamental scientific discoveries which have proved of importance to the electrical engineering industry; but there are many other sciences which have been of great value to electrical engineers. Some of the most valuable scientific work that has been done within recent years is that on engineering materials. It is, of course, many years since Barrett, Brown and Hadfield first published their researches on silicon iron, and showed how much smaller were the losses in this material when subjected to alternating magnetization than in ordinary iron. It is not too much to say that the discovery of silicon iron enabled as great an advance to be made in the design and construction of transformers as any other single experimental fact. It enabled the designer to reduce the weight of the iron cores of transformers to nearly half the value that would have been needed without it, and simplified the problem of cooling. More recently the discovery of cobalt steel has led to almost as great a revolution in the design of permanent magnets. Before its discovery a coercive force of 60 or 70 with tungsten steel was the greatest that had been possible, and this was a great advance on the figures with iron containing no tungsten; but a coercive force of nearly 250, such as is now possible with a steel containing 20 or 30 per cent of cobalt, has enabled permanent magnets to be made of less than one-third the weight previously required. Instead of the heavy horseshoe magnets previously needed in magnetos, it is now possible to use short straight bars 3 in. long and 1½ in. wide, such as no maker of permanent magnets would have attempted to use with materials of lower coercive force. Another alloy which has enabled great developments to be made is the nichrome wire now used so universally in radiators and heaters of all descriptions. In this connection I should like to refer to a series of experiments recently made at Liverpool University by Dr. E. C. Walton on the causes of failure of such substances when used in cookers and boiling-plates. The chief cause of failure is the presence of salt in any solution that may fall on the heated spiral. If such a spiral is immersed in fresh water and heated it will last well, but in the presence of a small quantity of salt electrolysis occurs and the metal corrodes rapidly. Milk also causes the heating element to become heavily coated with a thick hard mass which prevents the radiation of heat and finally causes the failure of the element. Fatty substances which do not contain salt have very little effect on the heating element. The effect of electrolytic corrosion with alternating current is very much less than with direct current. With one such wire electrolysis caused breakage after only 20 minutes' immersion in a 1 per cent salt solution when direct current was passed through it, whereas the same wire lasted for nearly 3 hours when alternating current having the same R.M.S. value was used to heat it. In milk the same wire lasted for 1 hour 55 minutes when direct current was passed through it, while with alternating current of the same R.M.S. value the wire showed comparatively little deterioration after 10 hours' immersion. This fact is of interest to central-station engineers who are now changing over their systems from direct to alternating current.

In a paper* by Robert Mallet on the "Action of Water on Iron," he states that alloys containing certain elements, e.g. nickel, cobalt, copper and chromium, are less easily corroded than iron, and that "Michael Faraday had found that alloys of most of the metals with steel which he had tried were much less acted upon by moist air than steel unalloyed." It was, however, a Sheffield man, M. Brearley, who first noticed that iron containing from 11 to 14 per cent of chromium would not rust. This, of course, has an increasing range of application in all kinds of electrical appliances, while chromium plating is becoming as common as nickel plating.

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* "Wireless Echoes of Long Delay," *Det. Kgl. Danske Vidernskabernes Selakab Mathematiskfysiske Meddelelser*, vol. 9, p. 5.

* R. Mallet: *Report of the British Association*, vol. 7, p. 265.

Among materials that have led to great developments in telegraph and telephone transmission, permalloy, discovered some years ago, should be mentioned. This material has a permeability nearly 300 times that of the best soft iron at low flux densities, and has greatly facilitated the loading of underground telegraph and telephone cables. It has recently been used in the form of a thin tape wrapped round the conductor of a 2 000-mile submarine cable. The loading of the cable has diminished the distortion in a manner similar to that in which it is reduced in distortionless telephone cables, and has increased the speed of transmission by more than five times as compared with older types of cable.

DISTRIBUTION NETWORKS.

One of the most important problems before the supply engineer to-day is the economical design of the transmission network. In some cases the cost of the distribution network is four times as much as the cost of the generating plant. The problem is one which requires intensive study, since the cheapening of the cost of electricity depends as much on a reduction in the cost of the distributing network as on any other factor. Here again science and scientific method have been able to render notable service. A most valuable series of researches was undertaken by the Electrical Research Association, the results of which have been published in the *Journal*,[*] with a view to determining the maximum current that can be passed through buried cables without danger to the insulation. This information is now available to the supply industry and will save it many hundreds of thousands of pounds.

In South Africa it is almost universal for the supply systems to remote districts to consist of overhead lines. The distribution network is carried by overhead wires supported on steel or ferro-concrete poles. Provided that care is taken in the placing of these poles their presence is almost unnoticed, and the saving in cost as compared with underground cables is very considerable. The problem of supplying electrical energy to the suburbs of towns like Johannesburg or Cape Town is much more difficult than it is in the case of the more concentrated towns in England; but with the development of the suburban area, with 8 and 12 houses to the acre, which now surround all our big towns, it would seem to be inevitable that the distribution network must be carried overhead unless the cost of electricity is to become prohibitive. For remote districts with very bad load factors it may be possible to use iron wires instead of copper and aluminium. If this is done it is important to have an exact knowledge of the behaviour of the metals which may be used as substitutes. Some figures giving the magnetic and electrical characteristics of such wires, and the chemical composition and treatment that results in the best quality, have recently been published[†] by Dr. Walton, and it is to be hoped that similar results will be available for the other cheap materials, giving the same detailed particulars of the mechanical and chemical properties of the substances to which they relate.

During a visit that I made this summer to South Africa, I was interested to find that the study of lightning and the nature of lightning discharges had been of no small service to the engineers in charge of the recently electrified Natal main line. During the summer the lightning storms in this district are very severe, and when electric traction was first installed the interference with the working by the almost continuous lightning storms threatened to jeopardize the success of the undertaking. The research engineers of the railway, however, made a complete study of the nature of the breakdowns, and have been able to prevent undue interference, thus saving the electrification scheme from failure.

MEASURING AND RECORDING APPARATUS.

Electrical engineering is concerned primarily with the construction of apparatus for the generation and distribution of electrical energy, or with electricity as a means of communication, but, like other applications of physical science, it owes much of its progress to accurate measurement and observation. The devising of instruments and apparatus for indicating and recording purposes has proved of incalculable value to the electrical industry. It was my good fortune to be associated for many years with the late Mr. Duddell, and I venture to think that the practical progress he made with the oscillograph, and the power it gave of observing quantities that were varying very rapidly, has helped the operator and the designer of electrical machinery and apparatus to a very marked degree. It was only after the oscillograph became available that some of the hitherto obscure phenomena in electrical machinery and apparatus were explained. The oscillograph did for electrical machinery very much what the indicator did for the steam engine. More recently the cathode-ray oscillograph has enabled the properties of materials to be investigated at wireless frequencies, and the klydonograph, when calibrated with a Dufour cathode-ray oscillograph, has given much useful information on the nature and intensity of lightning storms. The oscillograph also enabled detailed investigations to be made on Graham Bell's problem, the analysis of vowel sounds, and, with the development of broadcasting and the necessity for an exact reproduction of music and the spoken word, the study of what has been called the "new acoustics" has again become important.

It is impossible to lay too much stress on the necessity for accurate observation of electrical quantities. It was accurate measurement by the late Lord Rayleigh and Sir William Ramsay that led to the discovery of argon and other new gases that are now being used in the construction of gas-filled lamps. The utmost care should be taken to secure accurate results in all observations; it is notable that nearly all great discoveries have been based on effects which are relatively small. Oersted, Faraday and Thomson, to whom references have already been made, would never have observed the phenomena for which they obtained world-wide fame unless they had noticed small and insignificant effects. It is significant that big manufacturing undertakings all over the world have now established research laboratories on a very extensive scale, and that they do not confine their activities to the testing of apparatus and materials used in the factories, but employ many people who are engaged in the study of pure science.

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[*] *Journal I.E.E.*, 1921, vol. 59, p. 181; 1923, vol. 61, p. 517; 1926, vol. 64, p. 161.

[†] *Ibid.*, 1928, vol. 66, p. 1065.

H. D. Arnold of the Bell Laboratories may be quoted: "Our research problems are scattered along the whole frontier of the sciences which contribute to our interests, and extend through the fields of physical and organic chemistry, of metallurgy, of magnetism, of electrical conduction, of radiation, of electronics, of acoustics, of phonetics, of optics, of mathematics, of mechanics, and even of physiology, of psychology and of meteorology."

Manufacturers are not necessarily philanthropists: they realize that such study pays.

The universities have done a great deal in the training of men who can staff such laboratories—that is one of their primary functions; and they can best do this part of their work by encouraging their students to carry on investigations themselves. Although a great many of the discoveries that have proved of such importance have been made in university laboratories, many of those that have been described have been made by private investigators. It is of the utmost importance that such studies should be encouraged, and that investigation and discovery should not be hampered by lack of means. Faraday carried out his work for the love of knowledge, and there are to-day many research workers whose chief concern is the pursuit of knowledge for its own sake; but that is no reason why they should not receive adequate material recognition. Scientific discovery is the basis of all electrical engineering: without it the electrical industry would not exist. It is as necessary that it should be encouraged to-day as ever it was, for the discoveries of to-morrow may lead to as great a material revolution as did those of Faraday.

NORTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By Thomas Roles, Member.

(Abstract *of Address delivered at* Leeds, *29th October*, 1929.)

In this address I propose to review to some extent the progress which has been made, in matters appertaining to electricity and more particularly to the electricity supply industry, during the period of 15 years which has elapsed since I last addressed you as your chairman. That much of this progress has resulted from the War cannot be denied, as measures that were taken and inventions brought out and developed to assist in the prosecution of the War have in many cases since been utilized for the benefit of mankind under peace conditions; and the greatly increased use during recent years of electricity in various directions and for many purposes has been undoubtedly due in a large measure to the stimulus given during the War period to the invention and perfection of electrical apparatus for military needs.

The position as regards the electricity supply industry in this country in 1914 was, roughly speaking, that some 600 undertakings, company and municipal, were supplying electricity for public purposes, and that the total number of units sold by these concerns was under 2 000 millions per annum. This energy was very largely used for lighting and traction purposes, but electricity was rapidly being adopted in connection with power installations and for heating, chiefly where heat was only intermittently required. Amongst large power users electric driving had found favour in shipyards and such engineering and other works in which the machines to be driven were situated some distance apart, electrical transmission and the individual drive having been demonstrated to be more economical than power transmission by steam or by shafting. In some instances electrical driving had been introduced into textile mills and other similar establishments, but developments in this direction were made with difficulty owing to the conservatism of the majority of the power users, the necessity of quoting extremely low prices for electrical energy in order to secure consumers, and the fact that in many textile mills, particularly those connected with the woollen and worsted industries, a considerable amount of steam was required for process work, and boiler plant could not be dispensed with entirely.

The cheapness of coal also militated against the adoption of electricity for power purposes, as in many cases it was less costly to waste coal in running an uneconomical steam plant than to pay interest and provide for depreciation in respect of capital which would have to be expended on the installation of electrical plant.

The use of electricity for lighting purposes was recovering from the check experienced in the early years of the century when, by the development of the incandescent gas mantle, more especially of the inverted type, brilliant lighting effects could be obtained at much lower cost than by the use of the carbon-filament electric lamp. The competition of the incandescent gas lamp had been met by the introduction of the Nernst lamp, the tantalum lamp, the tungsten lamp, first of the squirted and then of the drawn-wire filament type, and finally by the gas-filled lamp. On the last-named being placed on the market but a year or so prior to the commencement of the War, anxiety was again caused to those responsible for the finance of a number of electricity supply undertakings, the incomes of which depended mainly on their output for lighting purposes, as these undertakings had barely recovered from the losses occasioned as a result of the substitution by their consumers of metal lamps for carbon lamps. It was not generally anticipated that this further reduction in the quantity of electricity required to produce a certain amount of light would be compensated for by the public adopting a higher standard of illumination and by the energy which would be demanded by the many additional consumers who would be obtained owing to the better and cheaper light provided.

There were, however, a number of undertakings which had realized that even on domestic premises there were other uses for electricity than the provision of light, and had framed tariffs designed to encourage the use of electricity for all purposes, and especially for heating and cooking. The electric fire had already become popular in districts in which such tariffs were in operation. The development of the electric cooking range had not proceeded so far as to give satisfaction except to enthusiasts. Electric irons and small pieces of cooking apparatus, in which, as a rule, the heating element was self-contained, were in fairly extensive use.

Early in the year 1915 the urgent call for munitions of war made it necessary that existing factories and workshops capable of producing material for war requirements should be extended and additional premises erected and equipped for this purpose. The problem of obtaining the necessary power to drive the machinery in these enlarged and new factories became a pressing one, as time did not permit of large numbers of boilers and engines being built, the power in many cases being needed immediately. The result was that the Government and firms and persons requiring power were brought face to face with the fact that power stations existed in most districts in the country, and from the majority of these power stations more or less electricity could be obtained which could be utilized for power purposes with but little loss of time.

During the earlier years of the War the chief concern of the authorities was the obtaining of electricity, and the question as to whether such electricity was produced economically or otherwise was but little considered. Later, however, owing to the large quantities of coal which were required to carry out many of the processes in connection with the manufacture of munitions, and the fact that the ranks of the miners were being depleted by reason of enlistment and, finally, conscription, economy in the use of coal in the production of electricity became a vital question. The Board of Trade was made aware of the fact that by a judicious linking up of groups of power stations in the country a considerable saving of coal could be effected, and as a result, in the middle of 1916, the Board issued a memorandum urging electricity supply undertakings to come to arrangements with each other for the linking-up of their respective power stations. A number of committees were formed in different parts of the country for the purpose of giving consideration to the recommendations contained in the memorandum and the means by which such recommendations could be carried out. For various reasons, however, one of the chief of which was the difficulty in obtaining material and apparatus for carrying out the schemes, comparatively little was done during the period of the War on the lines recommended in this and similar reports, but the idea had obtained firm root in Government and other circles, with the result that a Special Sub-Committee, called "The Coal Conservation Sub-Committee of the Reconstruction Committee," was appointed by the Minister of Reconstruction to consider the coal problem, and in December 1917 issued an Interim Report on "Electric Power Supply in Great Britain," in which recommendations were made for the reorganization of the system under which electricity was being supplied throughout the country, in order that production should be carried out on more economical lines, with consequent saving in the amount of coal consumed for the purpose. Other committees which were appointed dealt more or less fully with matters relating to the electricity supply industry, and a lengthy report was issued in April 1918 by a Committee appointed by the Board of Trade to consider the question of electric power supply. The conclusions of this Committee, which to a large extent followed the lines of those of the Coal Conservation Sub-Committee as to the conditions governing a cheap supply of electricity, included the following:—

Combined generation within suitable areas; well-situated stations, having regard to condensing water, fuel and distance from consumers; modern and large units of generating plant; uniform standards of system, frequency and pressure as far as now practicable; greater freedom for overhead wires and wayleaves; good technical and business management; adequate and cheap capital.

Having regard to the position of the electricity supply industry under the Rating and Valuation (Apportionment) Act, 1928, it is interesting to note that the Committee's report states that to the above might be added reduced valuations for rating purposes, especially in the case of transmission lines. The economies which might be obtained by the gasification of coal and the recovery of by-products in certain districts were also touched upon.

The report further recommended that a new body, to be called the Electricity Commissioners, should be set up to have, subject to appeal to Parliament in certain cases, general control over the generation and distribution of electricity in the United Kingdom.

Legislation was enacted in 1919 substantially to give effect to the recommendations of this Committee, and the Electricity Commission was thereupon established. Owing, however, to the manner in which, as a result of the opposition of various interests, the original Bill was mutilated in its passage through Parliament, the Electricity Commissioners found themselves unable to carry out to anything like its full extent the scheme underlying the Report of the Board of Trade Committee. In 1922 a further Act was placed on the Statute Book which extended and to some extent modified the 1919 Act, and under the provisions of this and preceding Acts some progress was made. Such progress was, however, in no way commensurate with the exertions of the Electricity Commissioners in the furtherance of the work for which they were appointed, and in their Report of 1925 the Commissioners intimated that they had been striving to supersede small-scale generation in some hundreds of stations, but were compelled by circumstances to sanction the construction of further small power stations and also extensions to power stations which would be shut down eventually.

The Government also being dissatisfied with the progress which was being made in connection with the reorganization of the electricity supply industry in the country, the Minister of Transport appointed a further Committee in 1925 to review the national problem of the supply of electrical energy, and the majority of the proposals of this Committee were embodied in the Electricity (Supply) Bill introduced by the Government in 1926. These proposals differed chiefly from those put forward in previous reports, in that whereas in the latter schemes covering districts were to be carried out by separate authorities set up within such districts, under the Bill of 1926 one authority—the Central Electricity Board—was to be established and made responsible for carrying out approved schemes throughout Great Britain. This Bill, after being considerably amended in its passage through Parliament, was duly enacted, after which no time was lost in the appointment of the Central Electricity Board, and no time has been lost by the Board in proceeding with the work with which it has been entrusted, so that in the near future we should be in a position to judge the results attained and likely to be attained as the outcome of the passing of the Electricity (Supply) Act, 1926.

Although disappointment is often expressed at the tardy progress which has been made in connection with the reorganization of the electricity supply system in this country since the passing of the Electricity (Supply) Act of 1919, I feel it must be conceded that the country has to a considerable extent benefited by the setting up of the Electricity Commission and the work which has been carried out by the Electricity Commissioners, as, speaking generally, since their appointment far greater attention has been paid to economy in connection with the generation of electricity by those responsible for the operation of electricity supply undertakings than was previously the case. The fact that it was generally known that under the various schemes put forward it was intended wherever possible to shut down the smaller generating stations and transfer their loads to the larger stations has stimulated electrical development, in that it has caused those responsible for the management of small stations to make strenuous efforts in the direction of finding load with a view to justifying their stations being enlarged to such a size that they could be retained in use in connection with any schemes which might be put forward for their districts. The fact also that economy in coal consumption would have a considerable bearing on the extent to which a station would be utilized in the future, and that particulars of the thermal efficiency and fuel consumption of all public generating stations are set forth in a report issued yearly by the Electricity Commissioners, has caused station engineers throughout the country to vie with each other in the production of electricity with the smallest possible consumption of fuel. The outcome of this has been that the average consumption of fuel per unit generated has greatly decreased.

As an indication of the saving in fuel which has been effected in the generation of electricity during the past nine years for which the Electricity Commissioners have issued their annual reports of analyses and summaries of the returns of fuel consumption and units generated made to them by authorized undertakers, railway and tramway authorities, and certain non-statutory undertakings, I would mention that in the report issued for the year ended 31st March, 1921, the total units generated in stations consuming coal or coke is given as 4 955 514 403, and the average consumption of coal per unit generated was 3·32 lb. The report recently issued for the year ended 31st March, 1929, shows that the number of units generated in steam stations using coal, coke or oil-fired boilers was 10 377 107 062, and the average consumption of fuel per unit generated (converted to a coal basis) was 2·05 lb. From this it will be observed that in this period of 8 years the amount of coal consumed per unit generated has fallen from an average of 3·32 lb. to 2·05 lb., representing a saving of 1·27 lb. Had the 10 377 107 062 units generated in steam stations, as given in the latest report of the Electricity Commissioners, involved the consumption of the average figure of 3·32 lb. of coal per unit generated, as in 1921, the consumption of fuel (converted to a coal basis) would have been 15 399 868 tons, as against the actual consumption of 9 516 419 tons, which shows that a saving of no less than 5 883 449 tons has been effected.

It may thus now be fairly claimed that, quite apart from any advantages which will be gained as a result of the Central Electricity Board's operations, the attainment of the position stated to be desirable in the report of the Coal Conservation Sub-Committee is well on the way to being accomplished.

Much has been said on the subject of Government interference with the electricity supply industry, which interference is stated by many to have retarded rather than encouraged progress. While sympathizing with many of the views put forward in this connection I think we may take it that, on the whole, the interest displayed by successive Governments in our industry has been productive of beneficial results, as the fact that the provision of an ample and cheap supply of electricity throughout the country has been made a plank in the platform of each of the political parties cannot fail to have had considerable advertising value, and the public demand for electricity has thereby been greatly stimulated.

Having reviewed the developments which have taken place in connection with the organization and control of the electricity supply industry during the past 15 years, it may prove of some interest if I touch upon the progress which has been made by the industry from a more technical aspect, more especially in relation to steam-electric generating plant.

To afford supplies of electricity required in the days immediately prior to the outbreak of War the larger power stations had for the most part been equipped with turbo-alternators, and in the smaller power stations it was becoming the practice to install machinery of this type. Many undertakings were, however, supplying the whole of their consumers with electrical energy in the form of direct current, even though in some of these cases the electricity was generated as 3-phase alternating current.

The usual steam conditions then obtaining in power stations in this country were pressures of from 160 to 200 lb. per sq. in. gauge and temperatures of from 450° to 550° F. There were, however, power plants on the Continent working at considerably higher steam temperatures than those usually adopted in this country, one plant operating with steam at 660° F. In some large power stations boilers having an evaporative capacity up to 40 000 lb. per hour were in use, and boiler-house efficiencies of from 65 to 75 per cent were attained.

As typical of turbo-alternators of the largest capacity in commission in 1914, mention may be made of the 15 000-kW 3-phase set, running at a speed of 1 000 r.p.m., installed in the Stuart Street station of the Manchester Corporation. This set had an overload capacity of 19 000 kW for a period of 30 minutes at a power factor of 0·95. The steam conditions at the turbine stop-valve were 190 lb. per sq. in., 530° F., and the vacuum was 27½ inches. The steam consumption at a load of 15 000 kW was 13·65 lb. per kWh.

At this period a good steam plant could attain a thermal efficiency of about 15 per cent.

Up to 1914 there were no turbo-alternators of 5 000 kW or over in this country running at a speed of 3 000 r.p.m., although at least one set of 5 000 kW capacity designed for this speed was at work on the Continent. In December, 1915, however, a turbo-alternator of 6 250 kW capacity built to run at this speed was started up in the Stuart Street station at Manchester.

Although 15 000-kW sets were considered large on this side of the Atlantic, the erection of 30 000- and 35 000-kW single-shaft machines was commenced by the Philadelphia Electric Co. in the United States towards the end of 1914. The steam conditions for the 35 000-kW set were 215 lb. per sq. in. pressure and 540° F. total temperature, the steam consumption being approximately 12·0 lb. per kWh. Had there been the demand for such large units of plant over here no doubt it would have been met by British manufacturers, seeing that in 1912 a 25 000-kW turbo-alternator was being built in England for the Commonwealth Edison Co. of Chicago.

The first radical departure in this country from the steam conditions which had been generally adopted was the installation during the year 1915 at the power station of the British Thomson-Houston Co., Ltd., Rugby, of steam-raising plant and a turbo-alternator designed for a steam pressure of 375 lb. per sq. in. and a temperature of 700° F.

In 1918 a 45 000-kW turbo-alternator was put into operation at the Connors Creek power station of the Detroit Edison Co., U.S.A. A notable feature of this set was that its generating pressure of 12 200 volts was stepped up to 24 000 volts by a single 3-phase transformer, the largest of its kind in use at that time. This power station had achieved what was up to this period the world's record for thermal efficiency, a figure of 17 per cent being attained with an annual output of approximately 210 million units, a maximum demand of 50 000 kW, and a load factor of 47·8 per cent. In this country the highest thermal efficiency reached up to that time was 16 per cent.

The year 1918 also saw 12 boilers each having an evaporative capacity of 50 000 lb. per hour installed in the Rotherham power station, these boilers being stated to be the largest up to then constructed in this country.

During the following year boilers of 91 000–104 000 lb. per hour evaporative capacity were installed in the Stuart Street station, Manchester, the steam pressure being 225 lb. per sq. in.

In the year 1920 the North Tees power station was started up, the first installation of steam-raising plant in which comprised 10 boilers each having an evaporative capacity of 42 000 lb. per hour, operating at a steam pressure of 475 lb. per sq. in. and a total temperature of 700° F. In this station re-heating was adopted, as were also the extraction of steam from the main turbines for feed-water heating and the preheating of air to the furnaces. The turbo-alternators installed were each of 20 000 kW capacity, designed for a speed of 2 400 r.p.m.

In spite of the notable increase in steam pressure at the North Tees station and the introduction of such refinements as re-heating, the general tendency in connection with power-station design was still to keep to more moderate steam conditions, as is instanced by the Dalmarnock power station of the Glasgow Corporation, which was started up at about the same time as that at North Tees. For the Dalmarnock station the steam pressure adopted was 275 lb. per sq. in., with a total temperature of 700° F. The first boilers to be installed in this station each had an evaporative capacity of 62 000 lb. per hour, and the turbo-alternators each had an output of 15 000–18 750 kW. The steam consumption of these generating units was 10 lb. per kWh, with a vacuum of 29·1 inches.

In 1921 a 30 000-kW set—then the largest in the country—was installed in the Rotherham power station. This machine, which was constructed to operate under steam conditions of 200 lb. per sq. in., a total temperature of 588° F., and 28½ inches of vacuum, was of the single-cylinder type running at a speed of 1 500 r.p.m. The steam consumption of this machine was 11·1 lb. per kWh.

By this time boiler-house efficiencies of about 80 per cent had been recorded and steam installations for pressures of 250 lb. per sq. in. had become common, and a number were either at work or under erection to operate at a pressure of 350 lb. per sq. in. Greater developments in connection with the increase of steam pressures were, however, being made by American engineers, and a number of stations were constructed in the States in which the steam plant was designed to operate at pressures of from 500 to 600 lb. per sq. in., and in 1925 the Edgar station of the Edison Electric Illuminating Co. of Boston, in which steam plant to work at 1 200 lb. per sq. in. was installed, commenced to operate. Since then other plants have been built in the United States to work at still higher steam pressures, and it is reported that two boilers will shortly be put into use in that country to produce steam at a pressure of 1 840 lb. gauge.

At the present time there is still no power station belonging to a public electricity supply undertaking in Great Britain which has boilers working at a higher pressure than those at the North Tees station, and until very recently no other boilers in this country were operated at so high a steam pressure. During this year, however, several very large boilers designed to work at a pressure of 800 lb. per sq. in. have been erected and put into commission by the Synthetic Ammonia and Nitrates, Ltd., at Billingham-on-Tees. A boiler and turbo-alternator constructed to operate at a pressure of 1 100 lb. per sq. in. gauge will shortly be put to work at Bradford, and statements have been made to the effect that a large manufacturing concern in the South of England intends to install boilers for working at a pressure of something over 1 800 lb. per sq. in.

With regard to the size of turbo-alternators, sets are now being built in this country to operate at a speed of 3 000 r.p.m., having a capacity of 30 000 kW at 0·8 power factor, and sets of 67 250 kW capacity to run at 1 500 r.p.m. are on order for the new Battersea station of the London Power Co.

In the United States of America very much larger machines are at work, one at the Hell Gate station of the New York Edison Co. being of 160 000 kW capacity, and another built for the State Line Co. of Indiana being of 208 000 kW capacity.

As indicating the progress which has been made in the direction of increasing the thermal efficiency of British steam-operated power stations, the recently issued report of the Electricity Commissioners shows six stations as having thermal efficiencies exceeding 20 per cent, the highest figure recorded being 21·35 per cent.

Much could be said with respect to developments in connection with plant and apparatus for the control, transmission, conversion, transformation, distribution and utilization of electricity, and also as regards progress in other branches of the electrical industry, as, for example, wireless telegraphy, wireless telephony and television, which since pre-War days has been most remarkable. Time, however, does not permit of these matters being even touched upon.

As members of the Institution we may feel proud of the part which has been taken by our Institution as a whole and by its members individually during the period covered by this retrospect. Its assistance and that of its most prominent members was time and again sought by the Government during the War, and has since often been solicited to afford help in the work of reconstruction. As a result the importance and influence of the Institution have become greater each successive year.

Great credit must be given to the Presidents, Members of Council and others who have played leading parts in connection with the Institution's wonderful development in recent years.

Through the medium of the Centres and Sub-Centres established in different parts of this and certain other countries the Council has been kept in touch with the needs and desires of all British members of the electrical industry, and has wisely made arrangements as a result of which the majority of the sections into which the industry is divided have found it more desirable that their personnels should enter into membership of the Institution rather than that separate societies should be formed in their interests. A Meter and Instrument Section, a Wireless Section and a number of Student Sections have thus been established.

The membership of the Institution, which was 7 045 in 1914, has now risen to 13 561, and the annual income from subscriptions from £15 454 to £34 693, and an examination of the Balance Sheet published in the *Journal* in July last will show the remarkable soundness of the financial position of the Institution at the present time.

We present members have in our Institution a goodly heritage, and it should be the endeavour of each one of us to do everything possible to increase the Institution's prestige and its usefulness to the industry, our country and the world at large, so that on our passing we may leave to those who follow a society which can, to a still greater extent, contribute to the good of its members and mankind in general.

SCOTTISH CENTRE: CHAIRMAN'S ADDRESS

By GEORGE MORGAN, Member.

(*Address delivered at* GLASGOW, 12*th November*, 1929.)

During the past few months the electrical resources of this city have been augmented by the completion and setting to work of the new refuse destructor works belonging to the Cleansing Department of the Corporation of the City of Glasgow. Since installations of this type are relatively rare in this country, and as the present example is probably unique, not only in point of magnitude but also in regard to coherency of design and completeness of detail, I have considered that some description of the methods by which the communal waste is turned to good account and the energy latent therein converted to the form most suited to modern industrial requirements, would prove of interest.

The inception of the present project dates back to the year 1912, when investigations were commenced with regard to the provision of refuse disposal works for the southern area of the city. The outbreak of hostilities in Europe naturally delayed the completion of this part of the work, and it was not until the year 1922 that the decision was finally made to undertake the installation of plant having for its principal object the generation of electricity from the city refuse.

The site ultimately chosen lies in the south-western quarter of the city, where the process of natural expansion is both rapid and certain. It extends to an area of some 15 acres, and is bounded on its southern side by the main railway line and on the east and west by main roads which tap the densely populated districts surrounding the shipbuilding yards and give ready access to the new arterial roads leading to new housing areas of the city. On the northern side, land for extension of the works is available when required.

Whilst, as I have already indicated, the main purpose of the plant is directed towards the generation of electrical energy, it will be readily appreciated that a heterogeneous collection of material, as represented by household and industrial refuse, contains many substances the value of which varies in accordance with the method of disposal. Realization of this fact has led, in the present instance, to the combination, as conveniently and economically as possible, of the functions of a modern salvage and destructor plant with those of an equally modern electricity generating station. The chief consideration with regard to the refuse is naturally that concerning its value as a fuel. It follows, therefore, that it must receive careful preparation, and all substances which are incombustible, or which are inherently valuable as scrap, must be removed in the initial stages, and the remainder treated in such a manner as to render its combustion a hygienic, reliable and economic process. Not the least of the many peculiarities possessed by a fuel of this nature is its liability to spontaneous combustion. In consequence, storage for a period longer than about 24 hours is undesirable, and the process of collection, treatment and combustion must proceed at a steady pace and in accordance with the exigencies of the electrical load on the station. Fortunately, the system into which this electrical output is delivered is a large one, and means are available whereby the load factor of the station may be kept high.

In order that the various functions which have been indicated may be properly accomplished, the works are divided into three main sections, each with its own separate building. These are, respectively, the reception and screening house, the incinerator and boiler house, and the generator house. Appropriate to each of these main divisions, subsidiary plant has been provided for such purposes as (1) the de-tinning of light containers, and their subsequent conveyance with other sheet-metal articles; (2) the crushing and grading of the clinker for road-making, sewage filter beds, racing tracks, and similar purposes; (3) the manufacture of concrete paving slabs, kerbs and steps; and (4) the utilization of flue dust in the manufacture of external finishes for stonework and rough-cast buildings. These few instances will, it is believed, prove to be but the forerunners of many other by-product plants concerned with the fuller utilization of the refuse and all that it contains.

It is, however, from the electrical engineer's point of view that I wish to present my brief review of the destructor works, and from this standpoint I believe that the simplest and most satisfactory way of forming a clear idea of the principles involved and the plant entailed, is to trace the course of the refuse from the moment it arrives until the energy it contains makes its exit through the outgoing e.h.t. feeders.

The crude refuse from the surrounding areas is collected and conveyed to the works in special electric trucks of which I shall have more to say later. These, after traversing a concrete ramp, about 450 ft. in length and with a gradient of approximately 1 in 15, arrive on the first or tipping floor of the screening house, into which are sunk four large rectangular hoppers with their upper edges flush with the floor-level. The contents of each truck, an average of some 5 tons in weight, are then tipped directly into these hoppers. The usual practice in such matters is here departed from inasmuch as, in order to achieve a particularly low loading line for these trucks, self-tipping gear has been excluded from the design, its place being taken by electrically operated overhead blocks. The tank body of each truck is arranged to hinge from either side, and by means of the overhead tackle it can be rotated on this hinge in such a manner as to discharge its contents into the receptacle provided, after which the truck proceeds down a corresponding exit ramp, and out upon another round of its district. These receiving hoppers are each fitted with low-speed apron conveyors which form the floor of the receptacle and gradually carry the contents towards the chute leading to the revolving screening drums, of which there are four, one to each hopper. Any large objects, such as baths, bedsteads, bicycles, etc., are here removed, and the remainder is allowed to pass on. In the initial stages the smaller particles are sifted out through the 3-in. holes in the screens, and the tailings pass on, to be dealt with by the magnetic separators, which remove all loose iron and steel articles and direct them down chutes for further treatment. Tinned articles in good condition are sorted out and sent by telpher conveyors to the de-tinning plant, whilst others not considered suitable for, or worthy of, this treatment are dispatched direct to the baling presses, there to be joined by those which have been de-tinned. The presses, of which there are two, are driven by electric motors and exercise a pressure of rather more than ½ ton per sq. in., producing a compact block measuring 1 ft. square by 1½ ft. in length. The remainder of the tailings fall into pulverizers of the swinging hammer type driven by motors of the high-torque type. These reduce the refuse to particles of approximately the same size as those which have passed through the screens, and render the whole mass much more homogeneous in nature. All subsequent operations, such as handling and firing, are thereby rendered much easier, besides enabling a certain amount of control to be obtained over the nature of the clinker formed in the furnaces.

Manual supervision is retained at all stages in the grading process. Dangerous or bulky articles are either removed or assisted on their way, and finally the initial screenings and the product of the pulverizers unite on the main conveyors, which are situated in pits formed in the ground floor of the screening house. These conveyors, in common with those which carry the screenings or deal with the tailings, are of the trough or belt type. The belt is of rubberized canvas, running on a system of rollers spaced at frequent intervals and arranged to give it a concave surface. The main conveyors, of which there are two, extend for a distance of rather more than 400 ft., and are housed in a covered corridor carried on gantries and rising gradually to a height of approximately 60 ft., where they terminate in a tower erected at the southern end of the incinerator house. At this point the refuse, which must now be regarded as fuel, is transferred to distributors of similar character which again feed shuttle conveyors. These latter are arranged directly over the furnace silos and are traversed on rails to the required position. The direction of motion can also be reversed, so that the fuel may be deposited in any one of the bunkers. As might be expected, the whole of this somewhat elaborate conveyor system is electrically driven, and on account of the extreme importance of its function a complete system of alternative working routes has been established, with push-button control at all vital points. An ingenious system of electrical interlocks prevents the possibility of errors of operation and reduces to a minimum the supervision which would otherwise be necessary.

The problem of firing boilers with such a relatively variable fuel as city refuse is likely to be, is no mean one. The calorific value may vary over wide limits, as may also the moisture content. These depend largely on the season of the year and the climatic conditions existing at the time. In the present instance, the calorific value is of the order of 4 000 B.Th.U. per lb., and the moisture content about 25 per cent. It has also to be remembered that mere combustion of the fuel is not the only problem to be solved. The clinker which is formed is a valuable by-product, and the solution must include means whereby this can be satisfactorily produced both as regards quality and quantity. Many attempts have been made in the past to meet these demands, and the present firing equipment merits description on account of its ingenuity and good general performance. Each of the silos already mentioned is in the form of an inverted cone, of such general proportions that packing of the fuel does not occur. At the lower end is fitted the transfer hopper. This can best be described as a drawer without a bottom, capable of motion to and fro in a horizontal plane. At its inmost position it is filled by gravity from the silos above. When occasion demands, it is drawn forward by the action of a hydraulic ram, conveying its contents towards the opening into the furnace cells below, at the same time closing the exit from the silo by means of a sliding shutter equipped with a shearing edge. On arrival over the furnace the contents are deposited on to the grate below, and the hopper is returned to its original position, during which process a firebrick-lined door is restored to its normal place over the furnace inlet opening. The furnace grates are themselves of a special type and are arranged to oscillate to and fro in accordance with the requirements of the fuel and the formation of a satisfactory clinker. These are two in number and are placed one above the other. The fresh charge on the upper grate is ignited by the incandescent clinkers which have been deposited on the auxiliary grate beneath, and after the lapse of a certain length of time, during which one or more charges have been thoroughly consumed, this grate is caused to move backwards towards the rear of the furnace, removing, by means of scrapers depending from its front edge, the partially cooled clinkers on the grate beneath, simultaneously depositing its own load in their place. The cycle is completed by a forward traverse of the upper grate, which permits the hinged scrapers already mentioned to act as spreaders, causing the new clinkers to be distributed evenly over the surface of the lower grate and in a position to ignite a fresh charge deposited on the grate above. There are five such cells or furnaces in each unit, each capable of dealing with about 10 cwt. per charge and two charges per hour, that is, 5 tons per unit per hour. The total equipment of the incinerator house is 8 units, or 40 cells in all.

The clinker, which amounts to about 30 per cent of the weight of fuel burnt and is cleared off the auxiliary grate in the manner already described, falls down a chute into the hopper provided for it. Small storage-battery locomotives, running in tunnels beneath the firing floor, periodically remove the clinker in self-tipping trucks and convey it to the quenching pits situated outside the incinerator house, adjacent to the railway sidings and clinker-crushing and -grading plant. Grab and telpher equipment is utilized in removing the quenched clinkers to either of these points, while a bucket-type conveyor disposes of the sludge direct into railway trucks or as otherwise required.

The products of combustion from each unit are led through a common combustion chamber to a boiler of the water-tube type and thence to one of four stacks—one stack to each pair of boilers. Forced draught is provided to each cell, and all the grate-operating gear, which is hydraulic, is provided with interlocking controls so that draught is cut off when the furnace doors are opened or the transfer hoppers are in operation. Careful firing and adjustment of the forced-draught pressure, in conjunction with the natural draught provided by the stacks, enables approximately balanced conditions to be obtained. Owing to the nature of the fuel, 1½ per cent of dust is carried over into the combustion chamber and its removal during the period of operation has proved rather a problem. A system of double doors has been devised which will, it is hoped, successfully circumvent this difficulty.

In recognition of one of the functions of the refuse works, the combustion chambers are adapted for the disposal of large carcases. Suitable doors are provided, both in the roof of this chamber and at the floor-level, while mechanical lifting gear eliminates the necessity for any manual handling.

The boilers are of the cross marine type and are fitted with superheaters, feed-water regulators and soot blowers. The nominal capacity of each boiler is 22 000 lb. of steam per hour at a pressure of 200 lb. per sq. in. (gauge) and final temperature of 650° F. It has been recognized that circumstances may arise in which alternative firing arrangements may be required, and, in view of this, four of the boilers are provided with additional furnaces designed for the use of coal as fuel. These, however, are regarded in the light of emergency gear and are hand-fired.

One of the most notable features of that part of the installation so far described is the general cleanliness which prevails in the various departments. This is in marked contrast to what might reasonably be expected when the nature of the fuel substance is taken into account, and has been achieved by the employment of mechanical handling gear of the most careful design at all stages in place of the manual labour more usually met with in such establishments. The same thorough attention to points of detail is again accorded the refuse from the technical point of view. From the moment it is tipped into the receiving hoppers it is regarded as a potential fuel and every reasonable precaution has been adopted to ensure that continuity of flow throughout the system which its nature and the purposes of the complete installation demand. At each stage in its progress an endeavour has been made to conserve, and ultimately to utilize in the highest degree, the calorific qualities of the refuse—the design and operation of the furnace units is a case in point—with the result that on an average 2·5 lb. of steam is obtained for each 1 lb. of refuse consumed. This represents a combined boiler and furnace efficiency of about 75 per cent, at the pressure and temperature concerned, and must be regarded as distinctly good for plant of this nature. The total capacity of this part of the complete installation is 640 tons of refuse per 24 hours, but the present normal rate of electrical output demands only 480 tons to be dealt with in this period. A margin of 33 per cent of plant is therefore available to cope with any breakdown which may occur.

Having now described in some detail the manner in which the heat energy latent in such unpromising material as city refuse is transferred into steam at 200 lb. per sq. in. and at 650° F. total temperature, I shall proceed to that part of the installation which is more familiar to the average electrical engineer, namely, the generating station. This building is entirely separate from, but adjacent to, the incinerator house. The general design is in consonance with present-day practice in such matters. A two-level arrangement has been adopted for the plant installed, the turbo-alternators and their control gear being on the first floor, while all auxiliary plant, such as the condensers with their associated circulating and extraction pumps, are accommodated on the ground-level. Moreover, the main units are placed transversely to the length of the building, with the steam end towards the wall adjacent to the incinerator house. This lay-out allows a simple and convenient arrangement of the main steam piping, and permits the electrical output from the alternators being taken by a short and direct route to the e.h.t. switchboard, which is housed in an annex to the generator house.

The turbo-alternators, of which there are two, are of the well-known high-pressure direct-coupled type and run at 3 000 r.p m. Each is capable of supplying 5 000 kW of 3-phase energy at 0·8 power factor at a pressure of 6 500 volts between phases. The frequency is 50 cycles per sec. and is, therefore, in accordance with the standard chosen by the Electricity Commissioners for the unification of supplies in Great Britain.

The turbines are of the impulse type and are representative of modern land turbine practice. The usual governor-controlled oil-operated valve gear is fitted, and permits an overload of 25 per cent to be carried automatically. Remote control of the speed is provided from the main generator panel on the e.h.t. switchboard.

Following what is now general practice in such matters, the condenser, which is of the surface type, is suspended directly from the exhaust casing of the turbine, part of the weight being taken on powerful helical springs placed below it. As a result of this method, trouble due to the differential expansion of parts at unequal temperatures is avoided. This principle extends also to all pipe lines connected to the condenser, copper expansion pieces being fitted in these. The initial vacuum is obtained by the use of an ejector type of air pump, while the extraction pumps are of the high-speed centrifugal opposed impeller type and are interconnected so that they may be used alternatively with either of the condensers. The absence of a natural supply of water for condensing purposes has necessitated the provision of cooling towers. These are of the usual wooden-chimney natural-draught type, and are capable of dealing with some 700 000 gallons of water per hour, from 93° F. to 75° F., under normal atmospheric conditions. Motor-driven centrifugal pumps, one for each of the condensers, deal with all the circulating water required, not only for condensing purposes but also for the cooling of all oil and air supplies demanded throughout the station. The water required to make good the losses through evaporation, etc., is drawn from the city supply mains. In pursuance of the general scheme for alternative working, these pumps may be interconnected to either of the condenser circulating-water systems as necessity arises.

The alternators have a maximum continuous rating of 6 250 kVA. They present no unusual features in design, being of the modern high-speed type with a non-salient rotor. A closed-circuit system of axial ventilation has been adopted, the air being circulated by means of fans attached to the rotor shaft. Short air conduits, formed in the foundation plinth, convey the exhaust air to a surface type of air cooler through which water, drawn from the main circulating system, is passed. This type of ventilation has several features to recommend it in the present circumstances. A direct-coupled exciter furnishes the current to the rotor winding, voltage regulation of the main machine being controlled by variation of the field current of the exciter at the main control panel on the generator switchboard. In order to minimize the extent of the damage which would ensue as the result of an internal fault developing in the windings, an emergency breaker of the pedestal type is included in the main rotor circuit and can be opened directly from its position beside the steam controls or remotely from the generator control panel. The electrical output from the alternator is taken by a short and direct path to the main 6 500-volt, 50-cycle switchboard. This gear is located on the same level as the turbine-house floor, but in an annex to it.

The switchgear is of the well-known metal-clad, compound-filled type. Its salient features lie in the fact that it is compact and that all live conductors and other parts are enclosed in a continuous metal casing, which is itself directly connected to earth. The horizontal draw-out principle, on which the whole design is based, greatly facilitates the removal from the live busbars of any one of the oil-immersed circuit breakers, either for overhaul or to ensure the absolute safety of workmen on the circuit which it controls. A notable feature of the apparatus is the very complete system of mechanical and electrical interlocks, which practically preclude the possibility of incorrect operation.

The switchboard itself consists of 9 panels or circuit breakers, viz.: 2 for the main alternators, 2 for the 6 500-volt side of the step-up transformer units, 4 controlling the circuits for the works step-down transformers, and 1 busbar sectioning unit, situated between the two main generator switches. Of these, the first four are electrically operated by remote control from the main control and instrument panels. The remainder are manually operated at the circuit breaker itself. All the circuit breakers, with the exception of the busbar sectioning unit, are equipped with electrical tripping gear connected to the particular type of protective system employed for the apparatus which it controls. Thus the main alternators and step-up transformers are provided with circulating-current protection, as are also the three works transformers, while the remaining circuit, which supplies the works garage, is equipped with overload and leakage protection.

With the exception of that which is required for works use, the generated energy is exported to the Glasgow Corporation Electricity Department at a pressure of 20 000 volts and a frequency of 50 cycles per sec. The switchgear for the control of this output is situated at the other end of the control-room annex and on the same level as that already described. Its general construction is similar, but it is designed for a pressure of 20 000 volts and comprises 6 panels—2 for the high-pressure side of the main step-up transformers, with a section switch between them, and 3 feeder switches. The transformer circuit-breakers are included in the circulating-current protective system already mentioned, while the three latter switches are of the special type used in conjunction with the split-conductor protection which has been adopted for the outgoing feeders.

The works substation is located on the ground floor of the switch-house annex, beneath the control-room floor. It comprises three 6 500/440-volt 500-kVA works transformers, two 6 500/20 000-volt step-up output transformer banks of 5 625 kVA each, along with a 440-volt metal-clad switchboard of the same general type as those already described, and a 60-kW 250-volt d.c. motor-generator set. The last named is utilized mainly for the supply of excitation current to the magnetic separators fitted to the screening plant and for the turbine-house overhead crane, but a number of smaller items are dependent on this source for their supply. These include the station lighting and ventilation systems and an auxiliary drainage pump. At week-ends or during the periods when the station is shut down, a stand-by supply at 250 volts (d.c.) from the Electricity Department's network is available at the d.c. switchboard.

In contradistinction to the normal electricity generating station depending on coal for its source of energy, a relatively large amount of power is used internally. This amounts to approximately 1 500 kVA, part of which is used for the manufacturing sections, such as the clinker-crushing and -grading machinery, the concrete-slab plant, and so on. The major portion of the demand is, however, made in conjunction with the fuel-preparation and conveyor gear.

The difficulties attending the storage of prepared fuel have already been touched upon and it will be readily appreciated that the successful functioning of an undertaking of the present description depends wholly upon a regular and adequate supply of fuel material at the lowest possible costs for transport. These onerous duties have been delegated to an extensive fleet of electric vehicles which have been specially designed for the work they have to do. The vehicle garage, which is situated in the south-west quarter of the site and adjacent to the exit ramp from the screening house, has accommodation for upwards of 50 large trucks and is complete with inspection pits, repair bays and offices. The chief feature of interest, however, lies in the electrical equipment for charging the vehicle batteries. Energy for this purpose is delivered at 6 500 volts from the main station busbars, and is reduced to 440 volts in a

3-phase 500-kVA transformer situated in the garage substation, which is equipped with low-tension switchgear of the same pattern as that in the works substation. Immediately adjoining this section is the motor-generator room, which contains also the switchboards and charging panels. Two motor-generators, each of 150 kW output, are installed. These consist of a squirrel-cage motor, with an oil-immersed auto-transformer startor, direct-coupled to a shunt-wound d.c. generator. The nominal pressure at the charging busbars is 120 volts, but means are provided for varying this pressure in accordance with the exigencies of the vehicle batteries on charge, thereby minimizing the energy which need be dissipated in the charging rheostats. The output from these sets is controlled on two d.c. generator panels placed in the centre of the complete switchboard.

On either side of the generator panels are the charging panels. These are of the unit type and are arranged symmetrically in columns and rows, so as to present a uniform appearance. Each charging-panel unit is complete in itself and can be removed without disturbing those surrounding it. The rheostat is interlocked with the circuit breaker, so that improper operation is rendered impossible. Moreover, the breaker is held closed magnetically so that the operation of putting a battery on charge and adjusting the current must be performed simultaneously. In the event of the circuit being broken at any point, the circuit breaker automatically opens, and it cannot be closed until the rheostat has been returned to the zero position. A further feature lies in the provision of a small pilot lamp which indicates that a battery has been connected to the charging circuit and is awaiting attention.

With storage batteries in general, and particularly in the case of those on constant and often heavy duty on vehicles, it is essential that accurate and continuous records of performance should be kept. With this end in view, each charging circuit is provided with an integrating ampere-hour meter to measure the total input of the battery. Such records, in conjunction with others of voltage and acid density, enable faulty cells to be quickly detected and, if necessary, removed for special attention. The charging current in each circuit, and its voltage, are indicated on centrally disposed instruments which can be connected to the circuit in question by operating a self-restoring switch on the appropriate panel. By means of these various devices, the charging process of all the vehicle batteries can be kept under continuous surveillance and a high degree of efficiency achieved.

In the garage a stand is provided for 48 vehicles, to which overhead supply cables are run on insulators. These cables terminate in vertical drops, conveniently placed to the charging-plug position on each vehicle. Means are also provided whereby they may be slung up out of the way when not in use, thus leaving the floor space unobstructed so far as the movement of the vehicles is concerned.

Of the vehicles, upon the successful behaviour of which so much depends, a few words of description may not be out of place. They are of uniform design and have a full-load capacity of 5 tons. A remarkably low loading level has been achieved, thus minimizing the labour entailed in packing the refuse into the tank. The steering lock has also received special attention, in order that manœuvring in confined situations may be facilitated.

The electrical equipment consists of a 40-cell battery of 522 ampere-hour capacity, placed in an accessible position immediately to the rear of the totally-enclosed driving cabin. This renders its removal when necessary a simple matter and also provides an ease of inspection that is reflected in a longer and more satisfactory life than might otherwise be the case.

The total weight of the battery is 1·85 tons, out of a gross laden weight of about 11 tons. The driving motor is nominally rated at 12 h.p., and is, of course, of the series-wound type, while the transmission gear follows automobile practice in so far as it consists of a cardan shaft, with a worm-driven differential gear on the rear wheels.

Neither clutch nor gear box is necessary in this type of vehicle, the required variations in speed, including reverse motion, being obtained by electrical methods. In practice, a speed of 12 m.p.h. on the level is obtained with a full load of 5 tons. In the course of their duties a mileage of about 40 is attained per charge, and this can be considerably extended by judicious boosting charges during the meal interval.

Not the least of the many advantages of these vehicles is their almost total silence of running. This feature is the more acceptable in that their excursions into residential areas are mainly nocturnal in character. As already indicated, the vehicles form the alpha and omega of a description which is of necessity somewhat general in character but, it is hoped, not the less interesting on that account.

From a broad standpoint, the most interesting feature of the whole installation is, I consider, the manner in which the refuse is constrained to accomplish its own destruction and at the same time liberate for other industrial purposes the major portion of the energy which it contains. All this work is done in a manner which, from the point of view of hygiene and economy, could scarcely be approached were it not for the fact that electrical methods have been applied at each step in the process. The whole installation provides but another instance of the manner in which mankind is destined to benefit when electricity, the highest known form of energy, is called upon to execute, on its behalf, any of its multitudinous tasks, menial or otherwise.

EAST MIDLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By A. D. PHILLIPS, Member.

(*Address delivered at* LOUGHBOROUGH, 8*th October*, 1929.)

In this address I propose to consider—very shortly and perhaps more from the commercial than from the technical point of view—some of the questions relating to the public supply of electricity.

The subject, apart from being more specialized than is generally appreciated, is a fairly wide one. I therefore propose to limit my remarks more particularly to the development of the type of area which has been brought somewhat prominently to the notice of the public during the last year or two, namely, the rural type of area.

The provision of an efficient and cheap supply of electricity is generally admitted to be of the first importance to the development of rural industries and the improvement of the amenities of the countryside. One of the first considerations, however, is as to whether and to what extent a rural supply can be made self-supporting. It has been found by experience that it is possible to do so in quite a large number of instances, provided the all-in cost of making the service available is kept at a minimum.

I do not wish to enter into a discussion on points of political significance, but I think I may postulate that the employment of capital not only does, but should, involve a proper charge payable by the person or persons making use of it or obtaining service from it. The electrical development of rural areas requires quite a substantial expenditure on capital account, and the charges resulting from such expenditure form a material proportion of the cost of rendering such an electrical service available. The only way to keep this proportion within reasonable limits is to see that capital commitments are kept within proper bounds and, further, that expenditure so incurred is employed to the best advantage.

By encouraging the use of overhead distribution lines and by their efforts to overcome the prejudice of local authorities and others against such use, the Electricity Commissioners are performing a valuable service to the community. A good deal, however, still remains to be done. Although the Commissioners have recently revised the code of Overhead Line Regulations, resulting in a quite substantial reduction in cost, overhead lines, more particularly distribution lines, are still more costly than they might be. In countries other than our own, the rural consumer has been specially catered for in a much less expensive fashion and without detriment to the public safety. It is pleasing to note, therefore, that suggestions have been made to the Electricity Commissioners that they should undertake a still further review of the Regulations within a reasonable period with the object of effecting still further reductions in the cost of overhead line construction.

Apart from the cost of actual construction, the cost of obtaining wayleaves and consents is in many cases much higher than it might be, owing to what may appear to be ill-conceived opposition on the part of certain persons and bodies. Such opposition is not infrequently met with and presented, irrespective of the merits or demerits of the particular case, and may savour somewhat of an attitude of obstruction. While rural electricity development is, owing to the enterprise of supply undertakings, making steady progress in certain parts of the country, the rate of progress is undoubtedly retarded by opposition of the nature referred to. This is a fact which the general public must be made to realize. Difficulties such as these will only be overcome in the course of time when the public generally become more enlightened as to the advantage to be derived from the development of rural industry and the improvement of rural conditions.

In this connection the Rural Community Councils which have been formed in certain parts of the country are doing good and valuable work. My experience is that these Councils are most willing to co-operate with the electricity supply undertaking, realizing, as they do, the advantage to be afforded by a rural electricity service and, at the same time, appreciating the fact that such service can only be given on reasonable terms if expenditure is kept within due bounds. Let us hope that these Rural Community Councils will continue to take a broad view on all matters in which they are interesting themselves, and more especially in regard to the necessary and proper use of overhead electrical distribution as being the only means whereby rural areas can be catered for.

No matter how anxious and willing a supply undertaking may be to carry out the electrical development of areas of the rural type, it must be clear to everyone that such work can only be put in hand if there is a reasonable prospect of the various schemes paying their way within a reasonable period of time. On the other hand, an undertaking which plays for safety all the time will make but little progress.

There are areas or parts of areas which admittedly cannot be catered for except at a loss. Such areas cannot be developed in the early stages. There are also areas where a sufficient income is readily obtainable without appreciable effort. Mid-way between these is the type of area which can be made to pay its way but only by the exercise of energy, forethought and determination, combined with the application of sound engineering and commercial principles. It is with such areas that several undertakers are doing their utmost to deal at the present time.

In doing so it has to be kept continually in mind that the margin between success and failure is somewhat narrow. If business does not accrue a loss is sustained. Enthusiasm alone is insufficient to combat such a position.

In order that business may come in reasonable volume and in such a way as to ensure commercial stability, it is essential not only that the selling price of the commodity should be right but that the charges made should truly and properly reflect the value of the service rendered. The fixing of the correct tariffs to be applied therefore becomes a matter requiring more than casual and haphazard determination. While this statement is really general in its application it is much more vital in its effect in the case of rural areas than in, say, densely populated industrial areas.

The cost of an electricity supply service—I use the term in its broad sense—is made up of two essentially distinct factors, viz. standing charges and operating charges. Allusion has already been made to the standing charges incurred by way of service of capital. There are, of course, other charges coming within the same category, one of these—and by no means an unimportant one—being that levied by way of local rating on plant and transmission lines. This in its incidence is not always as equitable as one might wish. While it is essential that all these charges should be kept within proper limits, it is equally essential that they should be met. They must therefore be reflected in some form in the electricity supply tariff.

The other factor, namely, the charges incurred in generating and distributing, referred to as operating charges, is perhaps more easily dealt with as bearing a closer relationship to the output when measured in units.

The vexed question of electricity supply tariffs has been the subject of a good deal of controversy for a very long time. It is a matter on which it is difficult to arrive at general agreement, although the underlying principles of a correct tariff are more or less generally accepted. Whatever views may be held, it must be conceded that the incidence and extent of the demand are material factors in the all-in cost of providing any particular supply of electricity. It is fully realized by all having knowledge of these matters that while, so far as its energy value is concerned, any one unit of electricity is equal to any other unit, the relative cost may differ very materially even when the supply is taken from the same plant and delivered in the same locality. This difference has to be taken care of in the tariff. An ideal tariff would be one which would automatically apportion in a proper manner the various costs incurred in furnishing the supply. This is somewhat difficult to attain and can only be arrived at by more or less close approximation.

Long-hour high-load-factor business should be encouraged, and, although purely short-hour lighting business has to be catered for, the price applying to such supply must be such as to carry a proper proportion of the standing charges. It is sometimes argued that a general improvement of the load factor on any particular system should result in a general downward adjustment of the price for all classes of supply. Such argument is fallacious and, if given effect to, would provide undue encouragement to the further development of low-load-factor business and result eventually in again lowering the average load factor on the whole system.

To provide and maintain what is the desideratum of all progressive electricity supply undertakings, namely, a high average load-factor on the system, the high-load-factor consumer must be given the full benefit of the advantages accruing from his particular conditions. These should not be passed on to the casual and intermittent user. The latter must be encouraged by other means to see the error of his ways.

A good deal has been said and written from time to time as to low tariffs for night load. Night load is all to the good so far as it improves, and is likely to continue to improve, the load factor on a system. One useful source of such a load is the electrical heating of water for storage and use during the day. The encouragement of such a service is worth while and no doubt apparatus will be forthcoming from the manufacturer in due course and at an economic price which will admit of its being fairly generally used. Meanwhile it has been suggested that such a supply could be given at practically the bare cost of fuel. The question is, however, "Can it continue to prove a stable condition?" There are a few undertakings having a daily load factor of the order of 50 to 65 per cent, even in winter months when the load due to lighting is at its maximum. It may be claimed that this is due to peculiarly fortunate circumstances. On the other hand it may be claimed equally that it is due to tariffs designed to encourage the more extensive use of electricity. Whatever the reason, it is clear that in such cases a night-load tariff based on the bare cost of coal might quite easily result in such an increase in the night load that additional plant would be necessary to cope with it. How are the additional charges to be met? Obviously by an upward revision of the night-load tariff. Any such revision would immediately call forth a justifiable complaint from consumers affected and would be accompanied by more or less permanent dissatisfaction. This is probably an extreme case and is simply put forward to emphasize the necessity of taking a long view in designing and fixing tariffs. It is essential that the ultimate effect on the cost of providing the service should be visualized and kept clearly in view when designing and fixing a tariff to meet any particular type of demand.

In the same way the question of the development of the general domestic load has to be considered in conjunction with its probable future effect on costs. It has been estimated that if the market for domestic coal in this country ceased to exist, the price of industrial coal would have to be advanced by at least 2s. per ton. This figure is given for what it may be worth and is only put forward to emphasize the advisability of taking the longer view and avoiding the possibility of creating future dissatisfaction amongst consumers who may otherwise feel that their business has been obtained under a misunderstanding.

There is no doubt whatever that, given proper, sound and fair tariffs, electricity can be sold for any purpose to which it can be applied, at prices which give satisfaction to the consumer and which, at the same time, provide a proper margin to the supply undertaker. In dealing with areas of the rural type, however, and in order to build up within a reasonable time the volume of business required to meet expenditure so involved, it is necessary to pursue a determined sales policy. One of the first essentials to a sales organization is a proper interpretation of the meaning of salesmanship.

Anyone can sell in large quantities almost any article at a giving-away price. That is not salesmanship. A brilliant salesman may for a time dispose of an article at very much enhanced prices. This does not make for permanence and cannot but result sooner or later in dissatisfaction and suspicion. The real salesman is one who has knowledge of the article for disposal, confidence in it, personal conviction as to the price being fair to buyer and seller alike, and the personality necessary to convey a similar conviction to those with whom he is dealing. It is the latter type of salesman that is required by the electricity supply industry. Even so, if he is to be a success in helping to develop the rural districts he must have still further qualifications. In the first place he has to set himself out to understand the point of view of the rural inhabitants. Those of us who have perhaps lived in towns and cities all our lives are apt to look upon the rural dweller as being somewhat simple and unsophisticated, and we may be apt to approach him accordingly. Experience teaches us, however, that we cannot get very far by doing so. We very soon learn that in general he is a very shrewd and careful individual. He is much more conservative than the town dweller. He is consequently more difficult to convince that anything which is different from that to which he has been accustomed may in fact offer him advantage by its adoption. This is perhaps another reason, and one which is sometimes not appreciated, why rural development does not proceed at a greater pace.

In order to hasten the pace of rural electrification it has been suggested in some quarters that a system of more or less intensive advertising should be developed. Advertisement by way of printed matter alone is of little use in rural areas. The organizing of lectures and talks, such as those provided by the Electrical Development Association, is, however, serving a useful purpose and is a matter in connection with which closer co-operation might be encouraged between that Association, the Rural Community Councils and the supply undertakings. No matter how hard all or any of these methods may be pressed, however, we cannot get away from the fact that personal contact and the desire to render the best possible service will provide the greatest and the most successful development. The best advertisement is, after all, the satisfied consumer.

No matter how earnest and sincere the supply undertaking may be in the desire to render public service, it is not sufficient to adopt a self-satisfied air and to stand quietly by pending the requisition of such services. The public in general are still woefully ignorant of the many uses to which electricity can be put and of the advantages, among which may be included the additional ease and comfort, which will accrue to them by such use. The education of the public is a matter which has to be taken in hand if progress is to be made. This may be accomplished in several ways, and perhaps the most general is by means of electricity showrooms.

The establishment of a number of showrooms by any one undertaker in each of several small towns or villages becomes a somewhat costly matter. There have to be met not only the cost of maintenance and attendance but also the cost of carrying substantially larger quantities of dead stocks. The question of showrooms is one in regard to which closer co-operation between supply undertakers and electrical contractors might with advantage be encouraged. In the case of rural areas the general provision of showrooms is ruled out by commercial considerations. It may be possible to acquire temporary premises for an occasional demonstration, but a more efficient and effective method is to provide a travelling showroom in the form of a suitably designed motor vehicle. Such a vehicle can be supplied with apparatus from one central showroom and can be sent out periodically with that type of apparatus especially suitable to the particular season of the year.

One of the difficulties which operate against the more rapid development of domestic load is the cost of appliances. This is a matter in connection with which the supply undertakers are entitled to look to the manufacturers to remedy. It is true that an attempt is being made to overcome this difficulty by the adoption of hire and hire-purchase methods. In so far as these methods result in increasing the demand for a specific article without encouraging the manufacturer to reduce the price where possible, they may be said to be wrong and to that extent they are bound to fail in achieving the desired end. It is pleasing to note, however, that certain manufacturers are themselves now willing to accept full financial responsibility for the hire-purchase of certain types of electrical appliances.

The electrification of rural areas not only provides advantages to the rural dweller, but should go a long way to assist in curing some of the ills resulting from modern industrial development. Such development has resulted in drawing industry and people from the countryside into crowded cities, giving rise to conditions which have produced the impression, in some minds at any rate, that what is good for business is not good for the people as a whole. While such an argument may be classed in the order of superficial philosophy it is still one which holds ground in certain quarters. By making possible the decentralization of industry without in any way impairing its efficiency—to put it no higher—electricity is providing a service the value of which it is impossible to calculate. If this may be claimed to be the true position it is extremely unfortunate that difficulties such as those to which I have referred as savouring of obstruction still continue to be placed in the way of more rapid electrical development.

These difficulties must, and will, be overcome, but courage, determination and enthusiasm are required. Let us see to it, however, that as engineers we do not let our enthusiasm outrun our discretion. Our industry must follow the natural line of economic progress, and if this is done the outcome cannot be in doubt. Not only efficiency in production but the efficient use of investment are the duties of any undertaking, whether public or private, and if any other course is taken the reckoning is bound to come sooner or later. Let us ever keep these facts in view so that our job may be carried out in such a way as to realize the only true and proper aim, namely, the provision of mutual benefit to the public whom we serve and to our own industry as one worthy of the public's hire.

DUNDEE SUB-CENTRE: CHAIRMAN'S ADDRESS

By R. J. LAWSON, Member.

"USE AND ABUSE OF MAN-POWER."

(ABSTRACT *of Address delivered at* DUNDEE, 10*th October*, 1929.)

We, as electrical engineers, belong to a profession of great importance to the well-being of our fellow-men, a profession which calls for a very high standard of efficiency from its members, irrespective of grade. We are responsible for the development of the application of electrical science, which has a considerable bearing on the degree of prosperity of our nation. For, as Herbert Spencer says, the manufacturer "who uses a bad machine cannot compete with another whose machine wastes less in friction and inertia. . . . The ability of a nation to hold its own against other nations depends on the skilled activity of its units. . . ." Because of this need of efficiency our Institution is indispensable to members of our profession. It provides an avenue through which the development of electrical science is made known to all interested. The quality of the papers published in the *Journal* is of the highest order and our monthly meetings help to keep us from getting into grooves—as Matthew Arnold says, "each day's petty dust obscures our vision."

I should like to suggest, therefore, that we look upon these meetings as a training ground for self-expression in public. As engineers we deal with public bodies, all classes of men—business and professional—and it is a valuable asset to the technical officer to be able to express his ideas in a clear, reasoned and cultured manner. I would urge that it is to the personal advantage of all members of the electrical profession to take a keen working interest in the affairs of the Institution.

I shall now proceed to discuss the subject of my address, viz. "The use and abuse of man-power"—a subject which I feel is boundless.

The present age will probably be known in the future as the "speed age." In the air, on the earth and on the sea, in trade and commerce the daily cry is "Increase your speed," "Increase your output per unit." To-day the manufacturer is burdened with heavy taxes. He has difficulty in competing with foreign countries because his prices for goods are higher than those of his competitors.

We realize that we must earn our daily bread. Nevertheless, there is a suspicion that those in authority forget that, to be of real value, all advances in the wealth of a country must tend towards a higher civilization and a higher type of manhood. They seem to forget, too, that the building-up of our manhood should come before the building-up of a petty bank balance. It is a commonplace to say that the wealth of a nation depends on its manhood. Perhaps I may, without being misunderstood, state that the wealth of a nation *is* its manhood.

Nevertheless we are faced with high costs in production. To reduce these many suggestions have been made, amongst which are the following:—(*a*) Reduce the wages of the manual worker; (*b*) Keep a young staff; and (*c*) Reduce all costs by from 10 per cent and upwards. I would describe (*a*), (*b*) and (*c*) in the words of Prof. Clay in his address on "The public regulation of wages in Great Britain," as "instances of the operation of the habit described by Dr. Cannan as 'proposing remedies for economic pressure without considering the question whether that pressure may not be an integral part of the existing organization which cannot be removed without causing disaster unless some efficient substitute is provided.'"

Early in the present year one of our prominent business men, in a lecture dealing with the outlook of commerce, advocated the use of up-to-date machinery, education on commercial lines, and careful organization.

One of our English newspapers stated that the recent trade trouble in Lancashire was due to "the rapid development of machine manufacture in the East and the Far East," and gave it as its opinion that British mills should be equipped with the best and latest machinery and directed by alert and progressive minds.

Quoting again from Prof. Clay's address, he says: "Lord Passfield and Mrs. Sidney Webb in their classic study of the effects of collective bargaining had laid chief stress upon its influence in increasing the efficiency of labour." The point that I wish to lead up to is that if we as a manufacturing nation are to keep our place in the world's markets we must have trained, efficient workmen interested in their work.

From observation, from inquiry and from experience I suggest that the interests of many of our workers have been diverted from legitimate to other channels. Workmen are not interested in their work, the reason probably being that they have not been taught the best way to handle tools. They do not appreciate the beauty of craftmanship and the dignity of workmanship, and their work is drudgery to them.

Newton said: "I have been able to accomplish what I did because I stood on the shoulders of giants." Again: "Men of the largest original power make the most use of the results obtained by other men." In music, art, literature, law, politics, sport, etc., we do follow Newton.

Bacon says: "Habit, if wisely and skilfully formed, becomes truly a second nature . . . but unskilfully and unmethodically directed it will be, as it were, the ape of Nature, which imitates nothing to the life, but only clumsily and awkwardly."

Two workmen, "A," fairly old, and "B," a younger man, were employed in the same workshop, on the same class of work and at the same piece-work rate. "A" had been trained under a master-craftsman, but "B" had not been so fortunate. "B" was a spectacular worker and visitors to the works invariably stood and admired the speed at which he worked, while they ignored "A," but "A" always earned the larger weekly wage. He required fewer strokes "to drive the nails home." Each knock counted, and consequently his output of work was greater. "B" went through many unnecessary movements which were wasteful in time and physical energy.

The point I wish to make is that if a man is to give his maximum output of accurate work as a normal and natural day's output he must in his youth have training in the art and practice of workmanship under a first-class workman, as a natural high speed of workmanship with accuracy is fundamental to low cost of construction. Let me put the matter in another way. Each man in his apprenticeship and early manhood develops what might be called his natural speed of movement. If, however, pressure be applied to obtain an increased working speed I suggest that the law of a "permanent set" would apply and something would give way. Further, I suggest that a man's working speed is determined by his early training and early environment.

I am certain that the need for the careful training of the youth in the art of workmanship is fully appreciated by our universities and our technical colleges and schools, and much is being done by these bodies towards this training. There is evidence, however, that in spite of the work of our colleges the practical training of the man whose life work is manual is not meeting to-day's requirements. It must not be forgotten that to-day we are in competition with foreign workmen who are in earnest. In the interests of self-preservation every man ought, therefore, to be fully trained in his particular calling to enable him to contribute his full complement of effective work of a high standard. To me the question naturally arises "Are we making full use of our man-power, which is of a very high order when cared for?" In other words, are our manual-work apprentices being fairly treated by their employers? Inquiries which I have made in many quarters have elicited the information that apprentices are being used as errand-boys, sweepers, etc., and that they are rarely taught the art of workmanship by a master-craftsman during working hours. This defect is, as I have said, being met to a degree by the evening technical classes.

The serious responsibility towards youth is thus emphasized by Herbert Spencer: "Is it then that the unfolding of a human being in body and mind is so comparatively simple a process that anyone may superintend and regulate it with no preparation whatever?" The conditions of business life to-day call for a very serious review of the steps taken to train or to develop the youth in the art of workmanship. The methods of certain firms in the training of apprentices tend to destroy the interest, the zeal for work and the enthusiasm of the average youth.

Before dealing with a constructive policy of training let us consider the broad question of education. Referring to this subject Herbert Spencer reminds us that amongst primitive people adornment comes before dress, and says: "It is curious that the like relations hold with the mind. . . . Knowledge which conduces to personal well-being has been postponed to that which brings applause. So a boy's drilling in Latin and Greek is insisted on not because of their intrinsic value but that he may not be disgraced by being found ignorant of them. . . . Definitions, rules and principles being put first instead of being disclosed as they are in the order of nature through the study of cases. . . . What with the perceptions naturally dulled by early thwarting and a coerced attention to books; what with making the pupil a mere passive recipient of others' ideas and not in the least leading him to be an active inquirer or self-instructor, and what with taxing the faculties to excess—there are very few minds that become as efficient as they might be. Examinations being once passed, books are laid aside; the greater part of what has been acquired, being unorganized, soon drops out of recollection—what remains is mostly inert. The art of applying knowledge not having been cultivated, there is but little power either of accurate observation or independent thinking. . . . While the rule-taught youth is at sea when beyond his rules, the youth instructed in principles solves a new case as readily as an old one. . . . In education we are finding that success is to be achieved only by making our measures subservient to the spontaneous unfolding which all minds go through in their progress to maturity."

"With few exceptions men are employed on the production, preparation and distribution of commodities. The efficiency of the employee depends on an adequate acquaintance with their physical, chemical and vital properties—otherwise science—which, according to Matthew Arnold, is confined to the domain of knowledge. . . . This order of knowledge . . . is the order of knowledge underlying the right performances of those processes by which civilized life is made possible."

We press for knowledge without considering that the question is not whether such or such knowledge is worth while but what is its relative value to a working electrician. One must be prepared to be ignorant of many things to be master of one's calling.

So far as the education of the young is concerned, I have said sufficient to indicate that our ideas and methods of education require careful review, and a number of societies are aware of the weakness of education and are working towards an improvement. To quote William Jones: "The great end of all education is to make our nervous system our ally instead of our enemy. For this we must make automatic and habitual as early as possible as many useful actions as we can, and as carefully guard against the growing into ways that are likely to be disadvantageous."

Lord Riddell tells of a man who can be relied upon to state accurately what a letter, memorandum or Act of Parliament contains, but who invariably gives an inaccurate account of a conversation. He is perceptive through the eye, not through the ear. I therefore suggest that a few men learn through books, but the majority are educated through their hands, and it is with the education of those who handle tools that I am concerned. I am concerned because it is largely on the manual worker that our well-being depends.

Let us pursue this a stage further. If the handiwork of a manual worker is equal to the design of the brain-worker we have a complete article exactly as the design. In other words, to produce there must be the labour of the designer and the manual worker. The knowledge of the latter must be such that he can interpret the work of another's brain. Now if the knowledge of the brain as indicated by a written paper can be assessed by the certificate issued, why should the same knowledge as indicated by hand-work not be assessed and a certificate issued accordingly? Let us examine this as to its bearing on the attitude of men to their work. The award of a certificate tends towards self-respect, and to work for it develops manly characteristics. Therefore, since to-day's needs demand thorough training, I suggest that before an apprentice joins a firm he should be required to attend a school of instruction in practical scientific work for a period of six months or more. The school should be attached to works of standing or to technical colleges situated in convenient centres. The teachers selected should be outstanding manual workers noted for their method, zeal, accuracy and punctuality, and inspired with the real spirit of craftsmanship and a thorough working knowledge of their jobs. The main point which the teachers should strive for is the development of the youth into a naturally quick, accurate and intelligent worker. A few of the fundamentals are:—The handling of tools in a naturally easy manner, i.e. the elimination of all unnecessary movements; training in the care of tools and material; method and order in the laying and the carrying out of works; thinking in advance to avoid an interval between stages of the same work; the habit of starting work punctually; the habit of thinking of time in terms of money or cost. The youth should realize that loss of time represents increased cost. The loss of 10 minutes per day represents a loss to the firm of one week's wages per man per annum, which adds to the manufacturing price of the article and tends to keep down wages. The youth requires to be told of this so that he may learn early to be diligent. The honour, the dignity and the importance of manual labour well done should be emphasized. The youth should be taught that the well-being of humanity depends on the efficiency of labour, that the manual worker who goes about his duties as an interested, intelligent man with a full working knowledge of his calling is indispensable.

As I have already stated, a workman, to be efficient, must have an adequate acquaintance with the physical properties of the material on which he is engaged. Further, the working electrician, to be master of his craft, must possess a working knowledge of the laws of electricity. As the period of apprenticeship is necessarily short, we can only consider knowledge of relative worth to a working electrician. Then there is the difficulty of imparting such knowledge. For the youth, when starting his class work, has not sufficient experience of the practical side of his trade to enable him to assimilate the theoretical part of the subject, and consequently interest in class work is often destroyed. Therefore, to maintain and to increase the youth's interest in his trade education I would combine practice with theory.

If the various points of interest in his work were explained to a youth by a capable, patient teacher while the youth was handling the material, the knowledge so gained by the apprentice would remain with him and be a real help. This would be education of everyday value.

How valuable it would be to the electrical industry if before an apprentice joined his firm he had acquired the correct method of handling tools and material. He would know how a job should be laid out, and he would understand the working laws of electrical science. What he now requires is experience or a chance to put into practice what he has learnt from masters of his trade, and that without hindrance.

At the close of the period of training the youth would be examined by an independent examiner in workmanship, with special reference to method. No written examination would be required. At the end of each year the employer would report to the training centre as to the boy's progress and experience, and the apprentice would present himself at the training school for an annual test in workmanship. After a recognized period of practical experience he would be eligible to undergo his final test. A youth attaining a certain standard of efficiency as a workman would be awarded a diploma certifying that the owner was a fully qualified working electrician.

The serving of an apprenticeship is not a guarantee that a man is an efficient tradesman. The importance and complexity of electrical works demand efficiency, which can only be attained by careful selection and a thorough training. Lord Passfield and Mrs. Sidney Webb lay stress upon the influence of collective bargaining in increasing the efficiency of labour. That may be so, but to me it seems that efficiency can only come through training, experience, interest and knowledge, and should precede bargaining. There is neither progress nor development amongst men whose pace is kept to that of the inferior and the slowest worker. Another fallacy, expounded by certain types of business man, is that college men are not so useful in business as the youth who goes to business direct from school.

The conclusion at which I have arrived is that fully trained workmen who are interested in their business are essential to-day, and that we are not delivering the goods. To offer a remedy is not easy, for one of the factors is tradition, and another is that it is no one's business to tackle an unpalatable trade question which is calling for review. The question, however, is, so far as Scotland is concerned, so important that it must be tackled, and the sooner the better.

Let us see, from our standpoint, what might be done.

A man's standard of knowledge to-day is measured by his ability to pass a written test of his knowledge of a subject or subjects. To the successful student a certificate is issued which indicates the student's degree of knowledge. There are difficulties in the way of introducing any scheme which interferes with tradition. What has been good for the father should be good enough for the son. Of course it has not been sufficiently good for the father, and conditions have changed. Further, if there were no difficulties to be overcome the engineering profession would die. I suggest, therefore, that if members in positions of influence in London and other large Centres combined with influential employers of high standing and the City and Guilds Engineering College, a practical scheme of training could be evolved, the fruits of which would be felt through the industry within the next few years. The improvement in the standard of men and work and the increased output per man would more than repay the expense of the training classes. Further, I suggest that as such training would lead to a recognized diploma it would create an interest in his job, and give pleasure to the worker.

There is still another factor to be discussed, namely those in authority. One writer says: "Insincerity, shiftiness and bluster have too often won the ear of the foolish and clouded the discerning eye." Again, "The perpetuity of organized life depends on the rise of superior men into positions of authority." The point which I wish to make is the fundamental need in the interests of output for the pull to be in one direction, namely towards good business and plenty of it. The responsibility for this rests mostly on those in authority. The working efficiency of an engine is regulated by the interest taken in the engine by the driver, who sees that all the bearings are free of friction. In a word, the engine is well cared for. So with man; he rises to his maximum efficiency under correct treatment. As John Graham says: "Every man is a special case and needs a special pill," and "You cannot work individuals by general rules."

G. K. Chesterton says: "There is a great man who makes every man feel small. But the real great man is the man who makes every man feel great." It is agreed that hard words are sometimes necessary, but before using them one should be sure of all the facts of the case. A word of well-deserved appreciation should never be omitted; it is a wonderful lubricant and a fine thing for increasing interest and loyalty towards the firm.

It is said that a competent chief can move among his men without having to draw an imaginary line between them, because they will see the real one if it exists. I refer to this because there are gems to be picked up which are often missed by false notions of one's dignity. Let me illustrate my point. Some years ago a promising young man was attached to a local firm. He was a capable and loyal employee; he was pulling his full weight in the interests of the firm which, as a direct result, was forging ahead. Those in authority continually grumbled at this energetic servant until the latter had to resign. To-day that man is at the head of one of the most widespread engineering firms in Britain. To carry this thought further I should like to remark that human nature is, in the interests of self-preservation, most adaptable. A young man of spirit and ambition who knows his business will not allow the development of his manhood to be interfered with by another man. He will seize his opportunity to strike out for himself. Initiative is a sensitive attribute and is easily destroyed; when wisely developed it is invaluable in all grades of men. Yet it often happens that those in authority, instead of wisely developing and guiding this important characteristic in youth, tend to curb it. Consequently there is the danger of such men never developing to their full degree of efficiency; they are as pawns in the game before they reach middle life. What happens to the many eager apprentices? Perhaps their wings have been clipped and in self-preservation they have adapted themselves to the whims of control until they have no power to think and to act wisely in a crisis—they must await instructions. An efficient head of a business should understand human nature; weld the team into one whole; develop the intelligence of the men so that the spirit of the instruction as well as its letter is understood and followed; and engender amongst the staff the spirit of interest, co-operation and loyalty.

John Graham tells of a young man who, on the death of his father, found his possessions to be a strong, clean, healthy body and a well-trained, educated mind. The only job available for him was one of manual labour, which he undertook. He applied his educated mind to his work and in time detected weaknesses in the organization. He accordingly suggested other methods which proved a saving in man-power and costs. The firm had, in its own interests, to adopt the newer ways, and incidentally the young man was promoted. This continued until he was appointed to the board of control.

Everything else being equal, the man with the best knowledge of industry and a fully developed brain is the man for the highest posts. I come back to the question of early training and its application. The man who can apply to business his university education has the advantage throughout life. On the other hand, the lack of the application of education in industry impoverishes industry. To be of value the fruits of education should enrich business, industry and leisure. Training and hard work tend towards success in industry. Work is a noble game with a trained team who respect the laws of the game. The playing ground has many hazards to maintain the interest of the players, and the results of the game depend on the degree of co-operation given by the players of all grades.

SHEFFIELD SUB-CENTRE: CHAIRMAN'S ADDRESS

By H. W. WALKER, Associate Member.

"LEAVES FROM AN ENGINEER'S NOTEBOOK."

(*Address delivered at* SHEFFIELD, 16*th October*, 1929.)

I selected this subject in the belief that a chairman's address should deal with matters of general interest to members rather than with some specialized subject of a highly technical character.

Nearly 20 years ago, whilst serving as junior engineer on the staff of a large power supply company, I wrote an article in which, after drawing attention to the many supply systems and power companies then in being, I remarked, with the optimism of youth, that ultimately it would only be necessary to link up the various concerns and Dr. Ferranti's "all-electric scheme" would become almost an accomplished fact. The linking-up process has now been commenced in earnest, and in many districts the lines have already been erected under the national scheme. Standardization of supply voltage and frequency will follow. A tremendous saving in conversion costs could have been effected had the matter been dealt with some 20 years ago. It has been suggested that the War period delayed the adoption of interlinking, but in my opinion this period advanced, rather than retarded, this development.

Many of us have wondered why railway electrification has not been developed in conjunction with the "grid." Possibly financial reasons were the chief obstacle, but the "grid" has undoubtedly been designed to facilitate railway electrification; and, with a commission of inquiry appointed to examine the matter, it would appear that the omission may shortly be rectified.

The next 20 years should show much more rapid progress in the demand for electricity for specific purposes. Any improvement in trade will soon be reflected in an increased demand for electric power in our great industrial centres, and in the event of a boom the national interconnecting lines, acting as equalizers, will enable the supply and demand to be dealt with more efficiently.

Rural industries and agriculture will be greatly facilitated by the extension of supply areas. Very large increases in domestic load will be experienced when the price per unit encourages cooking and heating by electricity in every household, as at the present time not more than 20 per cent of the houses are wired. Heat storage during the night is also a promising development and provides a means of considerably improving the load-factor curves.

With electricity "on tap" in the rural districts a great demand for lighting and power should be experienced, provided publicity is given to the matter. If villages in the Alps, at an altitude of 3 000 ft., can have their streets and houses electrically lighted, surely villages in this country which are richer and more prosperous should enjoy similar luxuries.

During a conference of lighting experts held in this city last year examples of street lighting by means of improved electric fittings were demonstrated and proved a great advance on the old style of gas lamp, so familiar to our grandparents and still in common use to-day. In spite of this the boulevard approach to one of our new universities has a splendid array of modern lamp pillars each fitted with a gas lamp, with the hanging-chain method of individual lighting and extinguishing. May we regard this as indicating a step forward, or backward? Few of our large cities so far appear to adopt electricity exclusively for street lighting, but almost all of them do so for illuminating their main streets and busiest thoroughfares. Electricity cannot always compete economically in places where gas companies have long been established and have all their mains laid, but in new streets, country towns and villages where a supply is available it undoubtedly can do so.

CHANGES IN PLANT.

It is to be regretted that the electric steel-furnace has dropped so much into disuse, many of the furnaces standing idle and some being dismantled altogether. Is this entirely due to the state of trade?

We are all aware that an electric-furnace load is not a really attractive one to the supply authorities, but these furnaces found favour and were a great national asset during the War. It seems a pity that those already in existence cannot be made use of, especially in view of the fact that foreign steel used in Sheffield could easily be made here, although foreign basic material might be necessary for producing the high quality of steel in demand. If the cost of current is prohibitive, why not encourage a night load by a substantial reduction in price during certain hours?

The high-frequency furnace appears so far to give great satisfaction to those concerned in its operation. With a reduction in cost, its use should be greatly extended, but an improvement in the design of the condenser units is needed in order to achieve complete success. A particularly irritating fault experienced with this type of furnace is that the container, being made of refractory material, is liable to fracture during a heat, thus releasing the molten metal. In such cases not only is the wooden casing burnt, but the tubular copper-coil element may be irreparably damaged. An improvement in the construction of the refractory containers, etc., is urgently needed.

I recently noted, with some surprise, a newly-installed rolling-mill driven by a crude-oil engine situated in the centre of an electric supply area. In my opinion such a plant cannot possibly compete as regards overall life, efficiency and reliability with an electrically driven mill, and I mention the matter to indicate that electrical engineers must still be alert to such competition.

So far as the electrical manufacturing industry is concerned, one may remark that it defies competition. The percentage of foreign electrical plant purchased in this country to-day is negligible, the chief reason being that our electrical manufacturers have risen to the occasion and cheapened their productions to a greater extent than any other engineering product on the market.

This applies perhaps especially to small and medium-sized motors and their accessories, which are procurable at extremely moderate prices and really represent remarkable value. The opinion is sometimes expressed that prices to-day are rather too keen and the rating too exacting. For the large saving in material effected by improved design and ventilation, and the smooth and silent operation which is so noticeable, our designers deserve great credit.

FAILURES OF PLANT.

No other power plant will run in such hole-and-corner positions, or under such neglected conditions, as electric motors frequently have to do, and yet complaints are made when breakdowns do occur.

Records of electrical plant in use in every class of industry, and under very varied conditions, show an average breakdown figure of approximately 7 per cent per annum. The term "breakdown" is applied to failures that necessitate dismantling and repair of the plant, as distinct from the renewal of bearings and similar work which is more correctly regarded as maintenance.

The following analysis of the causes of breakdown may be of interest, although it applies only to generators, motors and starting-gear. The figures are based on experience during the year 1928, and cover several thousands of machines of various ages.*

Analysis of Causes of Breakdown of Plant.

Cause	Generators	Motors	Starting gear
	per cent	per cent	per cent
(1) Accidental	15	20	19·8
(2) Dust, oil and neglect..	37	39	33·4
(3) Age and deterioration	20	22	18·4
(4) Faulty work and design	5	4·6	6·4
(5) Overloading	11	7·2	11·6
(6) Unascertained ..	12	7·2	10·4

It will be appreciated that these figures can only be approximations, because in many cases the effect of the breakdown is to destroy evidence of the cause. However, to deal with the figures generously we may conclude that lines (1) and (6) comprise quite unavoidable *bona fide* breakdowns, and in round figures constitute about 28 per cent of the *total*. The three causes specified in lines (2), (4) and (5) are normally avoidable and account for about 52 per cent of the breakdowns. Whilst "age and deterioration" is responsible for 20 per cent, it must be remembered that this figure is increased by "oil, dust and neglect" and "overloading."

It should be noted that the above figures relate to plant which is subject to a regular inspection service, each item of plant being regularly examined and carefully watched to detect any irregularity in operation. If this is the experience with plant subject to an inspection service, it may be assumed that the figure of 52 per cent will be very seriously increased in cases where no such regular service exists.

If the detailed costs of these breakdowns, including not only actual repair expenses but also the cost of works stoppage and inconvenience, were fully appreciated, many large users of electrical plant would adopt a system of regular inspection. A complete register of all items of the plant should be kept, and records of tests, rotor clearances, etc., and the general condition of each item, should be entered after each examination. Such a system would result in the prevention of many costly stoppages, and in the event of failure the records prior to its occurrence would be available to assist in avoiding a repetition.

In some instances where this procedure has been adopted the old adage that "familiarity breeds contempt" is often demonstrated by the negligence of the maintenance staff. It is mainly for this reason that many important firms employ specially trained outside engineers to make periodical inspection of their power plant. Such inspections are defined by Government departments in the case of boilers, pressure vessels, lifts and cranes, and also in the case of coal mines. If this procedure were enforced in connection with electrical plant generally, the advantages would be very great indeed and would lead to more efficient and safer working. Official interference, as this may be termed, is, of course, very objectionable to many of us; but it is probable that some such regulations will be issued in the near future.

It is not my intention to create an impression that electric motors are peculiarly liable to breakdown, but rather to suggest the causes of some avoidable failures, and if possible to reduce the percentage of breakdowns.

DIRECT-CURRENT MACHINES.

Direct-current motors are fast disappearing from public supply systems and are being replaced by a.c. machines; many private firms also are discontinuing their use, but large numbers are still in service.

The most vulnerable part of a d.c. machine is the armature, and, in a large proportion of the breakdowns, failure of the windings is attributable to commutator defects. Oil and dust deposits at the ends or on the surface of a commutator are the most frequent causes of short-circuted bars through carbonization of the mica, earthing of the V-rings, etc., but the leakage paths at the ends of a commutator are often quite inadequate. In other cases the mica inter-segments are much too thin for continued satisfactory operation.

Paste-filled commutators have proved quite unsatisfactory and should never be constructed. As regards those already in existence, the only remedy when trouble is experienced is to reconstruct them completely and to fit sections of good Canadian amber mica.

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* My acknowledgments are due to Mr. E. G. Hiller, chief engineer to the National Boiler and General Insurance Co., Ltd., for permission to publish these figures.

Clamping and locking rings and bolts should all be of steel, and the means of securing these, whether by bolts or threaded ring, should be at the front end, the whole commutator being mounted on a separate sleeve securely keyed to the shaft. Incidentally, the bursting of a large commutator some 3 ft. 6 in. in diameter was due to the use of cast-iron V-rings, the metal having crystallized.

With modern former-wound coils, impregnated and well insulated, very few pure winding faults are experienced, provided adequate space has been allowed in the slots and end windings. Yet, even where the greatest care has been exercised in forming and insulating the coils, one frequently finds that the insulation of the coil-supporting rings is quite inadequate. Quite recently the armatures of three 200-kW rotary convertors, less than 2 years old, had to be reconstructed for this simple reason.

Impregnation of armatures under vacuum is recognized as good practice when good-quality varnish is used, but when poor-quality varnish mixed with a proportion of shellac is substituted windings have literally to be dug out, rendering the replacement of separate coils an impossibility.

Steel-wire binders wound on mica insulation, the core being slotted to receive them, form the best means of securing the coils in the slots. If the binders are run on the core face they are apt to slip or become displaced in handling. Should phosphor-bronze wire be necessary, great care should be taken to see that the wire is ductile and is not made brittle when being drawn. Two recent serious failures of d.c. turbo-generators have been traced to the bursting of phosphor-bronze wire binders. Of course, phosphor-bronze wire is only used in cases where the induced currents in steel-wire binders would cause serious overheating, an example being the case of a multi-layer binder of a high-speed generator.

Fibre or wooden wedges often cause trouble owing to shrinkage, and this method is therefore open to criticism.

Armature cores should always be built on spiders, except in very small machines. When the cores are mounted direct on the shafts it is difficult to key them effectively, and they tend to become loose in operation, especially in the case of gear-driven plant.

Regarding shafts, reductions need filleting as much as possible, and every manufacturer should appreciate that the journal should be larger in diameter than the extended portion carrying the pulley, whether bushes or ball bearings are to be fitted.

When field coils are wound with cotton-covered wire on spools and the end turns are reinforced, very little trouble is experienced, especially if the whole coil has been impregnated; but if enamelled wire is used, and the coils are liable to dampness or overheating, defects quickly follow owing to the enamel cracking and scaling off.

Frequently the burning out of a field system or the puncture of a field coil is traceable to a startor. Very definite and reliable contacts are required on a d.c. motor startor in order to complete the field circuit and to ensure absence of variation or rupture of the field current. Costly repairs in rewinding field coils have been caused by an intermittent contact on a startor, aggravated by local vibration.

A different type of brush gear is used on almost every different make of machine, and it is satisfactory to note that attempts are being made to standardize brush gear. A substantial box-type holder having an adjustable spring, with a heavy pigtail connection between the carbon and holder, is to be preferred. It is insufficiently appreciated that the selection of the correct grade of carbon brush is essential for satisfactory commutation.

For instance, an uncommon failure of a large generator, costing £200 to repair, was recently traced to the use of an unsuitable grade of brush. Sparking had been experienced, and in order to remedy this a harder grade of carbon brush was fitted and in addition the mica sections were slotted. Sparking ceased, but after a few days it was found impossible to maintain the correct voltage, although the shunt resistance was cut out and the engine speed increased. Investigation showed that the field coils and armature were burnt out, due solely to the hard brushes causing copper drag in patches around the commutator and short-circuiting the bars.

Alternating-Current Machines.

As our future interests are mainly concerned with a.c. machines, a few points regarding them must be considered.

The necessity for fine clearance between rotor and stator is the chief cause of failures in a.c. motors, and probably 50 per cent of these failures are due to fouling between the rotor and stator. This class of breakdown usually necessitates very expensive repairs, and some simple protective device which would effectively prevent fouling would be of inestimable value to users of a.c. motors.

Light auxiliary windings, or splitting of the stator phase windings, can be so arranged as to balance when the clearance is equal all round the air-gap and to trip the circuit breaker when a certain difference in clearance has been reached. Such protection, however, must be applied during construction and adds considerably to the cost of the machine.

It was anticipated that the introduction of ball and roller bearings would eliminate this class of failure, but, since the clearances have also been very much reduced, the desired results have not been obtained in practice. Contrary to the expectations of some users of electrical plant, ball and roller bearings do wear out. Creeping of the inner races and wear of the shafts or bearing housings are often the result of unsuitable drives and account for much of the trouble experienced with this type of bearing. For large machines the white-metal lined sleeve bearing is usually preferred.

Fouling between rotor and stator cores is a most serious matter in large motors and can only be avoided by keeping a careful watch on the working clearance. Mere checking of the clearance by means of a feeler gauge with the machine stationary is often misleading. An additional check is to open-circuit the rotor by lifting the brushes and then close and open the stator switch. The clearances in these circumstances will approximate more closely to those which obtain under working conditions than will those observed with the stator unenergized. The magnetic pull on the rotor is, of course, only in proportion to the current circulating in the stator circuit, so that, if only a slight movement of the rotor is observed, immediate attention to the clearance is often necessary. By applying this test it is possible not only to discover whether the bearings are worn or loose in the housings, but any looseness of the rotor or stator core can often be detected.

With well-designed former-insulated coils, the stator and rotor windings of large low-speed machines have proved very reliable. They are characterized by ample spacing between coils and leads, and it is quite practicable to replace separate coils without disturbing the whole winding. There are, of course, exceptions.

These good features are not frequently found in medium-sized machines, and seldom in small ones. Many makers use " mush " windings as the standard for small machines and, judged solely from a manufacturing point of view, these are cheap, uniform and quite satisfactory. Unfortunately, owing to the compactness of the windings, complete rewinding of the stator or rotor is usually necessary in the event of any winding defect, however slight. In very few cases is it possible to thread in a new coil with the correct number of turns, and in order that this may be done the windings must be well spaced and clean.

With concentric grouped coils and a 2-layer winding, in the event of short-circuiting or earthing of a coil, even should this be in the back layer, replacement of about 3 pole-groups may be quickly and cheaply effected. Should breakdown occur, the chain-type winding referred to is therefore a desirable feature from the point of view of the plant owner and repairer.

There is still much controversy as to the best method of construction of the squirrel-cage rotor. End connections are found soldered, brazed, welded, and cast on, and rotors constructed with any one of these methods are to be found working satisfactorily. On the other hand, all the methods used cause far too much trouble for present-day practice to be regarded as final, and the ideal means of securing rotor end-connections has yet to be found.

The construction employing soldered end-rings has largely fallen into disuse, but has the merit of limiting damage, frequently to mere disconnection of the soldered rotor end-rings, in the event of an open phase in the stator circuit or fouling between rotor and stator. With the other three methods of construction, burning out of the stator winding often results under these conditions, and the cost of repair is very greatly increased.

At a recent discussion* on squirrel-cage induction motors, tables were published comparing breakdowns of slip-ring motors with those of squirrel-cage machines. The following figures were given:

Slip-ring motors.
Stator breakdowns: 27·8 per cent.
Rotor breakdowns; 35·4 per cent.

Squirrel-cage motors.
Stator breakdowns: 68·3 per cent.
Rotor breakdowns: 14·7 per cent.

With the squirrel-cage type of motor, rotor failures are 20·7 per cent less, but stator failures are 40·5 per cent higher, than with the slip-ring type. It is quite possible that the indestructible-type rotor accounts for the higher percentage of stator breakdowns in the case of squirrel-cage motors, suggesting that the rotor with soldered end-connections has some advantages over other types, at any rate until an indestructible stator is produced.

The following exceptional failure is an example of what may be expected if rate-cutting and reduction in clearances are continued. A 110-h.p. 720-r.p.m. motor was started up on a cold morning and, as occasionally happens, the oil rings refused to function. The machine stopped, and when the attendant attempted to start up again serious internal arcing occurred, causing fusion of the windings. On attempting to dismantle the motor for repairs, it was found that the rotor was jammed in the stator tunnel, and all efforts to remove it failed completely although a 40-ton hydraulic jack was pressed into service. The only alternative to scrapping the machine was to force the stator core out of the frame, remove the stator windings, and dismantle the stator core a few plates at a time. This was eventually done, and it was found that fouling had occurred between rotor and stator to such a degree that the teeth of the rotor and stator had become welded together around the whole rotor circumference, for a width of about 2 inches between the first and second rows of ventilating ducts. The original clearance of this motor was barely 15 mils and, as it was constructed with pedestal-type bearings, alinement to give equal rotor clearance all round was a very delicate operation. Fortunately this is an unusual case, but it serves to illustrate the disastrous effects which extreme competition may have upon design.

Standard industrial motors of the semi-enclosed type, with large fans at one or both ends, are in some cases unsatisfactory. The amount of enclosure is insufficient to keep out harmful dust, but tends to retain it, and also makes the machine awkward to clean and examine.

Totally enclosed or pipe-ventilated motors, designed to comply with the appropriate British Standard Specification, are the only machines which can be regarded as suitable for working in dusty situations or under conditions where attention will be infrequently given. Such machines should preferably be provided with bearings of the roller type and with covered holes to permit checking of the air-gaps. Removable covers should also be fitted over the slip-rings.

ACCESSORIES.

Many of these are quite unsuitable for use in connection with power plant.

Frequently one comes across an extremely robust iron case only to find, on opening the cover, badly-spaced fittings, flimsy contacts and impracticable terminals. The current-carrying capacity of a great deal of such apparatus, especially fuse fittings, is very much overrated. Overheating of contacts and arcing on to the iron cases causes many serious defects and stoppages.

OIL-IMMERSED APPARATUS.

With oil-immersed gear the condition of the oil is of primary importance. It should be tested at reasonable intervals, and if moisture is found to be present, or if sludging has taken place, it should be cleaned by passing through a centrifuge.

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* *Journal I.E.E.*, 1928, vol. 66, p. 438.

Moisture in the oil, due to varying temperature and atmospheric conditions, is probably responsible for more transformer breakdowns than any other cause. This is not altogether surprising when it is realized that a moisture content of 0·01 per cent may reduce the electric strength to one-tenth that of dry oil. If sludge is allowed to remain in the tank it tends to clog the circulating ducts, lowers the flash-point of the oil, reduces heat radiation, and in time becomes caked as hard as charcoal on the bottom of the tank and coil surfaces.

In the event of excessive vibratory humming the transformer should be lifted and the clamping devices tightened and locked, otherwise the movement will cause rubbing and chafing of the coils, leading to subsequent failure. Many transformer failures are due to such abuses as overloading or neglected inspection, but troubles due to pressure surges sometimes occur.

Years ago transformers were installed in any out-of-the-way place, and, whilst it may be admitted that many of these, mostly of the air-cooled type, gave little or no trouble, it should be remembered that this was before the days of e.h.t. transmission and before very large capacities were required. Recently I came across a case of an oil-immersed transformer, long neglected, which had completely burned out. The oil had become so heavily sludged that deposits had to be shovelled out of the tank.

In recent years oil-immersed static condensers have come to the fore, and whilst many failures are due to pressure surges, the condition of the oil is responsible for others. Failure is so much more frequent than one would anticipate with this type of plant, that special attention and research is called for. Most breakdowns have the appearance of being due to pressure surges resulting in burning and charring of some of the units. The consequent carbonization of the oil has a widespread effect on the remaining elements, and this can be determined by measurement of the power factor. In almost all cases of failure so far experienced it has been found necessary to renew the whole of the elements. The actual conditions which prevail prior to breakdown are still somewhat obscure. It seems probable that some ionization of the air entrapped between the layers of dielectric may occur and thus originate the trouble.

Recent improvements in the materials and construction of condenser elements may have a marked influence on the life of this type of plant.

Leading engineering insurance companies have realized the importance of the oil question in connection with electrical apparatus, and have equipped special testing laboratories for this reason. Samples of oil are taken by the companies' surveyors at regular intervals and despatched for testing, and the results amply justify the expense and trouble entailed. It is found that about 7·6 per cent of oil samples fail to comply with the requirements of the British Standard Specification, which stipulates that the oil shall withstand a pressure of 30 kV when tested between two spherical electrodes 0·157 in. apart. In addition, some 8·0 per cent of the examples examined contain a considerable amount of sludge. It must be understood these figures relate to oil samples taken in the ordinary routine way from apparatus which is actually in service, and not to samples of new oil.

In connection with the selection of electrical plant, a great number of consumers and purchasers of plant are non-technical men who do not realize the importance of high efficiency. There is consequently a tendency for them to purchase largely on the basis of first cost. It is a simple matter to take into account the factors of first cost and efficiency, and every case should be considered on its merits. With the prevailing prices for electrical plant and electrical power, it would in most cases pay to install plant of higher efficiency than that usually employed. Such efficiency should be secured by using lower current and magnetic densities, and not by reducing air gaps to dangerous values. In addition to the direct saving resulting from decreased losses, such machines would have a higher overload capacity, be more reliable and, by reason of working at a lower temperature, would have a longer life. Engineers should therefore use their influence to educate purchasers along these lines.

HAMPSHIRE SUB-CENTRE: CHAIRMAN'S ADDRESS

By B. HANDLEY, Member.

(*Address delivered at* PORTSMOUTH, *17th October*, 1929.)

As this is the first meeting of the Hampshire Sub-Centre, I have thought that, in my Address as the first Chairman of the youngest outlying branch of the Institution, it might not be amiss to address my remarks chiefly to the younger members and Students of this Sub-Centre upon their outlook in entering upon their profession. Not only will the progress of the Institution in the future depend upon the Students of to-day, but these same Students must in time become the directing forces in the electrical world.

Those who are now taking up the profession of electrical engineering are entering a profession which is daily becoming of more and more importance in the life of the community. Therefore the necessity of right understanding on the part of those young men who will ultimately control the electrical world cannot be over-emphasized.

The first thing which must be realized is that we are engaged in a profession in which change and new ideas are constantly occurring.

The use of electricity in the service of mankind has grown up in very recent times and now plays a most important part in the civilized life of the community. This very recent growth is but an offshoot of the use of any kind of power, which again is a development only slightly older.

To visualize how very recent this mechanical age is, we must remember that railways are only about a century old, which means that very many people to-day have spoken to men who saw the first railways laid down. These railways were extended with great rapidity throughout the country, and traffic was so diverted to them that the roads became of minor importance. In the last quarter of a century we have seen the development of the internal-combustion engine almost completely mechanize road traffic, so that now the number of men engaged in road traffic exceeds the number engaged in rail traffic.

Again, mechanical haulage on tramways is a very recent development, but in this case the indications are that tramways have passed their zenith and that their place will to some extent be taken by the omnibus driven by an internal-combustion engine.

The telegraph and telephone, and, recently, wireless broadcasting, are other examples of progress and change.

All these changes are very rapid and, to a great extent, correlated. An improvement in one industry leads to improvement in others. As an example of how interrelated all these advances and changes are, we might consider the development of aviation. Flying as we know it to-day would be hardly possible had not the invention of the pneumatic tyre—in the first case for bicycles—made travelling at high speeds in motor cars possible. The motor car led to the development of the internal-combustion engine, which afterwards made flying possible.

As another example, we have to-day in all countries power supplies distributed from central points over large areas. Let us try to realize how difficult this distribution over large areas would be without the motor car, and especially without the telephone. Taking a local example, in this area we have from this city a distribution reaching nearly to the River Hamble in the west, to Bognor in the east, and to Petersfield and Midhurst on the northern side. The electrical energy generated in this city passes over mains belonging to different local authorities and companies, before reaching its point of use by the consumer. Imagine what would happen if we were without our present facilities, and an interruption occurred at some distant point. All the local engineer would know would be that the supply had ceased. I should imagine that his next step would be to mount a bicycle or horse, or to take a train if possible, to try to meet the engineer in the contiguous area to see if his supply were all right. Think of the time that would be lost before the trouble was located. Now, thanks to the telephone and motor car, connection is established quickly between the various engineers, their reports are received and motor transport enables the trouble to be tackled at the earliest possible moment.

I merely mention these points as an indication to the young engineer how recent and how interrelated are all these mechanical and electrical services as we see them to-day. They are not only very recent but also in a continual state of change—not revolutionary changes, but quiet evolutionary changes, small in themselves, yet having remarkable effects in the aggregate.

In electrical engineering, as compared with engineering in general, we have perhaps an even more rapid change. The first transmission of power by electricity took place not many years ago. The first generating stations were started on extremely small lines, and were developed, in the light of our present-day knowledge, very slowly, until our accumulated knowledge and experience were such as to lead to improvements which developed the use of electrical energy in such strides as could not have been dreamed of many years ago. To-day the majority of our generating stations either have been built since the War, or at any rate use only machinery installed since the War.

Even our theories have in like manner gone through the same process of rapid evolution in such a way as to bear little resemblance to those of not very long ago. These theories, having served their purpose for the time, are superseded to make room for others.

I would therefore impress upon the young men to remember all the time that their knowledge, their theories, and their machinery must be in a state not only of change but of rapid change. When they see a power station built on the most modern lines, they must not imagine for one moment that there is any finality about it. What is the last word to-day will not be the last word next year. Let them keep their minds open all the time for fresh ideas. I remember once being in the company of a man when some of his old generating plant was being broken up. He remarked how sad it was to see the end of his old friends. It would have been wiser, perhaps, to have expressed pleasure at having something better to take its place.

This change which I am trying to impress upon you is evident not only in the activities which I have mentioned, but everywhere. Therefore you must keep your minds open to assimilate new ideas.

Looking for a moment towards the future, we can visualize the possibility of a time when there will be a far more convenient method of obtaining mechanical and electrical energy than by the combustion of coal; and, just as to-day we can transmit very small amounts of energy by wireless transmission, so can we visualize the future transmission of energy sufficient to meet our requirements in home, factory or traction, without the use of cables or wires. For the benefit of those who are leading the campaign against overhead lines on the South Downs, I may add that I am afraid such wireless transmission of power will not happen in their lifetime.

Having impressed upon you the importance of keeping your minds fresh and of not ignoring avenues of progress other than your own, I want now to come to another point to which attention must be given.

In your work you will have to deal with problems which your knowledge will enable you to solve with accuracy, and you will have to deal with machinery or apparatus which can be relied upon to give the results desired; this brings me to that part of your work in which reliability and accuracy must be attained by other methods. I refer to what is for many the most important part of the engineer's work, namely his ability, not so much to do the work himself, as to get it done by others working under his orders. This ability to get work done does not wholly depend upon his knowledge or experience of how the work should be carried out. We often see, in fact, that the man who has been the cleverest pupil or student does not attain any great success in the profession which he takes up. This may be to some extent accounted for by the fact that the clever student gets into the habit of working out problems with great accuracy and logical deduction, and that those same principles cannot operate with accuracy in dealing with mankind.

We must therefore try to get as plain an understanding of how man carries out his work as we try to get an understanding of how a piece of machinery works. First of all, let us remember that a man—either a manual worker or a brain worker—does not act according to formulæ or a chemical equation. We must also try to realize his component parts, just as we study the component parts of any machinery in order to understand how the whole works. Any failure to realize the functions of the different parts will cause failure in the complete understanding of the whole.

In engineering one becomes accustomed to analyse the functions of machinery in this way, and we must, if we wish to deal with mankind without failure, bring something of the same analysis to bear.

An important point to remember is that although all members of the human race conform to some general plan, there are countless varieties. When we study a mass-produced motor-car, for example, we know all the rest of that make; but when we attempt a similar comparison of mankind we are met by failure. Each of us has a standard by which there is always a tendency to judge others, and that standard is different for each of us. This unconscious tendency leads, unfortunately, to many mistakes and misunderstandings. Misunderstandings lead to irritation and strife, with consequent waste of energy, and to inefficiency, which every engineer must guard against, not only in his machinery but in the control of labour.

In trying to analyse man, we must remember that he is the product of countless ages of evolution. There must be in him many inborn, inherited instincts and all kinds of traits impressed upon him through the past ages. During the most recent part of his evolution there has grown up a civilization, learning and organized thought, so that to-day man has available the accumulated knowledge of the past, together with methods of organizing his thoughts for the acquirement of fresh knowledge. He has gradually learnt to think things out for himself, to put his proofs to the test, and to use his brain for considering what he needs and then inventing a method of supplying those needs. But all the time, and however efficient may be the brain power of any individual, we must remember the fundamental fact that the brain power is being operated by a child of countless ages with, to some extent at least, the impressed traits of those past ages, some of which crop out in one individual and some in another, but seldom exactly the same ones in different individuals.

You all know of otherwise intelligent people refusing to do things on Fridays, or to sit down 13 in number to a meal. Argue as you will, you will not dismiss that belief from the minds of those holding it. There is nothing extraordinary in this; it is merely the inherited instincts of the past, perhaps in this case the dread of the unknown, coming to the fore against the forces of their reasoning power.

I have even heard of a woman taking a violent dislike to another woman because she is wearing a hat of which the former does not approve. Again, illogical and absurd as it may seem to anyone trying to reason it out, there is nothing extraordinary about it. I can well imagine one of her forebears in the distant past coming across one of another tribe whose appearance offended him. As I believe that it was the custom in those days to walk about with a heavy club in one's hand, the result of the encounter can well be imagined.

Therefore I do impress upon you young engineers that you must not for a moment imagine that a man is a calculating or thinking machine. Any treatment based on that assumption is disastrous.

You must look upon human beings, including yourselves, as having all the foibles and inconsistencies which are our inheritance and the inevitable consequence of our evolution from the animal world.

You will never be able to get work done efficiently and cheerfully if you have any misconception on this point or if you fail to give consideration to the ideas and thoughts of those with whom you have to work. However absurd you may think the whims and ideas of others, yours may be considered by them to be equally absurd.

You must make allowances for all the seemingly inexplicable inconsistencies and uncalled-for irritation which man at times shows, remembering all the time that there is a reason for it, just as there is a reason for everything that happens, and if you can only ascertain the reason you are well on the way to remove the irritation.

You have to accept the state of things as they are, however inconvenient they may be for efficient working.

The final point which I wish to bring forward is that all engineering processes must have a commercial aspect. It is possible to do quite a number of engineering jobs which cannot be justified commercially, but if they cannot be justified in this way it is better not to do them. If a bridge has to be built it should be justified by the traffic that it will carry. If new machinery is to replace old machinery, the saving in the cost of running the new machinery must more than counterbalance the cost of installing it. Some things such as drainage systems, for instance, are justified by the results accruing to the community, results to which it is difficult to assign a money value, and in any case a broad view has to be taken in considering these problems. For instance, it is difficult at times to persuade a factory owner to electrify his plant if he considers only the cost of the power and will not take account of the fact that electricity will result in a bigger output per employee, which is often more valuable to him than the total cost of the power.

In conclusion I should like to say that the young electrical engineer of to-day is entering a profession which seems likely in a short time to be essential at almost every hour of the day to the inhabitants of large cities. You can look forward to the time when the mechanization and, I might add, the electrification of our activities in the home, office and factory, will be increased to a still greater degree, with a lightening of the housewife's burden and a greater output per man and greater earning power in the factory, with less exertion and more opportunity for recreation. You young men will also be able to look forward to our towns becoming cleaner and healthier by your activities, and possibly to the time when the burning of raw untreated coal will be a criminal offence.

There is still, in spite of all that has recently been accomplished, much work to do, and in rendering your services to the community I trust that the community will properly discharge the debt it will owe to you.

PROCEEDINGS OF THE INSTITUTION.

790TH ORDINARY MEETING, 24TH OCTOBER, 1929.

Lieut.-Col. K. Edgcumbe, T.D., R.E.T. (Ret.), Past-President, first took the chair, at 6 p.m.

The minutes of the Annual General Meeting and of the Special General Meeting, both held on the 9th May, 1929, were taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was also taken as read and was ordered to be suspended in the Hall.

The Chairman announced that during the period April–September, 585 donations and subscriptions to the Benevolent Fund, amounting in the aggregate to £504, had been received.

The Premiums (see vol. 67, pages 808 and 1064) and Scholarships and Grants (see vol. 68, page 83) awarded during the past session were presented by the Chairman to those recipients who were present.

The Chairman then drew the attention of the meeting to the arrangements made by the Engineering Department of the Post Office for the simultaneous transmission of the proceedings to special local meetings of members at Birmingham, Cardiff, Glasgow, Leeds, Liverpool, Manchester, Newcastle-on-Tyne, Portsmouth and Southampton, where loud-speakers had been installed enabling speech from any one point to be reproduced at all the other points. A " roll-call " of these meetings was taken, Colonel Edgcumbe calling upon each Chairman in turn to announce whether the meeting was in session; and the responses, which were all received in the affirmative, were reproduced in the Lecture Theatre by means of loud-speakers.

The Chairman then sent greetings on behalf of those present in London to the members of the Local Centres and Sub-Centres at the towns indicated above.

Mr. W. B. Woodhouse: It is 12 months since we met to welcome a new President. To-day we are here on the same business, and we have to say good-bye to the President whom we greeted last year. He now retires into the obscurity which is supposed to surround past-presidents, but I am sure from his activity in the past that, like some other past-presidents whom I see here, he will continue to take an active part in the Institution which he loves. I am sure that you will not wish to let this occasion pass without expressing your appreciation of the manner in which Colonel Edgcumbe has performed his duties. In representing the Institution publicly, and in particular during the Summer Meeting, he worthily upheld the traditions of the Institution. His conduct of the meetings and of the public business of the Institution needs no word of praise from me. Those of us who are on the Council have seen much more of the work that falls upon the President's shoulders. In Council and in Committee he has continued the good work which he has been doing for many years. He was not, if I may say so, elected President merely because he was so charming and because of his fluency and his humour, but because we knew by experience that he was deeply interested in every activity of the Institution and that he was anxious to help to keep our great organization to the fore. I am sure that those who have served with him on the Council appreciate very much his great energy and his great ability. We are sorry to lose him as President, but we are very glad to know that we shall still have him as a past-president. I have pleasure in moving a formal resolution: " That the best thanks of the Institution be accorded to Lieut.-Col. Edgcumbe for the very able manner in which he has filled the office of President during the past year."

Captain J. M. Donaldson: It is a very great honour to be asked, as I have been, to second the resolution which has just been moved by Mr. Woodhouse. I am lucky in having to follow him, because he has said, much better than I myself could have done, what I feel very strongly. There is no doubt at all in my mind, and I am sure that there can be none in yours, that Colonel Edgcumbe has worthily carried on the traditions of the office, and that he has in every way enhanced the dignity of the position. He has certainly made a reputation second to none in his after-dinner speeches. I have very much pleasure in seconding the resolution.

The resolution was then put to the meeting and was carried with acclamation.

Lieut.-Col. K. Edgcumbe: It is very pleasant to be thanked for what one has done, even if one has not done it, but what with four energetic vice-presidents, a Council that overlooks all one's shortcomings, and a most efficient Secretary and staff, the President's job is a very simple one. I have to thank the members firstly for the trust which they reposed in me by electing me their President, and then for having backed me up so wholeheartedly as they have done. I feel particularly grateful to the Centres and Sub-Centres, and should like to take this opportunity (one which has not come to any past-president previously) of thanking them personally and simultaneously for their hospitality and for the many pleasant hours which I have spent with them. I would add that I think we members in London have much to learn from the Local Centres as to the way in which they conduct their affairs. I cannot refrain from drawing attention to the new decorations and improved lighting of the Lecture Theatre which I am sure you will agree is equal to, if not better than, that of any similar building in London. The colour scheme is, of course, the work of the Institution's architects, Messrs. Adams, Holden and Pearson, but we are also much indebted to Mr. C. C. Paterson and Mr. H. T. Young for the large amount of time, trouble, and skill which they have given to devising this very successful blending of decoration and illumination.

The chair was then vacated by Colonel Edgcumbe and taken by **Colonel Sir T. F. Purves, O.B.E.,** President, amid applause.

The President then delivered his Inaugural Address (see page 1), at the conclusion of which Colonel Edgcumbe called in turn on Mr. J. Harcourt Williams to propose, from Manchester, and Prof. Magnus Maclean to second, from Glasgow, a vote of thanks to the President for his Address.

Mr. J. Harcourt Williams in proposing the vote of thanks, said: " On such a unique occasion as this when the President's Inaugural Address has been broadcast to the Local Centres and Sub-Centres, one is deeply sensible of the privilege that now falls to the Local Centres for the first time, of proposing and seconding a vote of thanks to him for his Address. May this not be the beginning of a new era, when we shall have papers read in London with members at the Local Centres taking part in the discussion? As one who has had to deal chiefly with the heavy side of engineering, I can only express admiration for the President's very clear and interesting review of progress in electrical communications since 1922—progress that has been very real and great. I am impressed by that part of his Address which deals with education, and by his sound remarks on the training of engineers. His plea is that they should be trained in such a way that they will know how to use their brains when, having left college, they find in actual practice the necessity of specializing. The use of automatic telephone apparatus in the Post Office has its counterpart in automatic gear in other branches of electrical engineering, with the same object of reducing the cost of labour and the consequent cost to the user. Again, the President's reference to the remarks of Mr. Frank Gill before this Institution in 1922, on long-distance telephony, makes us very conscious and proud of the influence exerted by our Institution all over the world. We can infer from what our President has said, that it must now have a great influence in maintaining the peace of the world, a very understandable and desirable effect. It also has, naturally, great commercial possibilities, and I know of one case where a firm, with interests on both sides of the Atlantic, holds conferences by telephone between their respective organizations collected round a table at each end of the line. I now have formally to move: 'That the best thanks of the Institution be accorded to Colonel Sir Thomas Purves for his interesting and instructive Presidential Address, and that with his permission the Address be printed in the *Journal* of the Institution.' "

Prof. Magnus Maclean, in seconding the vote of thanks, said: " I have great pleasure in seconding the motion so happily and appropriately proposed by Mr. Harcourt Williams at Manchester. The Address was heard here in Glasgow quite distinctly and the members present highly appreciate the choice of subject and the masterly way in which the President has treated it. The novelty of this meeting recalls to my mind that of another occasion, in the year (1902) when our President joined the Institution. It was our first Annual Dinner in the Windsor Hotel, Glasgow, and I had the honour of presiding. The novelty, I remember, evoked considerable curiosity and speculation at the time. Attached to the lighting brackets and hidden by greenery were arranged a number of loud-speakers connected to a transmitter in a room of the telephone exchange, nearly half a mile away. In that room was stationed a band which rendered solos and accompaniments in connection with the loyal toasts—the music of which was heard in the dining hall of the hotel with a clearness and distinctness which was thought extraordinarily remarkable and even eerie at that time, 27 years ago. Four years earlier when Marconi established stations to communicate between the Isle of Wight and Bournemouth, Lord Kelvin made his way to the Needles station and, sending a message by way of test, insisted on paying for it as evidence of his faith in the ultimate success of wireless communication as a commercial enterprise. He was thus the first person in the world to send a paid 'marconigram' and, as the message was for me, I was the first to receive one. We have travelled far since then, as the address and our programme this evening show. The author of Ecclesiastes has said: 'God hath made man upright; but they have sought out many inventions.' Man is at his old tricks—his feats of ingenuity, worse or, shall I say, more determined than ever to-day. But we no longer condemn. On the contrary, we cannot honour enough the men who, like our President, 'put girdles round the earth' in a way that even Shakespeare himself never envisaged. Puck, on the wings of imagination, could encircle the world in 40 minutes. It can now be done, as we all know, in the fraction of a second. I second the resolution with the cordial approval of all members of the Scottish Centre. 'Oidche mhath leibh, beannachd leibh.' "

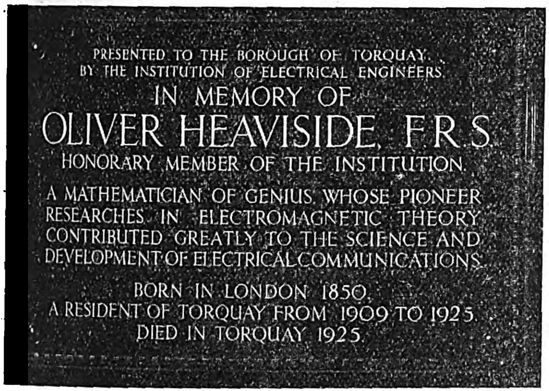
The resolution was then put to the meeting by Colonel Edgcumbe, Past-President, and was carried with acclamation.

After the President had briefly replied, the meeting terminated at 7.25 p.m.

INSTITUTION NOTES.

Oliver Heaviside.

The Institution recently presented to the Borough of Torquay a bronze tablet for erection in the Town Hall in memory of the late Oliver Heaviside, F.R.S., who was an Honorary Member of the Institution and died at Torquay in 1925. A photograph of the tablet is reproduced below.



PRESENTED TO THE BOROUGH OF TORQUAY
BY THE INSTITUTION OF ELECTRICAL ENGINEERS
IN MEMORY OF
OLIVER HEAVISIDE, F.R.S.
HONORARY MEMBER OF THE INSTITUTION.
A MATHEMATICIAN OF GENIUS WHOSE PIONEER
RESEARCHES IN ELECTROMAGNETIC THEORY
CONTRIBUTED GREATLY TO THE SCIENCE AND
DEVELOPMENT OF ELECTRICAL COMMUNICATIONS.
BORN IN LONDON 1850.
A RESIDENT OF TORQUAY FROM 1909 TO 1925.
DIED IN TORQUAY 1925.

Alterations to Bye-Laws.

The amendments to the Bye-laws agreed upon at the Special General Meeting held on the 9th May last have been allowed by the Privy Council.

Kelvin Medal.

The fourth triennial award of the Kelvin Medal has been made by the Joint Award Committee to Monsieur André Blondel.

Scholarships.

The following Scholarships have been awarded for 1929–1930:—

Salomons Scholarships (*value* £50 *each*).

R. B. Smith (Leeds University).
F. W. L. Horner (Belfast Municipal Technical College).

David Hughes Scholarships (*value* £50).

P. F. Soper (East London College).

Paul Scholarship (*value* £100).

K. H. Gillanders (L.C.C. Brockley County School).

War Thanksgiving Education and Research Fund (No. 1).

Grants of £50 each have been made for 1929–1930 to the following for research purposes:—

J. A. Clegg (University College, London).
A. F. Wilkins (Cambridge University).

Page Prize.

The Page Prize (value £2 10s.) has been awarded for the session 1928–1929 to Mr. R. Woodland for a thesis entitled " The Cryptophone."

" Science Abstracts."

The Council have decided to supply *Science Abstracts* to Students, and to Graduates under the age of 28, at a nominal annual subscription of 5s. for either the Physics or the Electrical Engineering Section, or of 7s. 6d. for both Sections. Full particulars are being sent by the Secretary to these members.

Graduates.

Under the revised Bye-laws, Graduates under the age of 28 years are entitled to the same privileges as Students, i.e. attendance at all Institution Meetings (including those of the Students' Sections), visits to works and social functions included in the Students' programmes.

National Certificates and Diplomas in Electrical Engineering (England and Wales).

The undermentioned colleges have been approved under the scheme drawn up by the Board of Education and the Institution:—

Approved for Ordinary Grade Certificates (*Senior Part-time Course*).

Barrow-in-Furness Technical College.
Croydon Polytechnic.

Approved for Higher Grade Diplomas (*Advanced Full-time Course*).

Nottingham University College.

Discussions at Meetings.

The Council wish again to remind members that the remarks of speakers at the meetings should not be read from manuscript, the view being held that the presentation of remarks in this manner is contrary to the true spirit of a " discussion " and that contributions in manuscript should more appropriately be sent to the Secretary for publication in the *Journal* as " communicated remarks."

Benevolent Fund.

An appeal to members to support the Fund will be found on the last page of the cover of this issue of the *Journal*.

Committees, 1929-30.

Among the Committees appointed * by the Council for 1929–1930 are the following:—

INFORMAL MEETINGS COMMITTEE.

Mr. E. S. Ritter (*Chairman*).

Mr. J. R. Bedford.
Mr. W. E. Bradshaw.
Mr. R. Grierson.
Mr. W. Lang.
Mr. A. Morgan.
Mr. C. F. Mounsdon.
Mr. W. A. Ritchie.
Mr. W. E. Rogers.
Mr. M. Whitgift.

And

A representative of the General Purposes Committee.
The Chairman of the Papers Committee.
The Chairman of the London Students' Section.

JOINT COMMITTEE FOR NATIONAL CERTIFICATES AND DIPLOMAS IN ELECTRICAL ENGINEERING (ENGLAND).

Mr. W. E. Highfield Prof. E. W. Marchant, D.Sc. Mr. W. M. Selvey	representing the I.E.E.
Dr. F. T. Chapman Dr. A. Morley Dr. C. F. Smith	representing the Board of Education.

JOINT COMMITTEE FOR NATIONAL CERTIFICATES AND DIPLOMAS IN ELECTRICAL ENGINEERING (SCOTLAND).

Prof. G. W. O. Howe, D.Sc. Mr. S. Mavor Mr. Robert Robertson, B.Sc. Prof. S. Parker Smith, D.Sc.	representing the I.E.E.
Dr. J. S. W. Boyle Mr. J. G. Frewin Mr. W. Hyslop Mr. F. W. Michie	representing the Scottish Education Department.

LIBRARY AND MUSEUM COMMITTEE.

Col. R. E. Crompton, C.B.
Mr. D. N. Dunlop, O.B.E.
Capt. C. E. Kennedy-Purvis, R.N.
Mr. W. M. Mordey.
Mr. D. S. Munro.
Mr. R. S. Whipple.

LOCAL CENTRES COMMITTEE.

Mr. J. R. Beard, M.Sc.
Capt. J. M. Donaldson, M.C.
Mr. J. S. Highfield.
Mr. P. V. Hunter, C.B.E.
Mr. Archibald Page.
Mr. E. E. Sharp.
Lt.-Col. W. A. Vignoles, D.S.O.

And the Chairman of each Local Centre and Sub-Centre.

METER AND INSTRUMENT SECTION COMMITTEE.

Mr. E. W. Hill (*Chairman*).

Mr. W. E. C. Alliss.
Mr. E. Fawssett.
Mr. C. H. W. Gerhardi.
Mr. A. J. Gibbons.
Mr. J. T. Haynes.
Mr. F. C. Knowles.
Mr. C. W. Marshall, B.Sc.
Mr. A. Middleton.
Mr. E. H. Miller.
Mr. W. Phillips.
Mr. G. F. Shotter.
Mr. R. S. J. Spilsbury.

And

A representative of the Council.
The Chairman of the Papers Committee.

"SCIENCE ABSTRACTS" COMMITTEE.

Mr. T. G. N. Haldane, M.A.
Prof. E. W. Marchant, D.Sc.
Mr. W. M. Mordey.
Mr. C. C. Paterson, O.B.E.

Dr. A. Ferguson Dr. D. Owen	representing the Physical Society of London.

SHIP ELECTRICAL EQUIPMENT COMMITTEE.

Mr. A. G. S. Barnard.
Major B. Binyon, O.B.E., M.A.
Mr. J. H. Collie.
Mr. S. Harcombe, M.A., B.Sc.
Mr. A. Henderson.
Mr. P. V. Hunter, C.B.E.
Mr. J. W. Kempster.
Mr. J. F. Nielson.
Mr. N. W. Prangnell.
Col. A. P. Pyne, R.A. (T.A. Res.).
Mr. S. G. C. Russell.
Mr. T. A. Sedgwick.
Mr. H. D. Wight.
Mr. E. T. Williams, O.B.E.

And	*Representing*
Mr. A. E. Laslett, I.S.O. Mr. W. McAuslan	Board of Trade.
Mr. W. Cross	Electrical Contractors' Association.
Mr. J. Carnaghan Mr. H. Ruck Keene	Lloyd's Register of Shipping.
Mr. James Barr Mr. T. R. Thomas	British Corporation for the Survey and Registry of Shipping.
Mr. J. Lowson	Institution of Engineers and Shipbuilders in Scotland. Electrical Contractors' Association of Scotland.
Mr. A. W. Stewart	Institution of Naval Architects.
Mr. W. T. Wilson	N.E. Coast Institution of Engineers and Shipbuilders.

WIRELESS SECTION COMMITTEE.

Captain C. E. Kennedy-Purvis, R.N. (*Chairman*).

Mr. R. H. Barfield, M.Sc.
Mr. F. W. Davey.
Mr. A. J. Gill, B.Sc.
Mr. J. Hollingworth, D.Sc., M.A.
Lt.-Col. A. G. Lee, O.B.E., M.C., B.Sc.
Prof. E. Mallett, D.Sc.
Mr. E. B. Moullin, M.A.
Mr. G. H. Nash, C.B.E.
Mr. L. C. Pocock.
Mr. C. E. Rickard, O.B.E.
Commander J. A. Slee, C.B.E., R.N.
Mr. P. K. Turner.

A representative of the Council.
A representative of the General Purposes Committee.
The Chairman of the Papers Committee.

And the following representatives of Government Departments:

Admiralty: Capt. C. E. Kennedy-Purvis, R.N.
Post Office: Lt.-Col. A. S. Angwin, D.S.O., M.C.
Air Ministry: Mr. F. S. Barton, M.A., B.Sc.
War Office: Major J. S. Yule, O.B.E., R.C.S.

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* The President is, *ex officio*, a member of all Committees of the Institution.

Wiring Regulations Committee.

Mr. Ll. B. Atkinson.
Mr. W. J. Bache.
Mr. H. J. Cash.
Mr. J. R. Cowie.
Col. R. E. Crompton, C.B.
Mr. B. M. Drake.
Mr. P. Good.
Mr. R. Grierson.
Mr. J. F. W. Hooper.
Mr. H. Marryat.
Mr. S. W. Melsom.
Mr. F. W. Purse.
Col. A. P. Pyne, R.A. (T.A. Res.).
Mr. E. Ridley.
Commander J. A. Slec, C.B.E., R.N.

And	*Representing*
Mr. J. Howard-Blood	Fire Offices Committee.
Mr. E. B. Hunter ..	
Mr. W. B. Trafford ..	
Mr. E. G. Batt ..	British Electrical and Allied Manufacturers' Association.
Mr. H. H. Berry ..	
Mr. J. R. Dick, B.Sc.	
Mr. A. R. Everest ..	
Mr. F. Broadbent ..	
Mr. W. F. Bishop ..	Cable Makers' Association.
Mr. F. R. Baldock ..	Independent Cable Makers' Association.
Mr. W. R. Rawlings	Electrical Contractors' Association.
Mr. E. A. Reynolds	
Mr. R. A. Ure ..	Electrical Contractors' Association of Scotland.
Mr. C. G. Morley New	Incorporated Municipal Electrical Association.
Mr. R. W. L. Phillips	
Mr. W. Lang ..	Association of Supervising Electrical Engineers.

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vol. 6.	Alternating current sub-stations, by P. Kemp. Substations: testing, maintenance and operation, by A. T. Thurman, J. H. Patterson, and F. Orchard. Automatic sub-stations, by C. J. Sarjeant.
vol. 7.	Instruments—Instrument transformers, by H. C. Turner. Electricity meters, by H. H. Jaques. Meter department operating routine, by O. Howarth. Control room design (Apparatus), by C. C. Garrard.
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Revised Bye-laws and Membership Changes.

The following transfers * have been effected by the Council in accordance with the provisions of Bye-laws 15 and 18:—

From Graduate to Associate.

Abaza, Mohammed Shoukry H.
Acock, Charles Edward.
Acomb, Frank.
Addison, Joseph.
Adie, Brooke.
Aggarwala, Harish Chandra.
Ahaluwalia, Rakharam.
Aiyar, Aiyalam Kasturi R. K.
Aked, W. T.
Aldridge, Percy Spencer.
Alford, Frederick Albert H.
Ali, Mir Laig.
Allan, John Edward.
Allen, Edward.
Allen, James.
Allington, Ernest.
Allkins, Arthur Warrington.
Allsop, David.
Alston, Basil Evelyn.
Ambalavanar, Pasupathippillai.
Amies, George.
Anderson, David Bruce.
Anderson, Herbert.
Andrews, Harold Arthur.
Ansell, A. M.
Appleby, John Harry.
Armstrong, Stanley Ignatius.
Armstrong, William Henry.
Arnold, John Frank.
Arnold, Louis.
Arnott, John Thomson.
Arnott, J. W.
Arte, Dattatraya Bhaskar.
Arthur, Austin Bassett.
Aspin, John.
Astley, Harold.
Aston, Walter.
Athaide, Lewis Michael.
Atkins, Leslie John.
Atkinson, Joshua Percy.
Atkinson, Raymond.
Attwood, Albert Henry.
Aust, Octavius Leonard Genge.
Avis, William John.
Avison, Robert Geoffrey.
Ayres, Talbot Martin.
Ayyar, Paghayannar Venkiteswara S.
Aziz, Jan Mohamed A.
Badhni, Jehangirshaw N.
Baggaley, Cyril Frank.
Bailey, Albert Clifford.
Bailey, Alfred.
Bailey, Arthur Rowland.
Bailey, F.
Bailey, John Wallis.
Bailey, Walter Horace.
Baillies, Douglas C.
Baker, Charles Hale.
Baker, William Frederick.
Balasubramian, M. S.
Balchin, Wilfrid George.
Baldock, G. J.
Baldwin, Douglas.
Baldwin, Norman Victor.
Ball, Wilfred Charles D.
Bamji, Hormusji Fardoonji.
Bancroft, Herbert Douglas.
Banerjee, Aswini Kumar.
Banerji, Srish Kumar.
Banks, Albert.
Banks, T. H.
Barkwith, Joseph William B.
Barnacle, Alfred B.
Barnes, Wilfred Charles.
Barnett, Reginald Hugh.
Barrand, Percy Christian.
Barrar, Sydney John.
Barrell, Frank.
Barry, Gerald Noel F.
Bartels, D.
Bartho, Francis Trenam.
Barton, Leslie Osborne C.
Basil, Bishen Duo.
Bassett-Lowke, Harold Austin.
Batten, Ernest Richard.
Baverstock, Charles James.
Baxendell, Leslie Wilfred E.
Baxter, Frank Sladdin.
Baxter, William Morley.
Beaglehole, Keith.
Bealing, Ernest.
Beaton, Cecil Arthur.
Beaumont, Leonard.
Bechar, Shivji.
Beddall, Walter Samuel H.
Bedford, Howard Edwin.
Bedford, Reginald.
Bee, Oswald Kestor.

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* A list of transfers from Associate to Companion will be published in a later number of the *Journal*.

From Graduate to Associate—continued.

Beebee, Arthur Thomas S.
Beeston, Harold Chas.
Belchem, Robert Henry.
Bell, Cyril Gordon.
Bell, Edgar David R.
Bell, Herbert Harry.
Bell, Hubert Vaughan D.
Bell, Ian.
Bennett, Arthur Edgar.
Bennett, Henry Percy.
Bennett, Wilfred.
Berg, Clement Leonard.
Beringer, Paul.
Bernard, Sattambisallage Don.
Berry, Edgar.
Berry, Jack Milton H.
Berry, John.
Betley, John Ernest.
Betts, Arthur George.
Beynon, Benjamin Thomas
Bhargava, Govadhan Prasad.
Bhargava, Har Saran D.
Bhise, Vishwanath Ramchandra.
Bickerstaff, Ernest.
Bickerton, Harry.
Bill, Ronald Archie.
Billingsley, Frederick Thomas.
Billingsley, Reginald Harry.
Bintley, Bryan Noel.
Birch, Ewart Evelyn.
Birkby, Harold.
Black, E. J.
Black, Richard Henry.
Blackburn, Harry Arthur.
Blackler, Clarence William.
Blakeley, Wilfred John.
Blashill, T.
Bleasdale, John William.
Bloemsma, Jan.
Bloome, Jack.
Bloore, Thomas Addison.
Boak, C. F.
Boddington, Frank Stanfield.
Bogie, Andrew.
Boiston, Alfred.
Bolton, E. S.
Bolus, John Edward.
Bond, Fred.
Bonn, Arthur Stanley.
Bonny, Arthur Geo. A.
Booth, Clifford.
Boscolo, Gioachino Riccardo.
Bostock, Clement Wildsmith.
Bourn, Leslie Edwin A.
Bourne, George.
Bowden, Lionel Maurice.
Bower, Dudley Alec.
Boyce, John Samuel.
Boyd, William John.
Bradford, Wilfred Brittain.
Bradley, Robert Walter.
Braggins, Albert Edward.
Brammer, Cyril George.
Brander, J.
Brant, William.
Brazier, Cyril James H.
Brewer, Arthur.
Briant, Frederick Gordon.
Brickhill, George Alexander.
Brierly, Richard Francis H.
Briggs, Bernard George.
Briggs, Richard Alfred.
Bristow, Ralph Eric.
Brocklebank, John.
Brockway, Cyril Hotston.
Brooks, John.
Brooks, John Joseph.
Brough, Leonard George.
Brown, David Gregory.
Brown, Edward.
Brown, Edwin Lionel.
Brown, Eric James W.
Brown, Frank Leader.
Brown, George Victor.
Brown, Hugh, Junr.
Brown, Robert Hartley C.
Brown, William Herbert.
Brown-Stephens, Charles.
Bruce, George Lance.
Bruce, Herbert Baillie.
Bruce, James Malcolm.
Bruce, Robert Francis.
Bryan, Francis Charlton.
Bryant, Frank.
Bryant, Roger Havelock.
Buchanan, George Macdonald.
Buchanan, Joseph.
Buckell, Victor Charles H.
Buckland, Bert.
Buckley, Joseph Duckworth.
Budge, James Walker.
Bull, Arthur John.
Bull, Robert.
Bull, Walter John H.
Bulley, Henry Samuel.
Bulman, Christopher Howard.
Bulman, George Reay.
Bunt, Charles Lionel.
Burcham, Leonard Walter.
Burford, Gerald George.
Burgess, William.

From Graduate to Associate—continued.

Burn, Walter.
Burns, John.
Burnett, Robert Ernest S. F.
Burton, Edward Arthur.
Bushell, John David.
Butler, Archibald Stephen.
Butler, William Richard.
Butterfield, Edwin.
Cadman, Horace Bert.
Cadman, Norman.
Calder, John Maxwell.
Calver, Frank Norman.
Cameron, Alexander Robert.
Cameron, William Charles.
Campbell, Archibald Stewart.
Campbell, Duncan.
Campbell, James Philip.
Campbell, Percy Oliver.
Caplin, William John.
Capper, Frank Wilton.
Carey, Hewett Clive.
Carlisle, Ralph Sydney.
Carr, Conway Buxton.
Carter, Ernest.
Carter, Frank.
Carter, Frank Alexis.
Carter, Gordon Leonard.
Carter, William.
Cass, Vernon Sydney.
Catford, Edwin Osmond.
Catton, Horace William.
Causbey, Reginald John.
Cerexhe, F. G.
Chakravarti, Girindra Narayan.
Chakravarti, Nripendranath.
Chalmers, John Wm. P.
Chamen, William Francis.
Chandler, A. F. N.
Chaplin, Walter Richard.
Chapman, Alfred Herbert.
Chapman, Eric Douglas S.
Chapman, Robert Frederick.
Charlton, Charles Cedric.
Charlton, Edward.
Charman, Cyril Edward.
Chase-Currier, Victor Charles.
Chauhdri, Ghulam Kadir.
Chayachati, Svasti.
Chester, William Haward.
Chesterton, Arthur James.
Chopra, Hukm Chand.
Christie, John Mills.
Churchill, Charlie Hembrow.
Churchill, Percy.
Clare, Charles Frederick.
Clark, Ernest Cameron.
Clark, Geo.
Clark, John Thomas.
Clarke, Albert Edward.
Clarke, Albert Stanley.
Clarke, Edgar Valentine.
Clarke, William Henry.
Clarricoate, John.
Clayton, C. E.
Clayton, William Henry.
Cleary, Herbert.
Clements, Henry.
Clewett, William Henry.
Clifford, Leonard Percy.
Clifford-Jones, Edward Thomas.
Clissold, William Cornelius.
Cobb, Frederick Arthur.
Cochran, Robert Jack.
Cockburn, Roland Arthur.
Cockerill, Henry Walter.
Coffee, Randall.
Colaco, Julian Antony.
Coldwell, David Kidd.
Cole, Henry James C.
Collard, Herbert William.
Collett, J. W.
Collier, Harold.
Collins, Herbert.
Collins, Thomas Lewis.
Collom, Frederick William.
Collyer, James Kimberley.
Colquhoun, James Browne
Condé, Harold Graydon.
Constable, Leslie Stuart.
Conville, Alfred.
Conway, George Harold.
Cook, Ernest Henry.
Cook, E. T.
Cook, John.
Cooke, Maurice Wyndham.
Cooke, Ralph.
Cooney, Alexander Patrick.
Cooper, Arthur.
Cooper, Edward Cecil.
Cooper, George.
Cooper, George William.
Cooper, H.
Cooper, John Ashton J.
Cooper, Walter Dunbar.
Coote, Charles Douglas.
Corbett, Francis William J.
Corder, George Falconer.
Corkill, William Alfred.
Corner, Arthur Charles.
Corner, Herbert.
Cottier, John Percival.
Cound, Richard Aubrey.

From Graduate to Associate—continued.

Court, Arnold Frederick.
Coveney, Henry Percival R.
Cowan, Eric William L.
Cowen, Alan Biddulph.
Cowen, Arnold Benjamin.
Cox, Cecil Louis.
Cox, Percy Harold.
Craig, Daniel.
Craig, Herbert Sidney.
Craig, John Lawrie W.
Craig, Samuel.
Crane, Sydney Frederick.
Cree, John Cherry.
Creighton, William Alexander L.
Creswick, Philip.
Cripps, Cyril Burton.
Crosbie, Sydney.
Cross, Arthur Firman.
Cross, Edward Alfred G.
Cross, William Gordon.
Crow, Arthur.
Crowder, Samuel Goddard.
Crowsley, Benjamin.
Crowther, Arthur.
Crymble, Clarence Frederick.
Cull, Edward Charles.
Cullinan, Reginald.
Curd, David Alfred G.
Currey, John Heylyn.
Curtis, Herbert Francis.
Curzon, Percy John P.
Cuttler, Norman.
Dain, Frederick Charles.
Dalal, Shavakshah Nasservanji.
Dale, John Harry.
Dale, Tom Jesse.
Dallison, Philip Henry.
Dallow, Norman Richard.
Dalton, Alfred John.
Dalton, Louis Fitzgerald V.
Damp, John William.
Dandy, Ernest Charles.
Daniel, John Vivian.
Daniel, Robert Richard.
Daniel, William Ernest.
Daniels, Harold Bentley.
Darling, John William.
Darlington, Walter Edward.
Dass, Amendranath.
Davidson, Gavin Hamilton.
Davidson, George.
Davies, Bertram Jones.
Davies, Pendry George.
Davies, Thomas Edward.
Davies, Tracy R.
Davies, William Barron.
Davies, William Richard.
Davis, Edward Saul.
Davis, Geo. Hedley.
Davis, Harold Norman.
Davison, Charles Fredk.
Daw, Sydney Ernest H.
Dawson, William James.
Deacon, Edwin Arthur.
Dean, Reginald Percy.
Dean, Shaikh Mehr.
Deane, Edgar Wooding.
Debney, Charles Edward.
Delves, F. J.
De Moss, George Henry.
Denné, Frank Ernest.
Dennis, Nigel Henry.
Dennis, William Hugh.
Deodhar, Anand Vishnu.
Desborough, John William H.
de Souza, Vivian.
Deveney, Frederick Gordon.
Dhar, Ashok Kumar.
Diaz, Enrique.
Dick, Moncrieff Steven.
Dickinson, George Taunt.
Dickinson, John Clegg.
Dickinson, Richard Heath.
Dighe, Krishna S.
Dinsmore, Harry.
Dixon, Arthur.
Dixon, Ernest George.
Dixon, George.
Dixon, George Skene.
Dixon, Herbert Edward.
Dixon, Reginald Griffith.
Dixon, Stanley Henry.
Dobell, Claude Herbert.
Dobson, Cecil Michael.
Dobson, Harold.
Dodd, John Hedley.
Donaldson, Thomas.
Donnelly, Kieran.
Dootson, James.
Dowding, George Victor.
Downes, Frederick Alan.
Downie, Christopher Edmund.
Downing, Herbert Edward.
Dowse, William Robert.
Dowson, Christopher Henry.
Drake, Robert Hamlyn M.
D'Rane, Bernard John.
Draper, Charles Vivian.
Drew, Gwerfyl Emrys.
Drewry, John Percy A.
Driscoll, Leo Frederick.
Duce, Geo. Leonard A.
Dudley, Edward Charles.
Duffill, Arthur Laurence.
Duke, George Edward.

From Graduate to Associate—continued.

Duncan, Frank Victor W.
Duncan, Hugo James.
Dunn, Leonard William.
Dunn, Spencer William.
Dutton, John Haigh.
Eades, John Henry.
Earle, Beresford Langston.
Earle, Robert Erasmus.
East, Frank George.
Easter, Charles Edward.
Easter, Herbert Arthur.
Eastwood, Cecil.
Eccles, Harry Bridge.
Eclair-Heath, Stanley.
Edwards, Alec Felix.
Edwards, Norman.
Edwin, Hugh Stanley.
Eggins, Leonard George.
Elford, Arthur Horatio S.
Eliades, Jacques Elies.
Ellahie, M. Fazal.
Elliott, John Stuart.
Ellis, Francis Arthur.
Ellis, Leonard George.
Ellis, Percy.
Elphick, E. de Bock.
Elsom, Leonard Ernest.
Embrey, Thomas James.
Emmett, Herbert.
Emsley, Albert Edward.
Emsley, Frank.
Engelbrecht, Ernest Henry A.
England, Benjamin.
Eusor, Eric Lovell.
Entwistle, Joseph.
Espitalier, Theodore.
Etches, George Bernard.
Ethelston, Simon.
Etherington, Herbert Edmund.
Evans, Arthur Vicary.
Evans, David Beynon.
Evans, Edward Stanley.
Evans, Evan William.
Evans, Ewart Gwyn H.
Evans, Llewelyn.
Evans, Thomas Ernest.
Evans, William Arthur.
Evatt, John George.
Everett, Reginald Edgar.
Ewart, Samuel John M.
Eyre, Percy.
Ezard, Gerald.
Fabian, Henry Charles.
Fairlie, John Adams.
Farmer, Frank.
Fathers, Leslie J.
Faulkner, A. M.
Faulkner, Arthur Spencer.
Fearnley, Bertie Ernest.
Fearnley, Ronald Arthur.
Felix-Smith, Leslie Eric.
Fellowes, H. S.
Fennell, Cory William.
Ferguson, Frederick Alexander.
Ferguson, John Donald.
Ferranti, V. G. S. Z. de.
Ferro, Thomas Edward.
Fidler, Frederick George.
Finding, Wilson.
Findlay, James Duffus F.
Fisher, Henry.
Fisher, Wilfred.
Fitton, Wilfred Robert.
Flanagan, Frederick.
Flanagan, Joseph.
Fleming, William Ernest.
Fleming, William Kirkland.
Fletcher, Mark Noble.
Ford, Joseph Manning.
Ford, William Arthur.
Formosa, Alfred Charles.
Fortnam, George William.
Foulkes, Heber Rees.
Fox, Stanley Charles E.
Francis, Morgan Rees.
Fraser, John Andrew.
Fraser, John Holden.
Fraser, Sidney Harold.
Freeth, Lancelot Gerhard.
French, Eric Arthur H.
Fricker, Edward Evan.
Friendship, Cyril Arthur.
Frith, Hubert William.
Fuge, William Valentine G.
Fuke, Francis Cecil.
Gabrielle, Harold Lionel.
Gaffney, Thomas.
Galloway, James Francis.
Galloway, William Chas. G.
Gangoly, Umadhava.
Ganguly, P. R.
Gardner, Ernest John.
Garewal, Kartar Singh.
Garland, Cecil Clifford.
Garman, Bertram Corbett.
Garner, Thomas Henry.
Garnes, John Christie.
Garnett, Albert.
Garrett, Henry Ralph.
Garrett, Percival Theodore.
Gates, Arthur George.
Gatland, Howard Charles.
Gaved, John Leslie.
Gazard, William Albert.
George, John Coslett.
George, Philip Herbert F.
George, Thomas Alfred.
Georgeson, Hector Macdonald.

From Graduate to Associate—continued.

Ghadiali, Manchersha Edulji.
Ghose, Monindra Nath.
Ghosh, Surendra Nath.
Gibbins, John.
Gibbons, William John.
Gibson, Franklin Henry.
Gibson, Thomas Thompson.
Gilbertson, Frederick James.
Giles, Ralph Bostock.
Gill, Benjamin Gerald.
Gill, Jack Howard.
Glass, Charles George.
Gleaves, Leonard Cecil.
Glendinning, William.
Glover, Arthur Reginald.
Goddard, Harry Webster.
Godley, Thomas.
Godsmark, Ernest George.
Golding, Arthur Joseph.
Golding, James.
Golds, Lionel Barton S.
Goldthorpe, Sam Leslie.
Goldup, Thos. Edward.
Goodfellow, William Muir.
Goodier, William Richard.
Goodman, Roi Howard.
Goodyear, Sydney.
Gordon, Ernest Alexander.
Gould, Frank.
Graham, Robert Batthews.
Grahame, Gerald Alston.
Grant, Ridsdale Henry.
Grapes, William Harvey H.
Gray, Charles Marshall.
Gray, Thomas Anderson.
Greatorex, John Lowe.
Green, Cyril Beaumont.
Green, Ernest.
Green, Geoffrey Stanhope.
Greener, Ernest William.
Greenwood, Harry.
Greenwood, James.
Gregory, Claude Barnard.
Gregory, Herbert Turberville.
Greig, George.
Grepe, Frederick Yorke.
Gresham, Samuel Roland.
Griffin, Samuel Royston.
Griffith, Ronald George.
Grimmitt, Howard Walker.
Groser, Stanley Rust.
Groves, William Albert.
Grut, Cecil Allan.
Gulati, K. Badri Nath.
Gunawardane, Siranama Tillakaratre D.
Gunn, George.
Gupta, Bahadur Singh.
Gupta, Bikash Chandra D.
Gupta, Krishna Chandra.
Gyi, Maung Mg.
Habgood, Edwin Valentine C.
Haddock, Ralph Burdon.
Hadfield, Tom.
Haffner, Howard.
Haigh, Harold Edwin.
Hainsworth, Harold Percival.
Hall, Cecil Stuart.
Hall, Charles Edward.
Hall, James Owen.
Hall, James Stewart.
Hall, John Charles.
Hall, Percival Henry G.
Hall, Richard Charles.
Hallett, Harold James.
Hambridge, Cecil James.
Hami, Mehmed Behaeddin.
Hamilton, Henry David S.
Hammond, Eric Noel B.
Hampson, William Percival.
Handley, William Cecil.
Hanks, Harry.
Hannant, Herbert William M.
Hansford, Robert George C.
Haque, Mahahmad Abdul.
Hardman, John.
Hardwick, Charles Philip.
Hargreaves, Harold.
Harral, Richard Harold.
Harris, Arthur Cornfield.
Harris, Charles Hardie.
Harrison, Walter James.
Harrower, William.
Harry, Charles.
Hart, Daniel.
Hartland, Sydney.
Hartley, Richard Kent.
Harvey, Hector Gordon.
Harwood, James Stanley.
Hatch, Thomas Parr.
Hawkeswood, Arthur Ernest.
Hawkins, Ernest.
Haws, John Haywood.
Hay, Andrew.
Hayes, Arthur Purchase.
Hayes, Philip.
Hazelgrove, Harry.
Heap, Hubert Leslie S.
Heath, James Garfield.
Heath, Percy Symons.
Heaton, Frank.
Heaton, Reginald George.

From Graduate to Associate—continued.

Hebbert, Reginald James.
Hebditch, Edward Gladstone.
Heelis, Arthur James.
Henderson, Francis Adrian.
Henderson, George Parker.
Henderson, John Alfred.
Henderson, Marshall Waitt.
Henn, Stanley Thomas.
Henning, Arthur James.
Henwood, H. J.
Henzell, George Peregrine.
Herbert, Robert Henry.
Herbert, Thomas Percy.
Herschell, Reginald George.
Hewitson, Maynard.
Hickin, Sydney Botevyle.
Hickleton, Charles John.
Higgins, Percy Victor.
Hill, Albert Rowland.
Hill, Hubert George W.
Hill, William Stephen.
Hillman, Reginald Victor.
Hinchliff, Leonard Fillingham.
Hinton, Sydney.
Hipwell, James Henry.
Hirst, Henry Cecil.
Hives, Herbert William.
Hobbs, Percy George.
Hobson, Ralph Silvanus.
Hocking, Thomas William.
Hockley, Harold William.
Hodges, Eric Samuel.
Hofman, Stanislas.
Holden, George Cuthbert.
Holliday, Wilfred.
Hollingshead, John.
Holman, Horace.
Holmes, Herbert.
Holmes, Hubert Jack.
Honour, Cyril.
Hook, Herbert James.
Hook, Reginald Vincent.
Hooper, Stanley Arthur V.
Hopwood, Robert Agar.
Hornblower, T. J.
Hothersall, William.
Hough, Sydney Lander.
Hounsell, Ernest Alfred.
Hounslow, Edgar Henry.
Housden, David Frederick.
House, William Edward.
Howard, Henry John.
Howard, Paul William.
Howden, Peter.
Howe, Alfred Henry.
Howell, Arthur.
Howson, Frank.
Hoyle, Frank Conquest.
Hudson, Harold Frederic.
Huggett, William Henry.
Hughes, Alfred.
Hughes, Cornelius Vincent.
Hughes, Edward Llewelyn.
Hughes, Lionel Jutson.
Hughes, Thomas Edward.
Hullah, Roland Gilbert.
Hulme, Harold Thomas.
Humphreys, Charles Fogden.
Humphreys, Harold Victor.
Humphreys, Herbert Frederick.
Humphries, Lawrence Milton.
Hunt, Joseph James H.
Hunter, Drummond William S.
Hunter, George.
Hunter, George James.
Hunter, Harley Kidd.
Hurle, Robert Hampton.
Hurst, Walter Greaves.
Hutton, Frank Willoughby.
Hyland, Frank George.
Irwin, Arthur Edward.
Ito, Keiji.
Iyer, K. Venkataramana.
Jack, John.
Jackman, Arthur Hulse.
Jackson, Charles Warburton.
Jackson, John William.
Jackson, Peter.
Jackson, Philip Harry.
Jacob, John.
Jager, Silvester Claude.
Jagger, Hubert.
James, Hubert Renshaw.
Jaques, Henry Hugh.
Jarvis, Harry William.
Jarvis, John Richard.
Jay, Henry Charles.
Jeans, Archie Edward.
Jeffery, Clifton Adin K.
Jenkins, William Arthur.
Jenner, Clifford George.
Jennings, Bruce Charles.
Jennings, Fred Hicks.
Jennings, Harry.
Jesson, George Edward.
Johnson, Arthur.
Johnson, Rowland Alfred.
Johnson, Samuel Henry.
Johnston, Eric Montague.
Johnston, Ernest Clifford.
Johnstone, Alexander Bernhardt.
Jones, Arthur Thomas.
Jones, Benjamin.
Jones, Edward.

From Graduate to Associate—continued.

Jones, Elvet Oscar.
Jones, Eric Ford.
Jones, Ernest Thomas L.
Jones, Joseph.
Jones, Richard.
Jones, Rupert Leonard.
Jones, Walter Ernest.
Jones, William Handel.
Kar, Hari Charan.
Karuven, Miliyil.
Kaye, Joseph Blamires.
Keating, Albert Ernest.
Keay, Edmund McLaren.
Keillar, Alan Bernard.
Kelly, John Philip.
Kelso, Alexander.
Kemp, Robert James A.
Kempson, Ernest Ephraim.
Kendall, Reginald William.
Kennard, Archibald.
Keogh, Louis Joseph.
Kerr, Philip Cameron.
Kerruish, Henry Cannell.
Khan, Abdul Aziz.
Khory, Keki Nowerozzi.
Kilby, James Wheatley.
Kilner, William Norman.
King, Frank.
King, George Herbert.
King, Herbert Harvey.
Kington, Arthur Charles.
Kington, Robert Wheeler.
Kitchen, Harold Jennings.
Kitchens, Harold.
Kitching, Donald Albert.
Knight, Harry Stanley Y.
Knobel, Johann Ludwig.
Knox, John.
Krishna, Rama.
Kuka, Jal Mehrjibhai.
Kyte, Sydney.
Lacey, Edgar William.
Lacey, Thomas Alfred.
Lalwani, Hotchand Gurbux.
Lamb, James Forrest.
Lambert, Alexander Barker.
Lambert, William John.
Lamden, Henry James.
Lamond, James.
Lamotte, Gerald William L.
Lancaster, Jack Kelvin.
Langlois, Edwin Mauger.
Langlois, Thomas.
Larnder, Harry.
Latham, Ashton.
Lauder, A.
Laughland, Andrew Percy.
Law, Francis Henry R.
Lawrence, Robert.
Leake, William Richard.
Leakey, Reginald Edward.
Leary, John Francis.
Leathes, William Henry B.
Ledward, Thomas Archibald.
Leece, William Lionel.
Leeds, Robert James.
Leftley, Joseph Richard.
Leng, Charles William.
Lennon, George Wheatley.
L'Estrange, Guy Gilroy.
Lewis, Gwilym.
Light, Cecil Stanley.
Limage, Narayan D.
Lindon, Charles Theodore.
Lisle, George Stanley.
Lisle, Patrick St. John.
Llewellyn, Frederick Langhorne.
Lloyd, Harold.
Lloyd, Norman.
Lloyd, William Fox.
Lobo, Alfred.
Lochead, Charles Kearney.
Logan, Alexander.
Loney, Herbert Howard.
Long, Alfred Porter.
Long, Thomas Charles.
Longbottom, Jack.
Longmore, Frederick William.
Longstaff, George.
Lord, Bernard Stevenson.
Lord, Ian Geoffrey S.
Lord, Will.
Love, Henry.
Lovell, Edward Philip.
Lowe, Walter.
Lowey, Samuel.
Lown, Stephen John.
Lowrey, Amos S.
Lumby, Frank.
Lundy, George Alfred.
Lupton, John Kenneth.
Lusher, Walter Randall.
Lyne, Robert Habby.
Mabbott, William Henry L.
Macadam, Ivision Stevenson.
McAinsh, Neville James.
McAlpine, James.
McCarter, Alan Lailey.
McCarthy, Joseph Michael.
McDermott, Harold Richard.
Macdonald, James Wright.
Macdonald, John Roughead.
Macdonald, William Ewing.
McEwan, John William.

From Graduate to Associate—continued.

McGillewie, Donald Irvine.
McGrath, Thomas.
MacGregor, William.
McGuigan, William.
McGuire, Alexander Thomas.
McJannet, David William.
McKechnie, Alan Francis C.
MacKinnon, Alexander.
Mackinnon, A. D.
Mackinnon, Lachlan.
Mackintosh, George Edward.
Mackintosh, Illtyd.
McKnight, William Alexander.
McLagan, Angus John.
McLaren, Joseph Colin.
McLennan, Grant A.
McLeod, Henry Francis.
MacMicking, Julius Manus.
MacMillan, Archibald.
McNab, John.
McPhail, Henry James.
Macpherson, A. W. Roy.
McShain, John Daniel.
Maddocks, William Arthur.
Magrow, Gordon Emm.
Mahmond, Mohamed Ahmed.
Maidment, R. F. J.
Maloney, Thomas Patrick.
Mandour, Moussa Ahmed.
Mangnall, Wilfrid Earlam.
Mani, Ramakrishna.
Manifold, R. W.
Manlove, Cecil William Walton.
Mann, Samuel Alfred.
Mantle, Rowland Shelley.
Manyam, Venkataram Subrah.
Maple, John Walter.
March, Clifford.
Marchant, George Samuel.
Marlowe, Thomas.
Marriott, Edward Stanley.
Marsh, John Rogerson.
Marshall, George Norman.
Martin, Harry Sloane.
Martin, Norman Hadlow.
Martin, Walter Dennis.
Mason, James Alfred.
Mason, William John.
Masters, Thomas Bertram.
Mathews, Edward Daniel.
Mathews, Eugene.
Mathur, Grimdra Sahai.
Matthews, Francis Albert.
Matthews, Harold Humphrey.
Matthews, Leslie Albert.
Matthews, Mabel Lucy.
Matthews, Percy Ira S.
Mavor, Albert Bernard.
Mayo, Edward Alexander.
Mazumder, Nripendra Nath.
Mead, Reginald Henry.
Menon, K.
Metcalf, James Norman.
Metz, Louis Gerald E.
Middleton, Edward.
Middleton, Samuel Charles.
Miles, Thomas John.
Mill, Eric Sidney.
Mill, Harry.
Miller, Morrell Herbert.
Miller, Thomas Taverner.
Miller, William Henry.
Millington, Stanley.
Mills, Thomas Herbert L.
Milne, Alexander James.
Milne, William Hamilton.
Milner, Ewart Guy.
Milton, Arthur Victor.
Milward, Frederic Andrew.
Minter, Robert William.
Misra, Munna Lal.
Mitchell, John Clark.
Mitchell, Thomas Alfred.
Modi, A. K.
Moiselle, Thomas Henry.
Moller, August Henry.
Montague, William McAdam T.
Moody, Harold Thomas.
Moody-Smith, Claude Gerald.
Moore, Douglas.
Moore, Eric John T.
Moore, Frederick.
Moore, Sidney Herbert.
Morgan, David Llewellyn.
Morgan, Ivor.
Morgan, Thomas Cyril.
Morris, Samuel Henry.
Morrison, James Douglas.
Morton, James.
Moseley, Ernest Gower.
Moussa, Mohamed.
Mukerji, Gopal Chandra.
Mukherji, Sachindra Nath.
Mulleady, Ricardo T.
Munro, James Alexander.
Munro, John.
Munro, J. W. W.
Murcott, Gordon.
Murgatroyd, Eric Hall.
Murphy, John.
Murray, John James L.
Mylchreest, Henry William.

From Graduate to Associate—continued.

Nadhan, Vaiankalatur Ramaswami H.
Nagabushanam, S.
Nagarajan, Tirupattur Krishnswami.
Naidu, S. R. M.
Narbeth, Charles Anstey.
Neal, Albert Edward T.
Neatherway, Gordon Stanley.
Needes, Edgar Charles.
Neilson, George Jeffrey.
Nettleton, William Edward B.
Newburn, Edgar Allan.
Newland, Ernest William J.
Newman, Arthur Sidney.
Nibloc, F. J.
Nicholes, Samuel.
Nicholls, William Henry.
Nicholson, Frederick Walter.
Nicholson, James Shepherd.
Nicol, Stuart Naxton.
Nimmo, Adam Arthur.
Nixon, William Geoffrey J.
Noble, Horatio James G.
Norman, Harry, Junr.
Norris, Harry.
North, Sydney Ernest.
Nuttall, R. A.
Oaten, Herbert Claude.
Obert, Ferdinand Thomas F.
O'Brien, Bernard Heath.
O'Brien, John Andrew.
O'Brien-Malone, Patrick Joseph.
Ogg, John George.
Ogilvie, Harold Erskine.
Oliphant, Thompson.
Olney, Ralph.
O'Meara, Esmonde.
Orchard, Patrick Connelly.
Orme, Alexander.
Orr, James.
Orrell, William.
Osborn, Thomas Lester A.
Otton, Albert Eric.
Outram, Frederick Colin.
Owen, John Ewart.
Owner, John Scorgie.
Oxley, Ernest.
Pacey, Stewart Oswald.
Packe, Cyril Leslie.
Padgett, Albert Stanley.
Padgett, George Thomas.
Page, Arthur.
Page, Cecil.
Painton, Claude Arthur.

Pairman, Rodion.
Paley, Frederick Raymond.
Palmer, Archie Emerson.
Palmer, Thomas Henry.
Panth, Bhola Datt.
Panthaki, Jehangir Sorabji.
Parker, Edwin.
Parker, Ralph Henry.
Parker, William Alfred.
Parker, William H. H.
Parker, William Jarvis.
Parry, Douglas Swift.
Parry, Herbert Percy.
Parry, Herbert Watkin T.
Parsons, James George T. G.
Parsons, Lionel Uniacke.
Parton, Victor Gordon B.
Passmore, William Oglesby.
Patel, N. B. B.
Paterson, David.
Patman, Reginald Horace.
Pattinson, Robert Raine.
Pavis, Cecil.
Payn, Cyril Thomas.
Payne, Charles Jeffery.
Payne, Eric Arthur.
Payne, George Edward.
Payne, George Inwood.
Payne, George Lewis.
Pearce, Cecil.
Pearce, William Robert.
Pedley, David.
Peers, James Henry R.
Pemberton, Norman.
Pender, Daniel.
Pennal, Herbert William.
Penstone, Walter St. George.
Perkins, Thomas Ewart.
Pernet, Frederick Harry.
Pernice, Harold Henry.
Perret, Louis Bryan.
Petrie, John.
Petry, Martin.
Pewtress, Noel Cecil.
Phillips, Alexander Stevenson.
Phillips, Alfred Samuel C.
Phillips, Charles George R.
Phillips, Cyril Bonville.
Phillips, E. R.
Phillips, Francis Eugene.
Phillips, Herbert Gordon.
Phillips, John Douglas N.
Phillips, Russel Vernon.
Physick, Nino William.
Pickford, Harold Leslie.
Pickworth, Ernest William.
Pimley, Gordon Haldane.
Pinder, Harry.

From Graduate to Associate—continued.

Piper, Ralph William.
Pistorius, Leo Henry.
Pitcher, Arthur Edwin.
Pitts, William Arthur.
Plascott, Vincent Leslie J.
Pocock, Hugh Shellshear.
Podd, Jack Kenneth.
Pointon, Herbert Vincent.
Pollack, Leonard Austin.
Pollard, Herbert.
Pollard, Thomas Royle.
Pollock, Wallace.
Pomroy, Richard Osborne.
Pope, Harold Charles G.
Porritt, Athol Edmund A.
Porter, Ernest Bellamy.
Porter, Frank.
Potter, Howard.
Potts, Leonard Kerr.
Powell, Reginald Alfred.
Prabhu, Manjeshwar Gooinda.
Prangnell, Frank Norman.
Prasad, Narayan.
Pratt, Joseph Hewitt.
Prescott, C. W. W.
Price, Joseph Edelsten.
Pritt, Stephen Edward.
Probert, George.
Prosad, Bhagwat.
Provand, Ninian.
Pulleyn, Geoffrey.
Pyke, Edward Joseph.
Pyott, James Thompson.
Raby, William James.
Radburn, Cyril George.
Raghavan, V. T. Srinivasa.
Rama, Raja.
Ramaswami, Kuppuswami.
Rampe, Percy Conrad.
Randall, D. P.
Randall, Roland.
Randall, Samuel Gibson.
Rangachari, Tirumalai Seshachari.
Ranganatham, Mayaravam Krishnasami.
Ranji, Maneck Jamshedi.
Rankin, John Stanley.
Ratcliff, Reginald Pickworth.
Rawlings, Bernard Clarence.
Rawlings, William John.
Ray, James Charrington.
Rayment, Kenneth Inge.
Rayner, William Eric.
Read, Eric Edward.
Read, Grosvenor Woodhouse.
Reddyhough, Harry Lythgoe.

Redfearn, Charles Herbert.
Redgrave, Harry Conway.
Reed, Arthur Weston.
Reed, Victor.
Reeman, Herbert Frederick.
Rees, Horace Edward.
Regis, John.
Rendell, Leonard Morey.
Rennick, H. C.
Rennie, William.
Renwick, William John.
Retallack, Frank Vyvyan.
Richard, Seward Thomas.
Richardson, Ellis Matthew.
Richardson, Richard Paul.
Richardson, William Ernest.
Rickwood, Henry Asher.
Ridley, Allison.
Ridley, John Harry D.
Riley, John.
Riley, Norman Williams.
Risbee, Frank Carrington.
Roach, John Carlyle.
Roberts, David Harold.
Roberts, Frank Rob C.
Roberts, Gwilym Richard.
Roberts, Henry James.
Roberts, Sidney Douglas.
Robertson, Leslie Reid.
Robinson, Henry John.
Robinson, Leonard Mansfield.
Robinson, Percy.
Robinson, Richard Edward.
Roddis, Charles Henry.
Rodgers, James Neil.
Rodrigues, John Rozario.
Rogers, Daniel Herbert.
Rogers, Henry Kenneth.
Rolph, John.
Rose, Arthur Harold W.
Rose, Francis Joseph P.
Ross, James Hugh.
Ross, Kenneth Fernley W.
Rothwell, Samuel Henry.
Roulson, William Percy.
Rouse, William Cameron.
Rowan, William.
Rowell, J. P.
Rowland, John Joel.
Rowson, Leslie.
Roy, Sunya Kumar.
Royal, James William.
Royle, William Arden.
Rudd, Donald.
Rudge, Frederick William.
Rudman, Rowland Richard.
Rudgeroni, J. V.
Russell, Edward Powys.

From Graduate to Associate—continued.

Russell, Frank Gerald.
Russell, Leslie Thomas.
Russell, Robert.
Ryan, Louis.
Ryder, Francis.
Sabine, Eric Alan.
Sahyal, Sukhbashi Ram.
St. George, Reginald Graham.
Sale, Arthur Jack.
Salter, William Seabrook.
Saltren-Willett, Charles Geoffrey.
Sampson, Charles Victor.
Sampson, Gerard William.
Sampson, Henry.
Samuel, Robert Philip.
Sandels, Harry George.
Sanders, Arthur Leslie.
Sanyal, Kshitish Chandra.
Sargent, Hugh Hamilton.
Sargent, John Alexander.
Satchell, Reginald William.
Satchwell, William Arthur.
Savage, Joseph.
Saxby, H. B.
Scaling, Thomas Nawton.
Schneidau, Tom Charles.
Schofield, Bertram Glass.
Schofield, Hubert Vane.
Sclar, David.
Scott, Douglas Murray.
Scott, Walter.
Scott, William.
Seaborne, William.
Sear, Norman Charles A.
Sedgwick, Arnold James.
Semple, James Hamilton.
Sen, Akshaya Kumar.
Sen, Mahendra Nath.
Sen, Mani Kanta.
Sen, Prafulla Kumar.
Sennitt, Albert Victor.
Sethi, Dhanpatrao.
Seymour, Walter Turnbull.
Shallcross, Herbert.
Shankariah, Nagalapur Sesha.
Shannon, William Edward.
Sharma, Gyan Chand.
Sharpe, Donald Claude.
Sharpe, Herbert Allen.
Sharrock, Charles Frederick Keith.
Shaw, Horace.
Shaw, Wilfrid Leonard.
Shead, Cecil Roland.
Shearer, James.
Shearer, Robert Edgar P.
Shears, Horace Humby.
Shelley, George Henry L.
Shepherd, Cyril.
Shepherd, David Kennedy.
Shepherd, Joseph.
Sheppard, George.
Sheppard, Maurice William.
Shewan, John Richard.
Shiels, John Herbert.
Shillitoe, John.
Shilson, Leslie James.
Shipley, Francis Ernest.
Short, Arthur Henry.
Short, William James C.
Shove, Horace Vivian.
Shukla, Bal Krishna.
Shute, Reginald Joseph G.
Shuter, Ernest John.
Sibou, Brijkrishna.
Silver, Harry George E.
Silverwood, Alfred Cyrus.
Simmonds, Henry.
Simmonds, Leslie Raymond.
Simpson, Alan Alfred.
Simpson, Alexander Victor.
Simpson, Henry Greeff.
Simpson, Robert Kidd.
Simpson, William.
Sims, Frederick.
Sinclair, George David.
Sinclair, Harold.
Sinclair, Robert John.
Sinclair, William.
Singh, Inder.
Singh, Lachhman.
Singh, Teja.
Skinner, Arthur Cyriac.
Skinner, Edward.
Skinner, Harold Edward.
Skinner, Leslie Carl.
Skittrall, Charles James H.
Sleath, Bernard.
Slevin, Edward.
Small, Charles Edward.
Smart, Henry Prescott.
Smith, Arnold James.
Smith, Arthur Henderson.
Smith, Arthur McDonald.
Smith, Charles.
Smith, Charles Henry.
Smith, Cyril Blake.
Smith, Francis Donald.
Smith, Frank Cyril.
Smith, Fred.
Smith, Hubert Alfred.
Smith, James Stanley.
Smith, Leslie Victor.
Smith, Percy.
Smith, Sydney Steele.
Smith, William.
Smith, William Monro.
Snipe, Norman Victor.
Solly, Leonard James.
Somayajulei, Bulusu Rama.

From Graduate to Associate—continued.

Speedy, Wilfred Henry.
Spence, Herbert Frank.
Spencer, John Francis.
Springsguth, Charles Edward.
Spruce, Samuel Raymond.
Squire, Reginald George H.
Staddon, Edward Charles.
Stainsby, James William.
Stancer, George Henry.
Stanley, Thomas Edward.
Steadman, Eric.
Stearn, George Fletcher.
Steel, Carlyle Stewart.
Steels, George Harwood.
Stephens, Arthur Reginald H.
Stephens, Cecil Arthur.
Stewart, Arthur Hay.
Stewart, William Charles.
Stobbs, John George.
Stone, Herbert John.
Stonebanks, Alec George.
Stout, Thomas Stephen.
Stowers, Arthur.
Stredwick, Stephen Bertie.
Stupart, Gustavus Henry.
Suarez, Antony.
Subramanian, Krishna Ayyar.
Subramaniam, Nanjundaiah.
Sud, Shio Nath.
Sulston, Leonard Edwin.
Summers, Albert Victor.
Suri, Kishen Das.
Sutcliffe, William.
Svarup, Anand.
Swain, Vivian Ernest T.
Swainsbury, Horace.
Swarsbrick, Joseph James.
Taggart, Henry Rawson.
Tait, Roderick Urquhart.
Tanner, Herbert Douglas.
Targett, Ernest Howard.
Tattersall, William.
Taylor, Cecil Robert F.
Taylor, Conway.
Taylor, Francis Gordon.
Taylor, George.
Taylor, Gerald Ernest.
Taylor, Harold.
Taylor, Harold Charles.
Taylor, Henry.
Taylor, Horace.
Taylor, John Delmore.
Taylor, William Alexander.
Teal, John Robert.
Teather, Reginald Herbert.
Terry, Thomas.
Thakkur, Khimji Bhangi.
Thakur, Manohar Lall.
Tharle, George Victor.
Thomas, Alan Ormond.
Thomas, David Evan F.
Thomas, Ernest.
Thomas, Frederick.
Thomas, Hubert Jasper S.
Thomas, John Hubert.
Thomas, Leonard.
Thomas, Thomas Herbert.
Thomas, William George.
Thomas, William John.
Thompson, Edgar.
Thompson, Samuel Henry.
Thompson, Thomas Barnes.
Thomson, George Hamilton.
Thorburn, G. L.
Thornton, Charles James.
Tilbury, Albert William.
Tilley, H. H.
Tilsen, Alban George.
Timberlake, Eric Johnson.
Tinker, Cecil F.
Tinker, Walter.
Tivey, Frederick John.
Tointon, William Norman H.
Tolley, Henry John.
Tomkinson, Alfred Hugh E.
Toms, William Harold.
Tonkin, Cecil Vivian.
Toplis, Leslie George.
Torrance, John.
Towndrow, Frederick Francis.
Towner, Herbert George.
Tozer, Charles William.
Tozer, Robert James McC.
Trail, Henry Percy.
Tree, Francis George W.
Tree, William George.
Tregoning, Vivian Hugh.
Tremain, Arthur Geoffrey.
Trim, Frederick Aine.
Troup, George.
Troutbeck, Wilfred Henry.
Truman, Leslie Harold.
Tubb, Burton Henry J.
Tucker, C. L. W.
Tucker, Frederick John.
Tuffill, George William.
Turner, Albert Edward.
Turner, Arthur Stephen.
Turner, George William.
Turner, Horace.
Turner, Wilfred Charles.
Turton, George Thomas.
Tyler, Leonard Benjamin.
Tyler, Stanley Suett.
Tyrrell, Frank.
Tyrrell, Frederick.

From Graduate to Associate—continued.

Underhill, Cyril.
Uplap, Narayan Peraji.
Vacy-Ash, William Maxwell.
Varley, James William.
Varley, Robert.
Veale, Frank Leslie.
Venkataram, Visvanatha.
Verity, Ronald Meysey.
Vinehill, William Francis.
Visvanathan, Manakkal S.
Vitty, William Lawrence.
Vora, Shamaldas Churilal.
Vowell, Christopher.
Vowles, George Alexander.
Waddington, Rupert Ronald.
Wade, Cecil Forrester N.
Wade, John Charles.
Wadham, Giles Anthony.
Waite, Frederick James G.
Walker, Albert.
Walker, Harry Parker.
Walker, Herbert.
Walker, James Smith.
Wall, G. P.
Wall, Harold Henry.
Wallace, Hugh.
Wallcroft, Frederick Ernest.
Wallis, Albert Edward B.
Walmsley, Thomas.
Walter, William James H.
Walters, George.
Walton, Edward Soilleux.
Warburton, Ronald.
Ward, George.
Ward, John Hunter.
Ward, Leslie Edward.
Ward, Thomas Moore E.
Ward, Walter.
Warder, Stanley Bernard.
Warman, Arthur Charles.
Warner, Cecil Etheridge.
Warwick, Henry William.
Waterhouse, Clifford Thwaite.
Watkins, Charles Leslie.
Watkins, Herbert William.
Watkins, Oscar Frederic J.
Watson, Alan Cairns.
Wayte, Frederick William.
Webb, Frederick George.
Webb, Leonard.
Webb, Roland.
Webbe, Horace Frank.
Webber, Harry.
Webber, Percival Hugh.
Webster, Charles John.
Webster, George Reginald.
Webster, Harold.
Webster, Israel.
Wedderspoon, William Carrick.
Weissenbach, John.
Welch, A.
Wells, Charles Frederick.
Wells, Harold Charles.
Wellsteed, Albert Edward.
Welsford, Douglas.
West, Frank Edward.
West, Stanley Birkett.
Weygood, Wilfred.
Whaley, Ralph Stanley.
Wheeler, Willoughby Shaw.
White, Albert Ernest.
White, Alfred.
White, Edward Paul.
White, Ernest Henderson.
White, Francis William.
White, Harry.
White, Sidney Robert.
Whitehouse, Alfred Edward.
Whitehouse, Harold Ernest.
Whiteley, Arthur Wellesley.
Whiteside, Richard.
Whittingham, Albert.
Whittle, Mark.
Whyte, Cyril Leonard A. de B.
Wicks, William Edgar.
Widger, Leslie.
Widgery, Robert George.
Wijesinghe, Don Martin.
Wijesinghe, Walter.
Wild, Frank.
Wild, John William.
Wilde, Charles Clifford.
Wilkins, Frederick John.
Wilkinson, Leslie.
Wilkinson, Thomas Edward.
Williams, Alec Duncan.
Williams, Charles Stewart.
Williams, Daniel John.
Williams, Fred.
Williams, George Edward.
Williams, Richard Francis S.
Williams, Robert Vernon C.
Williams, Thomas Davies.
Williams, Thomas Evelyn H.
Williams, W. R.
Williamson, Harry Cyril.
Willingham, Arthur John R.
Willis, S.
Wilson, Charles Henry.
Wilson, Herbert Walter.

From Graduate to Associate—continued.

Wilson, Lancelot James.
Wind, Herman John.
Wind, Hubert.
Winnard, Ronald.
Winter, Harold.
Withey, Walter Henry.
Wood, A. N. G.
Wood, George William.
Wood, Henry Guy.
Wood, William Robert B.
Woodcock, Herbert William.
Woodhams, William.
Woods, Alfred.
Woods, Fred.
Woods, Ronald Forster.
Woodson, Jonathan Plews.
Woollhead, Arthur.
Wray, Walter Dean..
Wright, George.
Wright, John Henry.
Wright, Maurice McGill.
Wright, Sydney Rowland.
Wurm, George Louis.
Wynne, Richard.
Yardley, Harry Frederick.
Yates, Edward.
Yates, Joseph Henry, Junr.
Yates, Leonard Harold.
Youdan, Denis.
Young, Clifford Neil.
Young, John James.
Young, William.
Yuen, Keyih Soochin.
Yule, Thomas.
Zambardas, D. Michael.

From Graduate to Student.

Aiken, Leslie James C.
Ashton, John Henry.
Brookes, Cyril Spencer.
Calam, Richard Hellyer.
Clarke, Cyril Edward.
Cole, Frank Jasper.
Croft, Hyla Bert.
Duncan, David McGregor.
Easton, Harold.
Ghosh, Jogajiban.
McFarlane, John.
McKay, Hugh Stewart.
Mathur, Lakshmi Narain.
Maycock, Alan.
Minister, John William.
Mittra, Madan Gopal.
Noakes, Ernest Stanton.
Oatley, Charles William.
Partington, Henry.
Pemberton, William.
Sengupta, Narendra Nath.
Tait, William McDiarmid.
Tonkinson, Alan Arthur.
Vickers, Harold Edwin.
Wallace, Norman Mordaunt.
Ward, Frank Stanley.
Woodward, George Lawrence.

From Student to Graduate.

Abba, Herbert Arthur.
Addison, James Donald.
Adkins, Bernard.
Allison, Roy.
Anderson, James Peter.
Anderson, William Cecil Carrick.
Anscombe, Leonard Douglas.
Archer, Leslie John.
Armitage, Geoffrey Lockhart.
Armour, James Orr.
Arnold, Sidney Roger.
Aschman, Geoffrey Donald.
Ashton, Edgar George.
Atkinson, Sidney.
Austen, Donald Edwin Horace.
Awcock, John Oswald.
Baguley, Eric.
Baird, Robert Alexander.
Baker, Claude Frederick George.
Baker, William Frank.
Baldwin, Alfred William Thomas.
Baldwin, Roy.
Barker, Harold Godfrey.
Barnard, George Philip.
Barnard, Roy Mayne.
Barnes, Harry William.
Barnett, Henry Edgar.
Barton, Charles Henry.
Barton, Richard Bernard.
Bates, Albert Edward.
Baxter, Henry Wright.
Baynton, Ronald Alfred.
Bean, George Robert.
Beanland, Charles Percy.
Bearn, James.
Beaumont, Frederick Norman.
Beckett, Charles Stephen.
Bedingfield, William King.
Bell, Charles.
Bennett, Arthur Edward Charles.
Bennett, Claydon.
Bennett, James.

From Student to Graduate—continued.

Bentley, John Grahame.
Berenbaum, Aaron.
Berens, Cyril Eustace.
Berry, Norman.
Bhandari, R. C.
Binns, Arthur William.
Bird, dEward P.
Bissell Frank Edwin George.
Bloomfield, Edward Nelson.
Bott, Francis Alfred Noel.
Bottle, Edward Kelvin.
Boullen, Harold Godfrey.
Bowers, Laurence.
Braid, Kenneth Edwin Paxton.
Brewer, Arthur Ernest.
Briggs, Arthur.
Brooke, Anthony John.
Brown, Jack.
Brown, John Carey.
Brunker, Edward George.
Buckland, Alec William.
Burbridge, Philip George Houlder.
Burdick, Robert Harry.
Burton, Colin Rupert.
Button, Cedric Lloyd.
Campbell, William Charlton.
Campbell, William Harold.
Cansdale, John Henry.
Capper, John Frederick.
Carfrae, William John.
Causon, Geoffrey Stephen.
Cawson, William Fox.
Chakraborti, K. T.
Chandiramani, Mangharam Bulchand.
Chapman, Ralph Eustace.
Chard, Frederic de la C.
Chaudhuri, Joy Deb.
Chifferiel, Gerald Raymond.
Child, Ivon Henry.
Christison, Norman Calder.
Chynoweth, Frederick.
Clare, Bernard Scott.
Clark, Henry Arthur Maish.
Clarke, Harold.
Clements, Vernon Arthur Hoernle.
Clifford, Albert Edward.
Clunie, Matthew.
Cocks, Maurice Hubert.
Collins, Thomas Eric.
Collinson, William.
Collis, William Blow Gurney.
Connor, Vincent Edward.
Cooke, William.
Coop, Eric.
Cooper, Herbert William.
Cooper, Maurice Ranson.
Cordiner, Basil MacLeod Davidson.
Corfield, David Nisbett.
Cornish, Henry Edmund.
Crews, Thomas John.
Crocker, Charles Henry.
Crompton, Archibald.
Cunningham, Alastair Andrew.
Daker, Horace Herbert.
Dall, William Christie.
Daniel, Leslie Henry.
Das, Amulya Krishna.
Davar, Lall Singh.
Davies, Henry.
Dawson, Alfred John.
Dean, Andrew Robertson.
De Beer, Charles Loxton.
De Bejar, Alfonso Antonio Luis.
Dempster, David.
Desbruslais, Denis William.
Dey, Neil Alan.
Dick, Robert.
Dick-Cleland, Alexander William Arthur.
Dickinson, David Walter Leopold.
Dimmick, George William.
Dixon, Douglas Leslie.
Dorrat, James Andrew.
Dowden, William Thomas.
Dowsett, Harry Lyttelton.
Drabble, Arthur Frederick.
Draper, Brian.
Drummond, Charles Robert.
Drummond, Christopher.
Dudley, Leslie Peter Clarence Jack.
Duerden, Tom.
Dunbar, James Quentin.
Dunn, Alwyn Walter.
Dunn, John Frederick.
Durbin, James.
Dwyer, Colin Henry.
Edmondson, Franklin.
Edwards, Eric Walter.
England, Robert Hassall.
Escott, Alexander John.
Everest, Francis John.
Ezckiel, Maurice.
Falkus, Arthur Everest.
Faragher, Arthur John.
Farmbrough, Ian James.
Farnes, Gilbert Henry.
Faux, Frank.
Fawssett, Frederick Arthur Boucher.
Felipes, Luis Genaro.

From Student to Graduate—continued.

Felton, Alonzo.
Fenton, Wilfrid David Drysdale.
Ferns, James Laurence.
Fitzpatrick, Hugh James.
Follett, Samuel Frank.
Foot, John Bartram Lovell.
Forster, Ernest William.
France-Hayhurst, Basil Walter.
Franklin, Ralph Herbert.
Fraser, Herbert James.
French, David Charles.
Frith, J. E.
Fryer, Ronald Waring.
Gachet, Ernest Jules.
Gainer, Harold.
Garrard, Charles Joseph Oliver.
Gaskell, John Leonard.
Gathercole, John.
Gettliffe, Rupert.
Ghosh, Eric Maurice Benjamin.
Giles, Percy Albert.
Gill, Francis Cawthra.
Gill, Thomas.
Gill, William John Reginald.
Gillingham, John Henry Searle.
Gilroy, Gordon Leslie.
Ginger, Lionel Alan McLean.
Gokarn, Prabhakar Ramchandrarao.
Gorkiewicz, Richard Habdank.
Gourlay, Colin Alfred Garrett.
Gover, David Frank.
Grahame, Thomas Ronald Yorke.
Grant, Douglas Frederick.
Gray, George William Ernest.
Gray, John.
Greasley, George.
Green, Gilbert Francis.
Green, Robert James Percy.
Green, William.
Greenhalgh, John Ward.
Greenwood, Ernest Blakeley.
Greenwood, Ernest Rupert.
Greer, Henry Leo.
Griffith, Anthony Frank Henry.
Grover, Khem Chand.
Grundy, Eric.
Gunzburg, Noah.
Gupta, Chimman Lal.
Gurney, Norman Richard Dawson.
Gurney, William Albert John.
Guthrie, James Robert.
Hagry, Soliman Aziz.
Hale, Thomas Charles.
Hall, Harold Stuart Meynell.
Halton, Geoffrey Herbert.
Hamilton, Robert.
Hamilton, William John Bruce.
Hamlyn, Arthur Macfarlane.
Handa, Jiwa Ram.
Harrabin, Frank.
Harris, Arthur Henry.
Harris, Frederick Henry (Rugby).
Harris, Frederick Henry (Singapore).
Harris, William.
Hart, Donald Alfred.
Harvey, Robert Antony.
Hawker, Michael Seymour.
Heaton-Armstrong, Louis John.
Henzell, Owen Maxwell.
Hewett, Cecil Frederick.
Higgins, Bertram George.
Hillier, Walter Muspratt.
Hinchliffe, Donald.
Hind, Harold Stanley.
Hinds, James Oliver.
Hitchcock, Gerald Edward.
Hoar, Harold George
Hodges, Leonard Allen.
Hodgson, Alan D'Arcy.
Hogarth, John Russell.
Holloway, Keith Henry.
Hornby, John Reginald.
Howard, John Llewellyn.
Hughes, Leslie Ernest Charles.
Hutchison, Eustace Neville.
Ife, Harold James.
Illingworth, John.
Iyengar, Seringapatam Venkatramiengar Garuda.
Jackson, Cyril Gordon.
Jackson, John Greenville.
Jackson, Thomas Eustace.
Jackson, Willie.
Jaffé, Charles Cecil.
James, Douglas John.
Jarvis, Raymond Frederick James.
Jehu, John William.
Jenkins, John William.
Johnson, Charles William.
Johnson, Edward Harrison.
Jones, Arthur Innes.
Jones, Geoffrey Charles.

From Student to Graduate—continued.

Kane, Bernard Fletcher.
Kanwar, Prithvi Nath.
Kapur, Bal Raj.
Keir, James.
Kelk, William Hyde Hastings.
Kennedy, John Ross.
Kenyon, Alec Hindle.
Kerr, Alexander Norman Dumay.
Kershaw, Richard.
King, Charles William.
King, Frederick Joseph.
Kingston, John Marshall.
Kirkby, Norman Reginald.
Klesel, K. J.
Knott, Bernard.
Kunning, George Alexander.
Lakhanpal, Dev Datta.
Lambert, David Nasmyth Hogg.
Lancaster, Oswin Burrowdal.
Landale, Stenard Ernest Andrew.
Langfield, William Thomas.
Langston, Frederick William.
Lappin, Henry.
Law, Denys Maurice Orlando Prideau.
Lawrence, Walter Francis Charles.
Lea, Jeffrey Tunstall.
Leeson, Donald Chetwode.
Le Fevre, Marcus Emile Louis.
Legg, John.
Le Grice, Ernest Wilfred.
Leigh, George Allan.
Leigh, Harold.
Le Jeune, Sydney Maurice.
Lester, Arthur Ernest.
Leung, Francis Simon Joseph.
Lewin, John Robert.
Lewis, Frederick William M.
Lewis, William Kenneth.
Lironi, Thomas Victor.
Love, Kenneth George.
Loveridge, Eric James.
Low, William Kemp.
Lowther, Gilbert.
Loynes, Ernest.
Lucas, Frank N.
Luke, Sydney Charles.
Lyddon, Percy Edward.
McCandless, Joseph.
McCormac, Arthur.
Macdermid, Robert Alexander.
McGavin, James.
McGibbon, Alexander Roxburgh.
McGreevy, Thomas.
McGregor, Archibald Andrew David.
MacGregor, Roderick Marcus.
Mackenzie, Donald.
Mackenzie, Evan John.
McMillan, Geoffrey Alexander.
McNeil, Hector.
McRostie, John Baxter.
Madgavkar, Manohar Balvant.
Maffett, Edward Hamilton Bloomfield.
Mahal, Bakhshish Singh.
Mainer, Oswald Edwin.
Maitland, Cyril Edmund.
Mannassi, Percival.
Marshall, Arthur Richard.
Martin, Donald Eustace.
Maskell, William Alfred Cottingham.
Mathews, Ernest Samuel.
Mawson, Spurgeon.
Maye, J. W.
Mayer, Cornelius Graham.
Mayhew, Thomas Alfred.
Meeke, James Denis.
Megaw, Eric Christopher Stanley.
Melhuish, Alan.
Messenger, John Harris.
Metcalf, Herbert Eustace Lionel.
Middleton, George Edward.
Millar, David Philip Maxson.
Millard, Robert George.
Miller, Albert William.
Mills, Eric Reginald.
Milner, William Stanley.
Minshull, Oliver Ward.
Mitchell, Ernest James William.
Mitchell, James Earnshaw.
Morgan, Conway Frederick John.
Morgan, William Reginald.
Mortlock, Joseph Ronald.
Moxon, Thomas.
Muir, Donald Somerville.
Mukhopadhyay (Mukherji), Radha Gobinda.
Murray, Cyril.
Myers, Anthony Joseph.
Myers, Clifford.
Myers, Frederick Horace Edwardes.

From Student to Graduate—continued.

Nash, Alfred James Lester.
Nash, Walter Adlington.
Neale, Alan Henry.
Nurse, Arthur Philemon.
O'Dea, William.
O'Dell, Arthur John.
Offord, William John.
Ogilvie, George Parry.
Oldfield, Norman.
Oliphant, William Douglas.
Oman, George Rendall.
Osborne, Charles Percy.
Osman, Abdelsalam Ahmed.
Pack, Stanley Walter Croucher.
Paige, Henry Hodson.
Palmer, Wilson.
Park, Robert Thomas.
Parker, Arthur Jack.
Parker, John Elliss.
Parkinson, Dawson.
Parnell, Cyril Horace.
Parsonage, John Frank.
Parsons, David Cyril Andrew.
Partridge, Thomas Henry.
Patel, Jethalal Chunilal.
Patel, Nathubhai Kahanjibhai.
Patel, Shivabhai Purushottamdas.
Paton, James Steele Park.
Peachey, Francis Arthur.
Pearce, Fred Esmond.
Pearce, Richard Randle Spencer.
Peasgood, Harold.
Peebles, George James.
Pendlington, Laurence.
Perkins, William Stanley.
Peters, Frank Martin.
Peters, James Eadie.
Pheazey, Frank Gerald.
Phillips, Leonard Hamlyn James.
Pienne, Adolphe Charles Georges.
Pierce, David Francis.
Pilcher, Cecil Walter.
Pilcher, Richard Hessey.
Pilling, John.
Pinto, Cyril Alexander.
Pirie, John Henderson.
Pizzey, James Herbert.
Plumbly, Richard William.
Potier, Oscar Norberto.
Pountney, Cyril Graham.
Pratt, William Thomas.
Price, Ernest Maurice.
Priestley, Frank.
Prince-Stevenson, Wilfred.
Prockter, Colin Edward.
Quayle, Joshua Creer.
Quvaishi, Mohd Abdullah.
Raahauge, George Alfred.
Raven, Leonard.
Ray, Susil Chandra.
Raymond, Matthew.
Reading, Joseph Lewis.
Reay, Cuthbert Ernest.
Reith, Ewart Laurence.
Reynolds, Edward George.
Rhodes, Cecil.
Richardson, George Gill Scott.
Ricks, Bertie William.
Rishworth, John Henry Fleming.
Ritchie, Henry Wilfred.
Roberts, Alwyn.
Roberts, Frank.
Roberts, George Albert.
Roberts, Hubert.
Roberts, Leonard Craig.
Robertson, Alexander Myron.
Robson, Henry.
Robson, Oswald Leonard.
Rogers, Frederic William.
Rowson, Robert Bryan.
Roynon, Frank Goodner.
Rufener, Eric Charles Moritz.
Rutherfurd, William Gordon.
Rutter, Gordon.
Ryburn, Raymond Steadman.
Sabherwal, Behari Lal.
Sadler, Ernest Henry.
Samphier, Leonard Ralph Gattcomb.
Schou, Gaston Recardo.
Schumacher, Charles George.
Scorrer, James Leonard.
Scott, Eric Ronald.
Scott, Eric Walter Marbury.
Sell, Richard Geoffrey.
Sercombe, Donald John.
Seymour, Norman.
Shackleton, Herbert.
Shah, Chandulal Trikamlal.
Sharples, John Thomas.
Shepherd, William Raymond.
Shroff, Soshil Rattan.
Shuffrey, Leonard Bentley.
Singh, Iqbal.
Singh, Jagjit.
Sirajuddin, Aslam Walter.

From Student to Graduate—continued.

Skinner, Charles Henry Walter.
Slade, Alexander Henry.
Smith, Douglas Macleod.
Smith, Frank Jervis.
Smith, Frederick Carwardine.
Smith, George Cruickshank.
Smith, Hugh John Casement.
Smith, James Russell.
Smith, John Reginald P.
Smith, Leslie.
Smith, Thomas Haworth.
Smith, Walter William.
Smyth, John Henry.
Smyth, Maurice Carlton Joseph.
Soi, Manmohan Nath.
Spear, John Edmund.
Spooner, Gerald William.
Stamford, Norman Charles.
Stanesby, Harold.
Stanton, William Alfred.
Steel, Walter Scott.
Stephens, George Montagu.
Stephens, Rupert Douglas.
Stevens, Charles Cyril.
Stevens, Sydney Arthur.
Stewart, Donald Arnott.
Stewart, Franz Schubert.
Stirrup, Reginald Brade Clark.
Storie, Robert Pow.
Strong, James Godwin.
Sturley, Kenneth Reginald.
Sugden, Eric William.
Summerfield, John Kynaston.
Summers, Eric George.
Sutton, Percy William.
Tabb, Richard Prestridge Edward.
Tanner, Ernest Basil Thornton.
Tannett, Anthony.
Tatham, Francis Everard.
Taunton, Robert Dixon.
Taylor, Cecil William.
Taylor, Ernest.
Taylor, John.
Taylor, William.
Temple, Frank Robert.
Thomas, Alfred Humphrey.
Thomas, Trevor Idris Henry.
Thompson, John Stevenson.
Thomson, George.
Thornley, Ernest Joseph.
Thornton, Cyril.
Till, Arthur James.
Tompsett, Francis John.
Tonkinson, William Eric Llewelyn.
Tregenza, Ernest Tutin.
Twiss, Joseph Mort.
Tyrer, Alan Richard.
Tyson, Lubbock Temple Ismay.

From Student to Graduate—continued.

Van Meeteren, Edward Henry.
Veevers, John Foster.
Venables, Albert Henry.
Vigoureux, Joseph Evenor Paul Louis.
Vines, Murray.
Vinten-Fenton, Charles Victor.
Vivian, George Edward.
Waddle, Robert Alfred.
Wade-Cooper, Frederick.
Wagstaff, William Percy.
Wakerley, Wallace Reginald.
Walker, Egbert Ernest.
Wall, Ronald.
Walsh, John Joseph.
Walton, Ernest Charles.
Walton, Frank Edward.
Warburton, John Henry.
Ward, Frank Rogers.
Wardle, Paul Gabriel.
Warren, Sidney Harvey.
Waters, George.
Waters, Malcolm.
Watts, George Ernest.
Webb, Allen Ashard.
Webb, Anthony.
Webb, Cyril George.
Wellard, William John Francis.
Weller, Herbert Lewis.
West, Francis Richard Joseph.
Wheeler, George James.
White, Jack.
White, Walter.
Whiteley, Claude Stuart.
Whitelock, George.
Whittome, Philip.
Whyte, William Langlands.
Widdup, Francis Alan.
Wilde, Samuel Francis.
Wilkins, Arnold Frederic.
Wilkinson, Charles George Eric.
Wilkinson, Eric.
Wilkinson, Kenneth James Rawcliffe.
Williams, Hugh Laity.
Williams, Robert Charles Gooding.
Williamson, David Blair.
Willis, Albert Henry.
Willis, William Roby.
Wills, William Henry.
Wilman, Donald.
Wilson, Eric.
Wilson, James.
Wood, Albert Gallatin.
Wood, Basil.
Woodbridge, Arthur William.
Woods, Reginald Arthur.
Wort, Frederick William.
Wrathall, Eric Thomas.
Wright, Henry Joseph.
Yarwood, Henry Ivens.
Yeo, Reginald Arthur.
Young, Norman James.

THE ANALYSIS AND MEASUREMENT OF THE NOISE EMITTED BY MACHINERY.

By B. A. G. Churcher, Member, and A. J. King, Associate Member.

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Summary.

The paper deals with part of a comprehensive investigation which is being carried out by a manufacturer of electrical plant on the noise emitted by machinery and other apparatus, a subject of great present and future importance. The need for treating the subject in a thorough and quantitative manner for engineering purposes is pointed out. The physical magnitudes involved in the measurement of the sound set up by a vibrating body are discussed generally, together with the characteristics of the ear. The characteristics that should be possessed by a sound-measuring apparatus intended for use in engineering problems are pointed out and a brief survey is made of existing types of apparatus. The principle, development and final form of the apparatus, which enables a complete analysis of a complex sound to be made, are described, together with the methods employed to verify the accuracy of the apparatus. The influence of the conditions under which sound measurements on engineering apparatus are carried out is discussed, and a special laboratory which has been set up for acoustical work is described. Some sound-test results on engineering apparatus are given as examples.

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List of Symbols.

A = strength of sound source in terms of maximum rate of emission of fluid (cm^3 per sec.).
a = area of diaphragm (cm^2).
B = flux density (lines per cm^2).
β = elastic restoring force (dynes for 1 cm displacement).
K_1 = Rayleigh disc constant.
d = linear deflection on scale.
E = maximum instantaneous e.m.f. (volts).
e = R.M.S. volts.
F = damping resistance (dynes for velocity of 1 cm per sec.).
f = frequency, in cycles per sec.
I = current, in amperes.
θ = angle between normal to Rayleigh disc and axis of tube.
$K_2 = NB \times 2\pi r \times 10^{-8}$; also mA/mV/mH.
$k = \omega/v = 2\pi/\lambda$.
L = inductance.
d_1 = distance from scale to mirror.
l = length of suspension (cm).
λ = wavelength (cm).
M = mutual inductance (henrys).
m_t = total mass of diaphragm.
m = correction factor for microphone dimensions.
N = number of turns on coil.
P = maximum value of alternating air pressure.
p = R.M.S. excess pressure (dynes per cm^2).
R = electrical resistance (ohms).
r = radius (cm) of sphere surrounding source of sound or distance from centre of source to sound detector.
r = radius of disc.
r_0 = radius of source of sound (cm).
ρ = density of air.
S = microphone sensitivity.
$\mathbf{T}_\mathbf{R}$ = restoring torque, in dyne-cm per radian per cm.
$\mathbf{T}$ = torque (dyne-cm).
t = time (secs.).
v_d = velocity of translation of diaphragm (maximum).
v = velocity of sound in air (cm per sec.).
v_0 = velocity at 0° C.
V = maximum air velocity.
W = average power per cm^2 at surface of sphere surrounding source (ergs per sec. per cm^2).
x = displacement (cm).
x = ratio of thickness to diam. of Rayleigh disc.
x = fractional frequency change.
Z = impedance (ohms).
$\omega = 2\pi f$.

(1) Introduction.

The work described in this paper was initiated in September, 1926, by a company engaged in the manufacture of electrical plant, with the object of attacking in a thorough and comprehensive manner the problem of the noise emitted by motors. Apart from the question of particular motors which may be considered to be too noisy, a definitely higher standard in respect of quiet running in motors in general is greatly to be desired. Although the need for the reduction of noise in motors led to the initiation of this work, the noise problem arises in many other types of engineering apparatus. Examples are transformers and integrating meters for domestic use, large generators and converting plant, gears and other mechanical apparatus. The technique and measuring apparatus developed in connection with sound tests on motors are also directly applicable to the other classes of apparatus. A considerable amount of useful work has been done on geared turbo sets as well as on motors. The apparatus can also be used for the quantitative determination of the characteristics of loud-speakers. There are other applications, many of which are outside the normal activities of the company.

It is necessary to be able to assess the noise emitted by a machine, for two main purposes: (*a*) to ascertain whether the noise is in excess of that desirable or permissible according to some definite standard, and (*b*) to ascertain the cause of the noise with a view to modifying or reducing it.

It has been suggested that as it is ultimately the ear which judges whether a machine is excessively noisy or not, there is no advantage in employing elaborate apparatus to measure noise. That this is not the case can be shown by the following considerations. Suppose a person is asked to listen to a machine for purpose (*a*). If he merely says that the noise is or is not excessive, his judgment will satisfy no one but himself and he will be asked to be more explicit. To be more explicit he must consider the noise in the two aspects of pitch and intensity or loudness. The average unmusical person can only express his sense of the pitch of simple sounds by such terms as very low, low, high, very high and so forth. On the other hand, some musicians have a keen sense of absolute pitch and can judge the pitch of an isolated note to within a semitone, i.e. to within 5 per cent. That is, however, a rare accomplishment. Then in regard to the all-important question of loudness, the sense of loudness of simple sounds can only be vaguely expressed by saying that the sound is moderate, loud, very loud and so forth. In practice, the sounds emitted by machines are nearly always complex in character, that is, several pitches are present simultaneously. It is then usually very difficult to pick out the pitches of the several components unless a few are particularly prominent, and it becomes even more difficult to judge loudness.

Thus, while the ear is an exceedingly sensitive and discriminating detector of sounds, it cannot yield the quantitative information required for purpose (*b*). As with other engineering quantities, it is necessary to deal with sound on a basis of measurement in terms of a definite standard rather than on the basis of the opinions of individuals. While physical quantities must be the medium by which sounds are measured and represented, the physiological aspect of the matter, namely, the susceptibility of the average ear to sounds of different kinds, must be given due consideration. This is particularly important when considering limits for the sound it is permissible for a piece of engineering apparatus to emit. Such limits must, of course, be fixed with reference to the physiological effect produced by the sound, and in that sense the average ear constitutes the fundamental standard. Physical measurement is necessary, however, in order to obtain quantitative results, to eliminate the vagueness of individual judgment, and to analyse complex sounds. In common with other physical measurements, it is a great advantage if the results can be expressed in absolute units under clearly defined test conditions, rather than in arbitrary units associated with some particular test method or apparatus. If this is achieved, the use of different types of apparatus by different investigators does not prevent their results being compared.

(2) General Considerations.

The occurrence of sound involves the action of three elements, the sound generator, which is essentially a vibrating body, the transmitting medium and the sound detector. In the problem of noise measurement, the sound generator consists of the apparatus under test, the air is the transmitting medium, and the ear or the acoustic element of a sound-measuring apparatus constitutes the sound detector. Suppose the source of sound consists of a small sphere which pulsates (expands and contracts) with simple harmonic motion by a small amount above and below its mean radius. Suppose that the sphere is placed in infinite space and no other bodies are present. The pulsating sphere sends out simple harmonic pressure waves in all directions, the length of the waves being equal to $\lambda = v/f$, where v is the velocity of sound in air and f is the frequency of the pulsations. If a detector is placed in the sound field so that it may be acted upon by the incident pressure waves, the moving element of the detector, e.g. a diaphragm, will be set in vibration by the alternating air pressure. The amplitude of the vibration will depend on the distance separating the source and the detector; the greater the distance, the smaller is the amplitude.

Let r_0 be the radius of the sphere, ρ the density of the transmitting medium, and $v_{max.}$ the maximum value of the pulsating velocity of the surface of the sphere.

The velocity potential at a distance r cm from the centre of the sphere is given by *

$$\phi = \frac{r_0^2(1 - ikr_0)v_{max.}}{r(1 + k^2r_0^2)} e^{i[\omega t - k(r - r_0)]}$$

where $\omega = 2\pi f$

and $k = 2\pi/\lambda$.

The pressure at a distance r cm due to the pulsating sphere is

$$p = \frac{\rho d\phi}{dt} = \frac{\rho\omega r_0(kr_0 + i)v_{max.}}{r(1 + k^2r_0^2)} e^{i[\omega t - k(r - r_0)]}$$

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* See Bibliography, (5), p. 121.

It is easy to show that the maximum value of this pressure, which oscillates with a frequency f, is

$$P = \frac{\rho\omega r_0^2 v_{max.}}{r\sqrt{[1 + k^2 r_0^2]}}$$

If we call A the strength of the source and define it as the maximum rate of emission of fluid from the source, $A = 4\pi r_0^2 v_{max.}$ cm^3 per sec.

The expression for P then becomes

$$P = \frac{A\rho\omega}{4\pi r\sqrt{[1 + k^2 r_0^2]}} = \frac{A\rho f}{2r\sqrt{[1 + k^2 r_0^2]}} \quad . \quad (1)$$

If r_0 is small compared with λ, then kr_0 is small and we have

$$P = \frac{A\rho f}{2r} \text{ dynes (max.) per cm}^2$$

In the case of transmission in air, the density ρ is 0·00122 gramme per cm^3 at 15° C. and 76 cm pressure.

$$\therefore P = \frac{0{\cdot}00061\,Af}{r} \text{ dynes (max.) per cm}^2$$

The velocity with which the disturbance is propagated from the source in air is given by

$$v = \sqrt{\left[\frac{\gamma Q}{\rho}\right]}$$

where γ = ratio of specific heats of air = 1·401, and
Q = pressure of the air, in dynes/cm^2.

It follows from this relation that the velocity is independent of the air pressure (since $Q \propto \rho$).

It is also easy to show that the variation in velocity with temperature is given by

$$v = v_0 + 61t$$

where v_0 = velocity at 0° C. = 33 130 cm per sec.
and t = temperature of the air, in deg. C.

For t = 15° C., therefore, v = 34 050 cm per sec.

Referring to equation (1) it is seen that as one moves away from the source the sound pressure varies inversely as the distance from the centre of the source.

The energy in a sound wave of maximum pressure P dynes/cm^2 is given by $W = \frac{1}{2}\cdot\frac{P^2}{\rho v^2}$ ergs/cm^3, so that the rate at which energy is flowing outwards through unit cross-section at a distance r from the centre of the source is given by

$$\frac{1}{2}\cdot\frac{P^2}{\rho v} \text{ ergs/cm}^2\text{/sec.} \quad . \quad . \quad . \quad . \quad (2)$$

This is to be expected, since, in the absence of energy absorption in the transmitting medium, the total power radiated is constant and independent of r, while the power per unit area of a spherical surface of radius r varies inversely as r^2. From equation (2) an idea of the magnitudes involved may be obtained. A pressure of 1 dyne per cm^2 corresponds to a fairly loud sound. The steady atmospheric pressure is approximately 1 million dynes per cm^2, so that a sound pressure of 1 dyne per cm^2 corresponds to a pulsation of 1 part in 1 million of the steady pressure. It is seen that the energy associated with this sound pressure is only 10^{-9} watt per cm^2, so that a very sensitive apparatus is required to detect sounds of low intensity. It is also seen that the power varies as the square of the pressure. It will be shown later that the range of pressure that the ear can perceive as sound is of the order of 10^6 to 1. Hence the corresponding power range is 10^{12} to 1. It is easier to grasp the significance of magnitudes occurring in the smaller range than in the larger, so that the authors have adopted the expression of sound intensities in terms of sound pressure rather than of sound energy. The unit chosen is the R.M.S. dyne per cm^2 at a specified distance from the sound source. So far it has been assumed that the sound generator emits waves of sinusoidal form. In practice, however, machinery almost always emits a complex sound wave. In some cases the wave-form is of very great complexity and, unlike the e.m.f. wave-forms of dynamo-electric machinery, the component frequencies are not necessarily simple multiples of a fundamental frequency. The analysis of these complex waves into their constituents is essential in the study of the factors giving rise to noise in machinery. The apparatus described later measures the frequency and pressure intensity of each component of a complex sound wave. In sound, as in other cases of wave motion, the principle of superposition holds for ordinary amplitudes; that is, the resultant instantaneous pressure at a point in a sound field is equal to the sum of the instantaneous component pressures at that point. The discussion in this section based on sinusoidal sound waves can therefore be applied to each individual component of a complex wave, and the sound emitted by a machine expressed as the pressure intensity and frequency of each component at a specified distance from the machine, certain other test conditions, which will be dealt with later, being observed.

(3) The Characteristics of the Ear.

The literature of this subject is considerable. Lord Rayleigh * investigated the lower limit of audibility for different frequencies, viz. the intensities that were "just easily audible." He found that if the limit of audibility at 50 cycles per sec. was denoted by unity, the intensity at 200 cycles was 0·13 and at 1 000 cycles 0·05. Wegel,† using more refined methods, measured both the upper and lower limits of audition. Fig. 1 is reproduced from his paper. The lower full-line curve represents the average minimum audibility for 72 normal ears. It is seen that the greatest sensitivity occurs at a frequency of 3 000 cycles per sec. and that the intensity is of the order of 0·0005 dyne (R.M.S.) per cm^2. The dotted curves on either side of the average curve give the approximate deviation from the average that may be expected among persons having normal hearing. The upper limit of audition is the intensity at which hearing merges into feeling. The upper limit is the threshold of feeling, in the same way that the lower limit is the threshold of hearing. Wegel states that near the upper limit the feeling is first a tickling sensa-

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* See Bibliography, (14).

† *Ibid.*, (20).

tion and then becomes acutely painful as the loudness is increased. From the maximum audibility curve in Fig. 1, which was based on 48 normal ears, it is seen that the greatest intensity that can be perceived as hearing is of the order of 5 000 dynes per cm^2 and occurs at a frequency of about 700 cycles per sec. At the upper and lower frequency limits where the curves intersect, it is difficult to distinguish between hearing and feeling. The upper limit is about 20 000 cycles per sec. and the lower about 20 cycles per sec. The sensation of feeling rather than hearing which proceeds from the 32-ft. pipe of an organ, which has a fundamental frequency of about 17·4 cycles per sec., is well known.

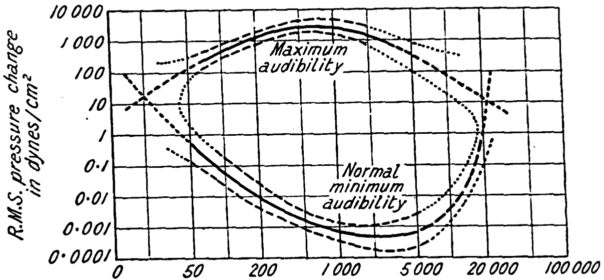

FIG. 1.—Frequency sensitivity of the ear.

So far we have considered the sensibility of the ear in regard to the limits of audibility. It is obviously difficult to construct machinery that will not emit sounds having intensities above the lower limit of audibility. The desired quantity is the value of the sound intensity which may be considered objectionable, due attention being given to the circumstances under which the sound is produced. From this standpoint the sensibility of the ear to sounds of ordinary, and not extreme, intensities and frequencies may be more pertinent. In a very able paper, Knudsen * deals with this aspect of the subject. He determines first how the sensibility of the ear to small changes in intensity varies with the loudness and pitch or frequency of the sound, and secondly how the sensibility of the ear to small changes in frequency varies with loudness and frequency. The "intensity sensibility" is expressed as the ratio of the smallest perceptible change in the energy of a note to the total energy of the note. As the authors prefer to work in sound pressure rather than energy, they will express the intensity sensibility as $\Delta p/p$. Similarly, the frequency sensibility is expressed as $\Delta f/f$. The experimental determination of these quantities, which it is unnecessary to discuss here, was carried out with great skill and refinement. The way in which the intensity sensibility varies with pressure is shown in Fig. 2. At a frequency of 100 cycles per sec. the intensity sensibility is seen to be relatively small for low intensities but increases rapidly when the intensity is increased to 1 dyne per cm^2. Above this value it becomes constant. Similarly, at 200 cycles per sec. the sensibility becomes constant for intensities above about 0·25 dyne per cm^2, and at 1 000 cycles per sec. above about 0·06 dyne per cm^2. The important point to notice is that the curves for all three frequencies converge to nearly the same value. For intensities above about 0·25 dyne per cm^2 the sensibility is very nearly independent of intensity and frequency over a frequency range of 100 to 1 000. Fig. 3 shows the intensity sensibility as a function of frequency. The curve was taken on a basis of a constant "loudness" of 100 times the threshold value. Taking Wegel's threshold values, this would correspond to pressures (R.M.S. dynes per cm^2) of about 5 at 100 cycles, 0·8 at 200 cycles, 0·2 at 500 cycles, 0·08 at 1 000 cycles and 0·06 at 2 000 cycles per sec., which are within the practically important range. It is seen that on this basis the average sensibility (of 19 ears in this case) is almost constant at the value 0·05 over the whole frequency range of 100 to 3 200 cycles. The curves marked "maximum" and "minimum" show the order of variation that may be expected among persons having normal hearing. Measurements up to 12 000 cycles per sec. showed that $\Delta p/p$ increases to about 0·1 at that frequency. Fig. 4 shows how the frequency sensibility varies with frequency. The intensities employed in these tests were 100 times the threshold intensities. It is seen that, while the ear can only detect a change in pitch or frequency of 1 per cent at 100 cycles, it can detect a change of $\frac{1}{3}$ of 1 per cent at frequencies above 800. The perception of a small change in frequency is, of course, an entirely different matter from the judging of the absolute pitch or frequency. This, as we have seen, can only be performed, even by a skilled musician, to an accuracy of about 5 per cent. Knudsen has also carried out observations on the effect of quality on the intensity sensibility of the ear, i.e. on the effect of adding harmonics to the fundamental on the value of $\Delta p/p$.

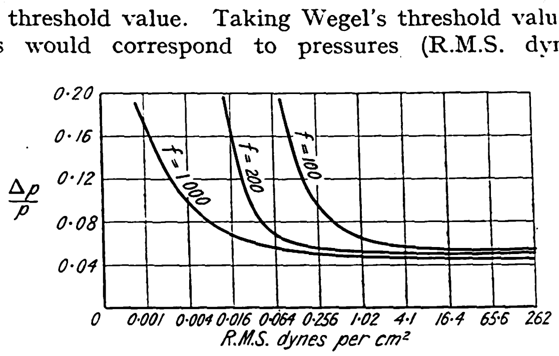

FIG. 2.—Intensity sensibility.

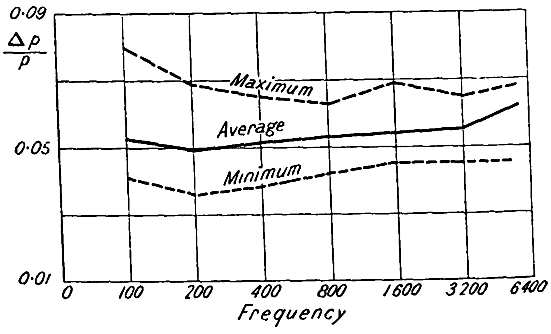

FIG. 3.—Intensity sensibility. Variation with frequency for constant "loudness."

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* See Bibliography, (17).

He concluded that the intensity sensibility is almost independent of quality. More recent work by R. R. Riesz[*] yields results in general agreement with those of Knudsen.

It may be noted here that it is the generally accepted view that in a steady complex sound wave the response by the ear is independent of the phase relation between the component frequencies. That this is very probably true can be seen when it is remembered that the degree of constancy of the component frequencies in a complex sound wave is seldom, if ever, such as to preserve a fixed phase relationship between them. In view of this unimportance of phase the apparatus and experimental procedure necessary in analysing a complex sound wave are very much simplified.

A discussion of the characteristics of the ear is useful in considering the qualities that have to be possessed by an apparatus suitable for general sound measurements on machinery, and it will be well to consider this matter briefly before discussing particular types of measuring apparatus.

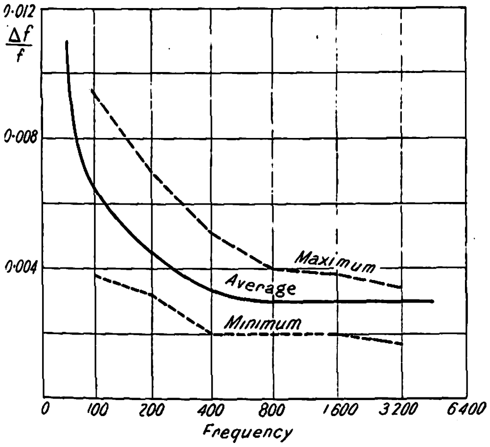

FIG. 4.—Frequency sensibility.

With regard to sound pressures, measurements have to be made on certain apparatus, such as integrating meters and transformers for domestic use, at pressures not very greatly in excess of the threshold values. On other apparatus, such as motors and heavy machinery, values of 1 000 or 10 000 times the threshold values may be reached. The measuring apparatus must therefore be sufficiently sensitive to detect the smallest intensities and yet have sufficient range of adjustment to be able to deal with the largest intensities. As regards the accuracy desirable in pressure observations, the relative accuracy of the measurements for ordinary intensities need not exceed 5 per cent and the absolute accuracy, say, 20 per cent, seeing that under favourable conditions the ear cannot detect a smaller pressure change than 5 per cent. With regard to frequency, the most generally important range is from 100 to 2 000 cycles per sec., and it is desirable to be able to take observations at any frequency from 25 to 5 000 cycles. Since the main object in measuring frequencies is to identify the source of each component of a complex wave, an accuracy of 1 per cent in the frequency observations is an advantage as it enables a distinction to be made between two components which do not differ greatly in frequency.

Table 1 may be of assistance in forming a conception of the relation between pitch, frequency and wavelength.

TABLE 1.

Source of sound	Fundamental tones	
	Frequency	Wavelength *
	cycles per sec.	cm
Highest pitch on pianoforte ..	3 520	9·7
"Middle" C of pianoforte ..	256	133
Lowest pitch of pianoforte ..	26·8	1 270
2-ft. pipe of organ	278	122
8-ft. pipe of organ	69·5	490
32-ft. pipe of organ	17·4	1 950
Note from 50-cycle electrical apparatus	100	340

* Velocity = 34 050 cm per sec.

(4) AVAILABLE SOUND-MEASURING APPARATUS.

We have seen from the previous Section that for engineering purposes we require an apparatus that will measure sound pressures in absolute units over a range of at least 100 to 2 000 cycles per sec. and deal with sound intensities ranging from very feeble to very loud sounds. In addition, the apparatus must be capable of reasonably rapid operation and also of measuring transient as well as steady sounds. In this connection it may be pointed out that, in dealing with transient sounds, some sort of graphical record, such as an oscillogram, is necessary. The sound-measuring apparatus, when of an electrical type, must therefore be capable of actuating an oscillograph when required. For steady sounds, however, oscillograms should be avoided owing to the complexity of the sound waveforms usually obtained from machinery. The analysis of these wave-forms into their components by graphical methods is a very slow and laborious process, while in many cases the wave-form is so complex as to make graphical analysis impracticable. For accurate work the direct measurement of the frequency and amplitude of each component in turn is essential. The apparatus must also be capable of being used in a works, where it may have to be put down on a rough bench and where a fair amount of vibration and electrical disturbance may be present. It must also be reasonably portable and not liable to suffer damage with ordinary handling in transit. It is not proposed to discuss in detail the various types of measuring apparatus that have been evolved. There are several instruments capable of measuring the frequencies of sounds with a fair accuracy, provided the sound wave is not very complex in character. An expedient that used to be adopted some years ago for estimating the frequency of a note emitted by a machine was to get some musical member of the staff to produce a note of equal pitch on a violin and, from the note known to correspond to the observed position of the finger on the string, to obtain the frequency. Another apparatus that has been used is a metal tube of variable length fitted with an ear-piece. The tube is adjusted until the air column it contains is in resonance with the incident sound wave, the resonance point being judged by listening in the ear-piece. While these methods, which have the great advantage of simplicity, are capable of determining the frequency of a prominent note, they give no information in regard to intensity. A simple method of obtaining a rough measure of the relative intensity of sounds of the same quality is to couple a telephone transmitter, located near the machine to be tested, to a telephone receiver placed in a fairly soundproof enclosure. The sound of the machine will be heard in the receiver and, by shunting the latter with a resistance box, the resistance required to make the sound in the receiver just inaudible can be observed. If, now, the intensity of the sound is changed, a new value of resistance for inaudibility is found. A rough measure of the relative intensities in the two cases can then be obtained from the plug-box resistance and the impedance of the receiver. The reference point used in these measurements is, of course, the threshold intensity for the observer's ear. The results are only relative so long as the sound is constant in quality, which makes the utility of the method very limited.

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[*] See Bibliography, (19).

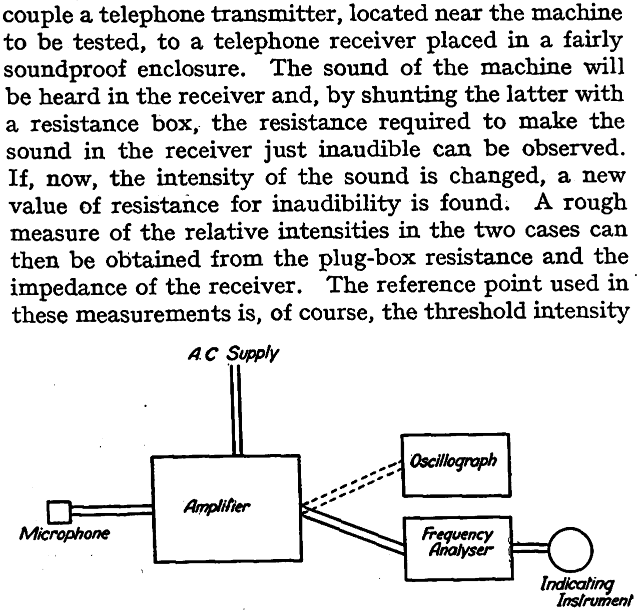

FIG. 5.

Turning now to the more ambitious methods, it is found that, broadly speaking, the methods which yield sound intensities in absolute measure are suitable only for laboratory use on account of the delicate apparatus required. Examples of absolute methods are the Rayleigh disc and the radiation pressure method. While these methods are not directly applicable to measurements on engineering apparatus, they are of great importance as absolute laboratory standards and will be discussed later in connection with the calibration of testing apparatus. Many instruments have been devised with the object of providing a simple and portable means of measuring sound. For quantitative work these instruments unfortunately suffer from one or more serious limitations. Some of them give indications in the form of a trace of the sound wave on a photographic film, which, as we have seen, is difficult to utilize for quantitative purposes. Others, especially those of the non-electrical type, employ horns and sharply resonant diaphragms, which cause the indications for a given sound intensity to vary widely and in a complicated manner with frequency. This characteristic, when embodied in an instrument which gives graphical indications, naturally causes an excessively distorted picture of the sound wave to be obtained. Another difficulty with the non-electrical types of apparatus is that the whole apparatus has to be placed in the sound field and the dimensions of the apparatus may be such as to cause serious distortion of the sound field even at comparatively low frequencies.

Electrical methods have much greater possibilities than purely mechanical methods so far as the completeness and precision of the results obtainable are concerned, and the large range of frequency and intensity that can be covered. These considerations have led the authors to concentrate on electrical methods and to develop the apparatus described in the next Section.

(5) AN ELECTRICAL SOUND ANALYSER.

(*a*) *General Principle.*—The apparatus consists essentially of a microphone which generates an e.m.f. having a known relation to the incident sound pressure, an amplifier of known characteristics, which amplifies the microphone e.m.f., and some means of measuring the complex electrical wave-form of the amplifier output. This is illustrated schematically in Fig. 5. One method of dealing with the amplified voltage of the microphone is to take an oscillogram of it. The microphone-amplifier-oscillograph combination has been used by several investigators for obtaining the frequencies of prominent components of sound wave-forms, but its use for the quantitative measurement of intensities has received very little attention. As previously pointed out, the difficulty of analysing graphically an oscillogram of a complex wave is a serious disadvantage of the use of an oscillograph, so that while we have made the method available its use is confined to transient sounds or to cases where a picture of the sound wave is desirable. It may be pointed out that in order to obtain a true record of the sound wave the instantaneous output voltage from the amplifier must at every instant be proportional to the instantaneous sound pressure. To secure this, the R.M.S. e.m.f. generated by the microphone per unit R.M.S. sound pressure must be independent of frequency and pressure, a characteristic very difficult to obtain in practice. In addition, the amplification factor of the amplifier must be independent of frequency and applied e.m.f. over the material range. This latter condition can be obtained without great difficulty. The other method of dealing with the amplifier output is to measure the frequency and amplitude of each of the components in turn by means

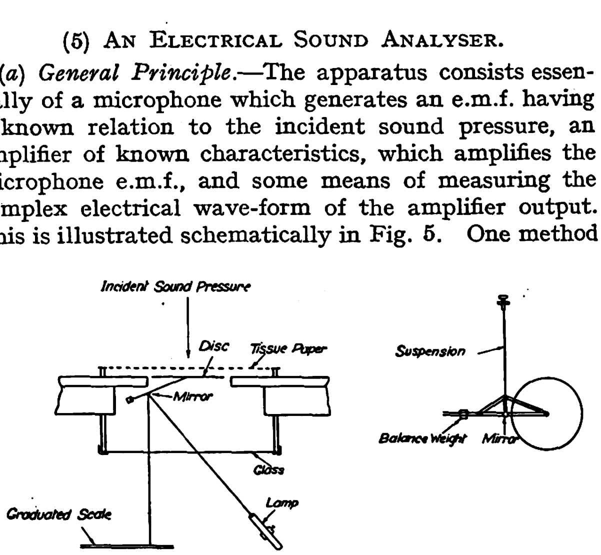

FIG. 6.—Apparatus for radiation pressure measurements.

of an electrical frequency analyser. By making the required measurements directly, this method eliminates the analysis of complex oscillograms and so obtains the values of frequency and amplitude with far greater accuracy than can be obtained by inspection of a non-periodic curve to which the ordinary rules of analysis do not apply.

Two sets of apparatus have been constructed. The original or No. 1 apparatus was largely experimental and was built before some of the many conditions which it is necessary to fulfil were fully appreciated. It will, therefore, be described very briefly. The No. 2 improved apparatus is described in detail in Section (7).

(*b*) *Considerations of the Microphone Characteristic.*—The first type of microphone contemplated for this work was the moving-coil cone type with permanent-magnet field. The great attraction of this type of microphone for quantitative work is the possibility of obtaining an instrument of permanent and calculable sensitivity and so avoiding the difficult problem of absolute calibration. Consider such a microphone under the action of an alternating air pressure.

Let m_t = total mass in grammes of the moving coil and cone;
a = effective area of the cone;
F = damping resistance in dynes per cm per sec.;
P = maximum value of the alternating air pressure;
v_d = maximum value of the alternating velocity of the cone;
x = displacement of the cone from its mean position of rest;
β = restoring force per cm deflection due to the cone support.

Then $$\frac{m_t d^2x}{dt^2} + \frac{Fdx}{dt} + \beta x = Pa\cos\omega t$$

from which $$\frac{dx}{dt} = \frac{Pa\sin\omega t}{jF + \left\{\omega m_t - (\beta/\omega)\right\}}$$

When the natural frequency of the suspended cone and coil is very low, say less than 15 per sec., the transient term is of no importance and ωm_t is large compared with β/ω over the working frequency range. If the friction term F is small compared with ωm_t we can write for the maximum velocity of the system

$$v_{m_t} = \frac{Pa}{\omega m_t} \text{ cm per sec.}$$

If, however, the damping force F is made to preponderate over $\left\{\omega m_t - (\beta/\omega)\right\}$ we have

$$v_F = \frac{Pa}{F}$$

Let the voltage generated by the moving coil per unit velocity be denoted by K_2 volts per cm per sec.

Then $K_2 = NBr \times 2\pi \times 10^{-8}$ volts per cm per sec.

where N = number of turns on moving coil,
r = radius of moving coil, and
B = average flux density in the air-gap.

The maximum voltage generated by the mass-controlled microphone is therefore given by

$$E_{m_t} = \frac{PaK_2}{\omega m_t} = \frac{PaNBr \times 10^{-8}}{fm_t} \text{ volts (max.)}$$

For the friction-controlled system the corresponding voltage is

$$E_F = \frac{PaK_2}{F} = \frac{PaNB \times 2\pi r \times 10^{-8}}{F}$$

Comparing these two equations for the voltage generated by the two types of microphone it is clear that the first one consists entirely of perfectly definite quantities which can be measured with considerable accuracy. In the second, however, the friction term F is very difficult to measure and cannot be pre-determined with any accuracy.

The great advantage, therefore, in making the mass effect preponderate over the other controlling forces is that it is possible to calculate the velocity of the diaphragm, and therefore the voltage generated by the moving coil, for a given incident sound pressure, knowing the constants of the system and the frequency of the incident pressure wave. There are, however, two disadvantages which have led the authors to use a microphone of a different type. Firstly, the use of a large mass to extend the useful range of the microphone to very low frequencies has the immediate effect of reducing the sensitivity at all frequencies. Secondly, the measurement of a small high-frequency sound and a large low-frequency rumble (a common combination) on the same apparatus is rendered difficult unless some form of frequency correction is interposed between the microphone and the amplifier. If an oscillographic record is being taken, the large low-frequency sounds, augmented by the high sensitivity of the microphone, give large amplitudes on the film, while the small high-frequency sounds, reduced by the low sensitivity of the microphone, give amplitudes too small to measure. Difficulty is also experienced when a frequency analyser is used, owing to limits on the maximum permissible amplification imposed by the last valve of the amplifier and the large low-frequency voltages generated by the microphone. To correct this unfortunate characteristic of the microphone the amplifier can be arranged to give an amplification proportional to frequency by using, for example, a suitably proportional mutual inductance to couple the first two valves of the amplifier. The overall sensitivity of the combined amplifier and microphone is then independent of frequency over the working range.

A complete apparatus on the above lines, consisting of a mass-controlled microphone, a 3-stage resistance-coupled amplifier with an additional frequency-correcting stage, power valves and output transformer, and a tuned-circuit frequency analyser, has been designed and made. As the apparatus was purely experimental and was built before all the operating difficulties were fully appreciated, the description is a general one. A more detailed discussion of apparatus design will be given in connection with No. 2 apparatus.

(*c*) *No.* 1 *Apparatus.*

The Microphone.—The magnet system is of the now familiar permanent-magnet pot type, having 8 magnets of cobalt steel. The gap density, as measured by a search coil of the same dimensions as the moving coil, was found to be 7 000 lines per cm^2. The diaphragm consisted of a 90° cone made from Bristol-board. The coil had 680 turns of 0·002 in. diam. enamelled copper wire with a mean diameter of 2·05 cm. The voltage constant, K_2, of the system is therefore 0·307 volt per cm per sec. The mass of the diaphragm and coil was originally 3·72 grammes and the effective area 64 cm^2, so that the sound sensitivity when mass-control operated was $0 \cdot 84/f$ volts per dyne per cm^2. The instrument was mounted in a bakelite tube 15 cm diam. and 18 cm long, covered at the back by a sheet of bakelite and loosely packed with cotton waste to prevent internal cavity resonances.

In order to make the amplification proportional to frequency the first valve was mounted in a separate copper-lined box together with its H.T. battery and anode transformer. The latter consisted of two primary coils in parallel and two secondary coils in series, the two pairs being arranged astatically to reduce trouble from stray fields. A non-inductive resistance of 80 000 ohms in series with the primary made the primary current independent of, and the secondary voltage proportional to, frequency up to a frequency of 5 000 cycles per sec. Provision was made for using four stages of resistance-coupled amplification, each in its own copper-lined compartment. Anode resistances of 200 000 ohms and grid leaks of 5 megohms were employed, so that in order to give good amplification at 25 cycles the capacity of the coupling condensers was made 0·01 μF. Two 66-volt dry batteries were accommodated in a compartment alongside the amplifier and supplied the requisite H.T. supply of 120 volts. The valves used had 6-volt filaments and voltage amplification factors of 35. Two power valves in parallel were supplied with 36 mA and 250 volts H.T. from the works' 250-volt d.c. mains, through a smoothing circuit. The combination had a voltage factor of 6 and, with a 3 000-ohm load in the anode circuit, gave 1 mA anode current per grid volt.

In designing the transformer for feeding the oscillograph or analyser, advantage was taken of the low magnetizing force required by certain nickel-iron alloys. This could be done only by filtering the a.c. component of the anode current from the mean value. A high-impedance choke in conjunction with a 10 μF condenser effected the filtering. Several secondary tappings were provided so that, whatever the load impedance, its value referred to the anode circuit would be 3 000 ohms.

A suitable 3-element oscillograph giving accurate records up to 2 000 cycles is available for connection to the output transformer. Records of transient sounds can thus be taken, with the added advantage that other quantities, such as currents or voltages, can be recorded simultaneously and the results correlated.

In considering an electrical frequency analyser, a few calculations based on the use of a single tuned circuit, consisting of an inductance and variable condenser, indicated that the selectivity of such an arrangement would not be good enough unless a large and expensive coil were used. In addition to being expensive a very low-resistance circuit has a very sharp resonance peak, necessitating great constancy in the frequencies being analysed. By using multiple-circuit analysers, the required selectivity can be obtained without the apparatus being highly sensitive to changes in frequency, a point of great importance in engineering testing. While analysers having more than two circuits have theoretical advantages, all that is desired may be obtained with two circuits. In such an analyser, resonance is indicated by adjusting both circuits so that a maximum current flows in the secondary circuit. Subject to certain limitations, which are discussed later in detail, the secondary inductance, capacity and the resonant frequency are then connected by the relation $4\pi^2 f^2 LC = 1$.

(6) METHODS OF CALIBRATION.

In order to be able to make measurements of sound intensity with the apparatus described, it is necessary that each link in the chain from sound energy to the deflection of the final galvanometer should be of known, permanent performance. The units involved in this transformation are the microphone, the amplifier and the frequency analyser or oscillograph. As regards the first, we must know the voltage generated by the microphone when acted upon by a sound of unit intensity at any frequency over the range required for tests, and we must also know that the voltage is strictly proportional to the sound intensity over the range of pressures encountered during testing. As in all measurements, the possibility of any change in the quantity under observation due to the presence of the measuring apparatus, in this case the microphone, must be considered. The amplifier must give a known current output per millivolt input when feeding a definite load at all frequencies considered, and must be free from appreciable amplitude distortion up to its rated output. In the same way the response of the frequency analyser or oscillograph must be known, particular attention being paid to the calibration of the analyser as a frequency meter. Finally, an overall calibration of the whole apparatus in galvanometer deflection per unit sound input is advisable as taking into account any mutual effects between the components.

The methods and technique of calibrating will be dealt with in three parts: (*a*) the intensity calibration, outlining the various methods tried for obtaining sounds of known intensity; (*b*) the frequency calibration, giving details of the frequency standards used and the method of checking test frequencies against the standards; and (*c*) the correction which, owing to the dimensions of the microphone, it is necessary to apply to the observed intensities.

(*a*) *Intensity Calibration from Moving-coil Microphone Constants.*—From the constants of the microphone, the voltage (millivolts) generated by an incident sound wave of unit intensity [1 dyne per cm^2 (R.M.S.)] over the frequency band where mass-control operates can be calculated from the relation

$$e = \frac{aprNB10^{-5}}{m_t f} \text{ millivolts (R.M.S.)}$$

where p = sound pressure in dynes/cm^2 (R.M.S.).

The next step is to determine the response of the amplifier and the final measuring device in terms of the input millivolts. When the amplifier is feeding an oscillograph we wish to know the deflection on the screen per millivolt applied to the input of the amplifier, but when the analyser is used the calibration has to be in terms of galvanometer deflections. In order to apply known small voltages to the amplifier the voltage-drop across a known non-inductive resistance carrying a measured current was included betwen the microphone coil and the filament circuit. It was thought advisable to leave the microphone coil in circuit as its impedance at the higher frequencies might affect the amplification of the amplifier, but actually no such effect has been noticed. The small known resistance consisted of a non-inductive plug-box, and the current flowing through it was measured by a thermo-junction and galvanometer. This current was supplied by a loose coupling to a valve oscillator adjusted by suitable condensers to oscillate at the requisite frequency. Having adjusted the amplifier supplies such as filament, H.T. and grid-bias voltages, including those of the frequency-correcting stage when one was used, the input voltage at a known frequency was gradually increased from zero by adjustment of the current and input resistance until a suitable response on either the oscillograph or analyser galvanometer was obtained. With the analyser, of course, both circuits had to be tuned to the test frequency and the coupling between them kept within the limits for linear response outlined in the next Section ("Design"). From the results obtained it was possible to draw graphs connecting the amplifier output or oscillograph deflection per millivolt input with frequency. Similarly the current (mA) in the secondary circuit of the analyser per millivolt input per unit coupling between the two circuits was deduced over the whole range and plotted against frequency. As measurements of amplification were made on the various studs of the potentiometer control in the anode circuit of the second valve in the amplifier and also with the first valve removed, a factor was deduced for each stud with two and three stages of amplification so that for any setting the sensitivity could be referred to that at the standard settings of three valves, stud 1 (3S1) and two valves, stud 10 (2S10).

At any frequency, therefore, within the tuning range of the coils the deflections of the oscillograph or the readings of the galvanometer measuring the secondary current of the analyser can be interpreted into millivolts generated by the microphone and so, assuming mass control, into sound pressure in dynes per cm^2 at the diaphragm of the microphone. The question as to whether that is always the same pressure as would exist if the measuring instrument were not there will be dealt with in a later Section.

Source of Known Strength.—The early attempts to check the microphone sensitivity were based on the calculation of the sound field set up by a moving-coil loud-speaker, similar in construction to the microphone but situated in plane baffles of various sizes. Tests were first made in a large laboratory, but it was soon obvious that the standing waves set up in the room made the results of little value. In order to prevent this distortion of the field due to wall reflections, the apparatus was moved on to the spacious flat roof of a laboratory building, the loud-speaker being mounted in a hole in one wall of a hut containing the oscillator for supplying the currents of varying frequency to the source. To reduce reflection from the floor and so approximate to the semi-infinite radiating space contemplated by Lord Rayleigh, large sheets of thick felt were placed on the floor underneath and in front of the loud-speaker. On plotting the response of the microphone with distance from the source at various frequencies, a series of wavy lines, each having a rectangular hyperbola as a mean, was obtained. These mean sensitivities calculated from the loud-speaker constants agreed fairly well with the values calculated from the microphone constants up to 600 cycles. The agreement was improved by providing rubber insulation between the loud-speaker and the wall of the hut, so probably the latter was vibrating and making the field strength higher than the calculated value. Above 600 cycles the sensitivity of the microphone deduced from the loud-speaker was from 1·5 to 4 times that predicted from the microphone constants. However, at 4 000 cycles the agreement was again very good. Numerous modifications were tried, such as enclosing the microphone in a padded tube, leaving the back off, removing the tube and fitting baffles of various sizes, but it was obvious that all that could be deduced from the measurements was a confirmation of the order of the sensitivities of the microphone and loud-speaker. However, in view of the reflection troubles encountered it was deemed advisable to design and make a smaller microphone on similar lines to the first. The constants of the No. 2 instrument are:—

Area of cone = 16·7 cm^2.
Radius of moving coil = 0·6 cm.
Gap flux density = 2 900 lines per cm^2.
Total mass of moving system = 5 grammes.
Calculated sensitivity = $46{\cdot}5/f$ mV (R.M.S.) per R.M.S. dyne per cm^2.

Radiation Pressure.—When a sound wave suffers normal reflection at a perfectly reflecting surface there is on the surface a resultant unidirectional force * of $0{\cdot}75\ p^2$ micro-dynes per cm^2, where p is the maximum pressure in the incident wave in dynes per cm^2. This suggests an absolute method, independent of frequency, of measuring the intensity of a sound wave, provided a sufficiently delicate radiometer can be made. The method adopted for a trial was to suspend an aluminium disc 6·5 cm diam. in a slightly larger hole in a large wooden partition 10 ft. by 9 ft. by 2 in. thick, erected across the laboratory and dividing it into two parts. As indicated in Fig. 6, the disc was supported on a light triangulated framework of small-diameter aluminium tube hanging from the finest phosphor-bronze suspension obtainable, and was balanced by a small brass weight. The line of the suspension was, for convenience in mounting, behind the plane of the disc and to one side of the edge of the disc to make sure that when a uniform normal pressure acted on the disc all the elements of the force would produce on the suspension a turning moment in the same sense. A small mirror attached to the framework at the point of contact with the suspension provided a delicate means of recording movements of the suspended system by a spot of light from a lamp reflected from the mirror and focused on a translucent scale. Since the order of the force to be measured with an incident sound pressure of 1 dyne per cm^2 was 25 millionths of a dyne or 40 micro-microgrammes weight, it is not surprising that trouble due to draughts was immediately experienced. The back of the disc, including the suspension aluminium framework and balance weight, was boxed in by a short length of bakelite tube with a glass lid, and all joints were made with putty, but still the system was unstable. The other side of the partition, where the walls, floor and ceiling were covered with 4 in. of cotton waste to prevent reflection, was covered in by a draught screen of thin tissue paper, but comparatively large circulating currents of air, probably of thermal origin, within the enclosure persisted. Owing to iron impurities the magnetic properties of the aluminium reacted with the earth's field to provide another control which did not disappear when a mica disc and glass framework were used. The method was therefore abandoned.

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* See Bibliography, (5).

The Rayleigh Disc.—Mallet and Dutton* used a Rayleigh disc in their experiments, in a lined testing cabinet, on telephone receivers. They calibrated the disc directly by steady air currents and found the torque to be proportional to the square of the air velocity as predicted by König's formula† for thin discs

$$\mathbf{T} = \frac{4}{3}\rho r^3 V^2 \sin 2\theta$$

where $\mathbf{T}$ = torque in dyne-cm,
ρ = density of air,
V = velocity of air maximum,
r = radius of disc,
θ = angle which normal to disc makes with stream-lines of air-flow.

Later, Barnes and West ‡ went a step further and confirmed in a thorough manner the constants of König's formula. They measured the sensitivities of several discs by a mechanical apparatus producing known low-frequency alternating air currents and got very good agreement between these measured values and those calculated by the formula from the constants of the discs and suspensions.

It is clear, therefore, from these researches that the Rayleigh disc does measure particle velocities as deduced by König's formula, provided that:—

(1) The disc is thin compared with the diameter. If x be the ratio of thickness to diameter of the disc and $\mathbf{T}_0$ the torque for an infinitely thin disc, König deduces that $\mathbf{T} = \mathbf{T}_0(1 - 0{\cdot}3x)$.
For $x = 0{\cdot}01$, therefore, the correction is negligible.

(2) The diameter of the disc is small compared with the wavelength of the note under test. Barnes and West give a ratio of 1 to 5 as giving results accurate to 2 per cent in velocity measurements.

(3) The disc diameter is small compared with the diameter of any enclosing tube. A value of $\frac{1}{3}$ is quoted in the above paper as giving results accurate to 3 per cent.

For an alternating current of air $V \sin \omega t$, the torque is

$$\mathbf{T} = \frac{4}{3}\rho r^3 \sin 2\theta V^2 \sin^2 \omega t$$

$$= \frac{4}{3}\rho r^3 \sin 2\theta \frac{V^2}{2} (1 - \cos 2\omega t)$$

That is, it consists of a steady component proportional to the mean square velocity and an alternating component of double frequency. The latter has a negligible effect because the natural frequency of a thin disc supported by a fine suspension is so low and the air damping relatively high. Considering only the steady deflection, therefore,

$$\mathbf{T} = \frac{2}{3}\rho r^3 V^2 \sin 2\theta \text{ dyne-cm}$$

If the length of the suspension is l cm and the control per cm equal to $\mathbf{T}_\mathbf{R}$ dyne-cm per radian, then the twist of the disc is given by

$$\delta\theta = \frac{2}{3}\rho r^3 V^2 \frac{l}{\mathbf{T}_\mathbf{R}} \sin 2(\theta + \delta\theta)$$

If the initial inclination, θ, of the disc is $\frac{1}{4}\pi$ we have

$$V^2 = \frac{3\mathbf{T}_\mathbf{R}\delta\theta}{2\rho r^3 l \cos 2\delta\theta}$$

If a lamp is directed towards a mirror attached to the centre of the disc the reflected beam of light moves through an angle $2\delta\theta$ corresponding to a linear deflection d cm at a distance of d_1 cm from the mirror.

$$\therefore \frac{d}{d_1} = \tan 2\delta\theta$$

and
$$V^2 = \frac{3\mathbf{T}_\mathbf{R} d}{4\rho r^3 l d_1}\left(\frac{2\delta\theta}{\sin 2\delta\theta}\right)$$

For values of $\delta\theta$ not exceeding $0{\cdot}1$ radian we can write, with an error not greater than $0{\cdot}4$ per cent,

$$V = \left(\frac{3\mathbf{T}_\mathbf{R} d}{4\rho r^3 l d_1}\right)^{\frac{1}{2}} \text{ cm per sec. (max. value)}$$

Since the authors' microphone is a pressure-operated device and the Rayleigh disc measures particle velocity, it is necessary to work in a field of known distribution and with a definite relation between the pressure and velocity at two points. As experience with the radiation pressure apparatus urged the authors to adopt a sealed testing chamber, it was decided to use a closed tube containing standing waves. The relation between the maximum pressure at the ends of the tube and the maximum velocity $\frac{1}{4}$ wavelength away is given by*

$$P = \rho v \times V \text{ dynes/cm}^2 \text{ (max.)}$$

where ρ = density of medium, and
v = velocity of sound in medium.

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* See Bibliography, (34).
† *Annalen der Physik und Chemie*, 1891, vol. 43, p. 43.
‡ See Bibliography, (36).

* See Bibliography, (7), vol. 2, p. 49 *et seq.*

Working in R.M.S. values, therefore, we have, for the pressure at the end of a tube in terms of the deflection on the scale due to the twisting of the disc supported $\frac{1}{4}$ wavelength from the end,

$$p = \rho v\left(\frac{3\mathbf{T}_{\mathbf{R}}d}{8\rho r^3 l d_1}\right)^{\frac{1}{2}} \text{dynes/cm}^2 \text{ (R.M.S.)}$$

i.e. $$p = K_1\sqrt{d} \text{ dynes/cm}^2 \text{ (R.M.S.)}$$

where $$K_1 = v\left(\frac{3}{8}\cdot\frac{\mathbf{T}_{\mathbf{R}}\rho}{r^3 l d_1}\right)^{\frac{1}{2}}$$

The conditions for the production of standing waves in the tube are satisfied if there is any whole number of half wavelengths between the fixed reflecting ends. In order, however, that the Rayleigh disc shall be at a velocity loop, the distance between it and one end must be an odd number of quarter wavelengths. The general arrangement of the apparatus is shown in Fig. 7.

The first measurements were made in a bakelite tube 137 cm long, 19·7 cm inside diameter and 21·6 cm outside diameter.

The Rayleigh disc, a disc of mica 3·8 cm diam., was suspended by a fine phosphor-bronze suspension, having a control force $\mathbf{T}_{\mathbf{R}} = 0{\cdot}66$ dyne-cm per radian per cm, from a torsion head let into the tube 35·5 cm from one end. The free length of the suspension was 8 cm and a torsion pendulum experiment gave the control of the actual suspension used as 0·083 dyne-cm per radian. Two discs of hard wood 4 cm thick were made to fit in the tube with just sufficient clearance to allow them to be moved about. A hole 2·5 cm diam. in the middle of one of the wooden discs allowed the mouth of a diaphragm type loud-speaker element to be inserted with a rubber insulating bush. The other wooden disc had a hole 7 cm diameter cut in it to take the small No. 2 microphone. Various methods were tried in order to get a beam of light axially along the tube to be reflected by a small mirror on the Rayleigh disc through a window in the wall of the tube on to a scale. The first method was to provide another little window alongside the microphone for a beam of light to shine up the tube, but this method had obvious limitations in the wavelengths to which it could be adapted. An improvement was therefore effected by supporting a small inclined-plane mirror on the axis of the tube in front of the Rayleigh disc mirror so that the beam of light could enter and leave by the same side window as indicated in Fig. 7. The lowest frequency that can be measured in this tube corresponds to a wavelength equal to the greatest distance between the inner faces of the two wooden reflectors, because the velocity measurement is made $\frac{1}{4}$ of the tube length from the microphone. This wavelength is 126 cm and the frequency approximately 265 cycles per sec. as measured by the analyser.

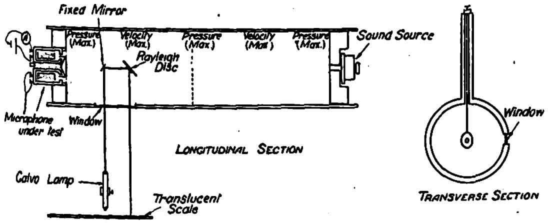

FIG. 7.—Apparatus for absolute calibration of a microphone by the Rayleigh disc.

It was found to be important to fill up all cracks and joints between the tube and wooden discs with plasticine. It was also found that unless temperature gradients over the length of the tube were prevented, a wandering zero was obtained, indicating stray air currents of the same order of velocity as those being measured. Taking the coefficient of reflection from hard wood as being unity, the corresponding factor for the microphone might be very much lower. To test for any effect due to diminished reflection from the microphone, the two wooden pistons were fixed with their inner faces at distances of 31·5 and 94·5 cm from the Rayleigh disc as indicated in the sketch, and one complete standing wave was produced in the tube. This was accomplished by feeding the loud-speaker element from a valve oscillator with frequencies in the neighbourhood of 265 cycles and adjusting the vernier condenser tuning the oscillator until the deflection of the Rayleigh disc was a maximum. A hard-wood plane disc was sub-

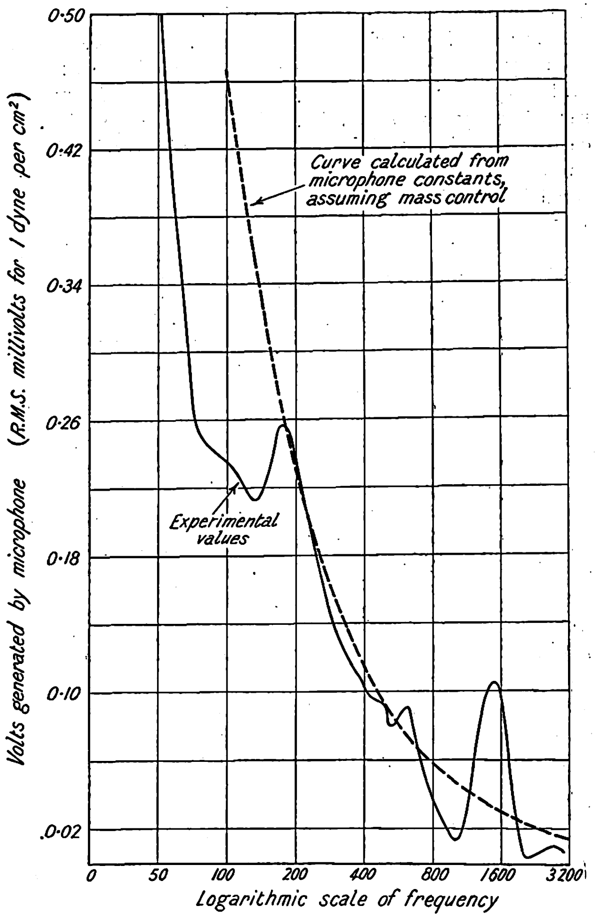

FIG. 8.—Calibration curve of No. 2 microphone.

stituted for the microphone, and the same voltage, as measured by a valve voltmeter, was applied to the loud-speaker. The resonant frequency was the same but the deflection was more than doubled. The reduction due to the microphone may have been caused by the conical shape of the diaphragm or by leakage of air between the moving coil and the central pole-piece. The cone was therefore filled in by a flat celluloid diaphragm supported from the cone by ribs of the same material. The above test, when repeated, gave the effect of the modified microphone as causing a decrease of 18 per cent in deflection or of 9 per cent in velocity. Accordingly the plane disc across the mouth of the cone was retained in all subsequent calibrations and measurements.

The sensitivity of microphone No. 2 was determined step by step by noting the response of the amplifier and frequency analyser with a sound wave of amplitude recorded by the deflection of the Rayleigh disc. By calibrating the amplifier and analyser immediately after each test at the frequency employed in the test the sensitivity of the microphone in millivolts per dyne per cm^2 was deduced.

During this calibration, which naturally necessitated taking very many readings, several important points were investigated. In the first place, measurements were made with the microphone in the centre of the wooden piston, and then the measurements were repeated with a new piston having the microphone as near to one side as possible. The readings were the same within the limits of experimental error, viz. 2 per cent.

The next point was to find out whether the results obtained with $\frac{1}{2}$ wavelength between the pistons agreed with those found with one complete wave in the tube. This was found to be the case and, moreover, the results obtained were still the same with a greater number of half wavelengths in the tube. The greatest number of half wavelengths ever used in this tube was 23, when a frequency of 1 710 cycles was tuned by a tube length of 202 cm with the Rayleigh disc at the centre. The wavelength then was of the same order as the diameter of the tube, but the results agree very well with check results made later. This discovery considerably shortened the work involved in calibrating a microphone, as it is possible to set the tube length for a low frequency, make a measurement of sensitivity, and then, with the same tube setting, make measurements on the 3rd, 5th, 7th, etc., harmonics of the gravest mode of oscillation. It is clear that the even harmonics cannot be used, as the Rayleigh disc, to be at a velocity loop, must always be an odd number of quarter-wavelengths from the reflecting pistons.

The fact that the tube responds to harmonics called for an investigation into the possibility of errors due to the presence of harmonics in the exciting unit. The analyser is very selective and its indication is unaffected by harmonics many times as large as the fundamental note. It has been shown that the Rayleigh disc does not respond to even harmonics but that it is deflected by odd harmonics. Attempts were therefore made to measure the odd harmonics of several typical notes by tuning the frequency analyser to each odd harmonic in turn. In all cases the harmonics were too small to measure, although some third harmonics could be heard faintly in a pair of telephones included in the analyser secondary circuit. This freedom from harmonics was probably due to the loosely-coupled circuit taking power from the valve oscillator to the loud-speaker element.

It was thought that if the tube diameter were of the same order as the wavelength there would be a possibility that the pressures and velocities at all points in any cross-section of the tube might not be consistent. Accordingly another testing tube was made, 76 cm long, 9·5 cm inside and 11·4 cm outside diam. Since it was impossible to accommodate a sufficiently delicate suspension inside the tube, a suspension tube having a small central hole and a torsion head at the top was made to house the phosphor-bronze strip. The hole leading into the calibrating tube is 1·5 mm diameter but, as no excess pressure ever exists there, leakage into the suspension tube does not tend to take place.

A disc 2·55 cm diam. was made by sticking together two thin sheets of paper with varnish and fastening to a suspension 31·3 cm long. A torsion pendulum experiment gave the control as 0·0208 dyne per cm per radian. With the scale 1 m from the disc the pressure is given by $p = 7\cdot 22\sqrt{d}$ dynes/cm^2 (R.M.S.), where d = deflection in cm.

As the disc was set one-quarter of the tube length from one end, the lowest frequency that can be tested in this tube is 500 cycles, corresponding to a wavelength, and distance between microphone and loud-speaker pistons, of 67·2 cm. The microphone sensitivity was measured between 500 and 1 000 cycles in the two tubes and very good agreement was obtained except at 600 cycles, when the small tube gave a result 25 per cent greater than the large tube. The difference between these two readings at 600 cycles was traced to resonance of the larger Rayleigh disc, and it is interesting to note that Barnes and West traced a 25 per cent difference to the same cause. To enable the authors to check their measurements in the large tube and also to decrease the possibility of errors due to resonance of the Rayleigh disc, a new suspension system incorporating a 1 in. diameter mica disc was made on the same lines as that for the small tube. The two measuring systems, one with a 2-in. disc and short suspension and the other with a 1-in. disc and long suspension, were arranged to fit the same hole in the top of the large calibrating tube so as to be easily interchangeable and of approximately the same sensitivity. As a result of comparative tests the 1-in. disc is used at all frequencies above 500 cycles, while the 2-in. disc, which is a little more sensitive, is used at all lower frequencies.

By adding extra sections to the large tube a length between pistons of 680 cm has been obtained with the Rayleigh disc at the middle, and so readings have been taken down to a frequency of 25 cycles.

Fig. 8 gives the results obtained by the Rayleigh disc and also the calculated sensitivity of the No. 2 microphone, assuming mass control. The agreement is fairly good between 170 and 700 cycles, but outside this band the performance of the microphone is modified by resonances. The large discrepancy at the low frequencies is due to the predominance of friction control in that region, while the large increase in sensitivity at 1 500 cycles is due to resonance in some part of the instrument.

However, the close average agreement is a satisfactory confirmation of the general accuracy of the measurements. To check the linearity of response of the microphone, observations were made with pressures up to 30 dynes per cm^2. No departure from linearity was detected.

With regard to the question of permanence of calibration, check observations taken on this microphone after an interval of 3 months of general use showed no change of calibration greater than 2 per cent.

(*b*) *Frequency Calibration.*—The amount of power required for the various stages in the calibration of the microphone amplifier and analyser was very small, amounting at the most to a few watts, but it was essential that it should be continuously variable in frequency and amplitude while remaining prefectly stable at any setting. Sine-wave generators of ample power and frequencies up to 2 000 cycles were available, but owing to the variations in the power supplies it was not possible to obtain the degree of constancy of frequency necessary for making precision measurements on sharply resonant circuits. Accordingly, a 10-watt valve oscillator was constructed with suitable coils and variable condensers to cover the frequency range 24 to 16 000 cycles in several stages. One pair of tapped coils was used up to 2 000 cycles and another pair overlapped with the first and went up to the highest frequency required.

For setting the frequency of the oscillator a range of standard tuning-forks calibrated by the National Physical Laboratory was available and these were used in the early measurements. To set the oscillator to one of the forks the operator stood with a pair of telephones on his head near the oscillator coils when the stray field was sufficient to give an audible note without connecting the leads to a search coil. A rough setting by adjusting the coil tapping and coarse-tuning condensers was made first until beats could be heard when the correct tuning-fork was set in vibration and held with its handle pressed against one telephone ear-piece. Adjustment of the vernier condenser on the oscillator then reduced the beat frequency to zero, giving an exact match. After a little practice, more points could be filled in on the calibration curve by matching harmonics of the oscillator with the forks, and vice versa, but, owing to the rapid " die away " of the 2 000-cycle fork, frequencies above this figure were very difficult to check. Accordingly the 1 000-cycle tuning-fork was maintained in vibration by a valve and suitable iron-cored coils arranged between and outside the prongs. As the method of matching by beats was getting difficult a Western Electric cathode-ray oscillograph was fed with voltages derived from the constant-frequency source and from the variable frequency oscillator, and immediately the work of frequency setting became simple and sure. The sensitivity of the oscillograph with 300 volts applied to its anode is about 1 cm deflection for 11 volts between the deflecting plates, so that it was easy to get good deflections in both directions. In general the fluorescent screen of the oscillograph is illuminated by a blue haze, but when a simple relation exists between the two frequencies the picture settles down into a simple figure. For instance, if the two frequencies are equal the general shape of the trace is an ellipse which can, however, degenerate into either of two straight lines with suitable adjustment of the relative phasing of the two supplies. When one frequency is twice the other the figure is either a " V " or an " 8." It is much easier to work with the simple " V " figure where the spot of light retraces its steps, thereby doubling the illumination, than with the other " continuous journey " figure. When the frequency ratio is 4 : 1 a " W " is obtained, and in general if there are n " V's " the frequency ratio is $2n$: 1.

In carrying out the above method for referring the oscillator frequency to the standard a small vernier condenser tuning the oscillator was mounted beside the cathode-ray oscillograph so that one observer could preserve the required pattern stationary while the other made the measurements of high-frequency resistance, amplifier response or overall characteristic of the apparatus. In this way readings could be taken at frequencies corresponding to even multiples and even sub-multiples of 1 000 cycles. In order to fill up the gaps it was found to be sufficient to make a very stable reference oscillator of another frequency, e.g. 800 cycles. To ensure consistency both anode and grid circuits were tuned and only just sufficient reaction was used to maintain the oscillations. In addition, the fitting of a high-resistance grid leak made the frequency less dependent on the supplies to the valve. The frequency of this reference oscillator, checked by a standard tuning-fork, did not vary 1 part in 1 000 in an hour.

It was hoped that a standard 1 000-cycle valve-maintained tuning-fork made to Dr. D. W. Dye's design would have been available before the completion of the calibration of the apparatus, but unfortunately this was not possible. However, the accuracy obtained is more than sufficient for commercial testing.

(*c*) *The Effect of Microphone Dimensions on Calibration.*—If we wish to measure the sound intensity at any point in space and suspend a microphone there for that purpose, it is clearly essential that we should satisfy ourselves whether or not the pressure which we measure is that which would have existed in the absence of the microphone. If the microphone forms part of a large reflecting surface, then the pressure immediately in front of the surface is the sum of those due to the direct and reflected waves. For a good reflector, therefore, the voltage generated by the microphone is twice what it would be if the measuring instrument were of negligible size. It is obvious that the size of reflector required to produce this doubling effect must depend on the wavelength of the incident sound, since a given reflector might be large compared with the wavelength of high-frequency sounds and negligibly small compared with that of the sounds of low frequency. Microphones Nos. 3 and 4 are both about 10 cm diameter, so that one naturally expects them to have no effect on low-frequency sounds but to have a transition stage as the frequency is increased, until, at some high frequency, complete reflection takes place, resulting in an apparently doubled sensitivity.

To investigate this point a series of tests was carried out in the non-reflecting room of the acoustic laboratory, which is described in Section (9). The walls of this room are lined with cotton waste to minimize reflection effects, and a preliminary exploration of the sound field produced by a source in the centre of the room indicated that reflection had been very nearly eliminated. A point 150 cm from the sound source, a small loudspeaker unit, was chosen as being in a uniform part of the field, and the microphone, supported on its spring stand, was placed there. The stand itself is designed to offer as little obstruction as possible to the sound field. A range of baffles from 11·5 to 76 cm diameter was obtained with central holes 9·8 cm diameter to fit the microphone tightly, so that it was a simple matter to make rapid alterations in the effective dimensions of the detector. With a constant input of a definite frequency to the source the response of the microphone by itself and with each one of the baffles in turn was noted, frequent checks on the source being made by returning to the no-baffle condition.

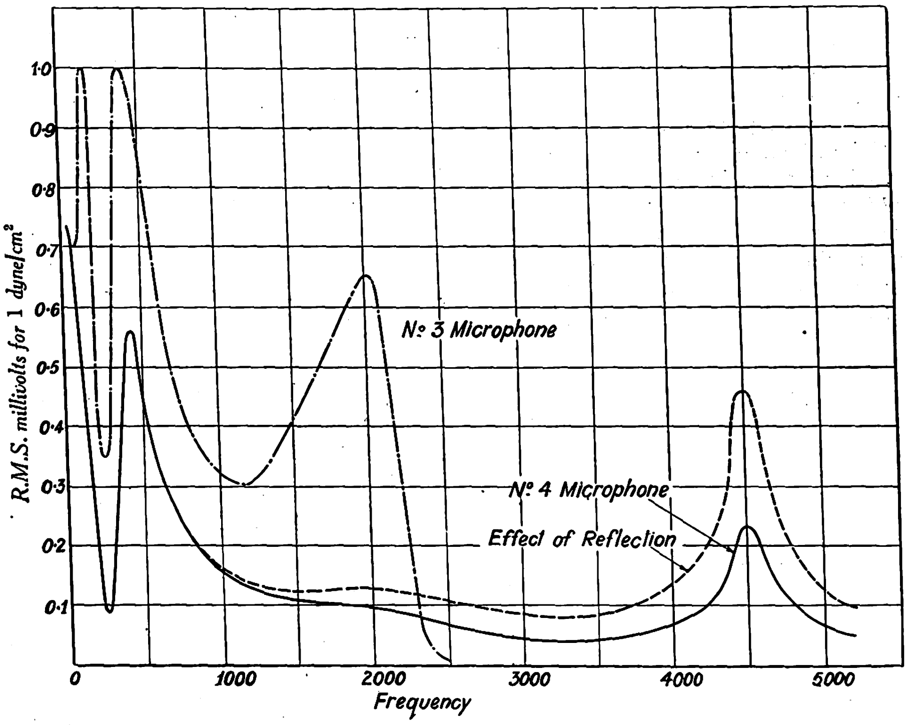

FIG. 9.—Microphone calibration curves.
Sensitivity in mV/dyne/cm² (both R.M.S. values).

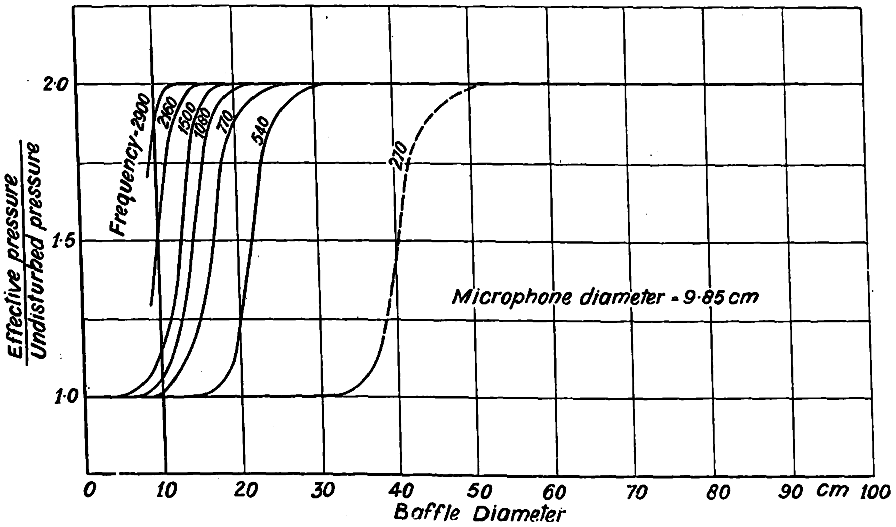

FIG. 10.—Effect of microphone dimensions.
Test carried out in non-reflecting room 587 × 587 × 293 cm high. Source at centre of room and 110 cm from floor. Microphone 150 cm from source.

The results obtained are indicated in Fig. 10. At the lower and medium frequencies the change-over from the case of the undisturbed field to that of complete reflection is clearly shown; the results have therefore all been plotted on a common arbitrary scale of 1 to 2.

At the high frequencies, however, appreciable reflection takes place from the microphone by itself. When, therefore, an increase in baffle diameter produced no corresponding increase in response it was assumed that the condition of complete reflection and doubled sensitivity had been reached. Taking this value as 2 on the scale the values for the smaller baffles and microphone alone were readily deduced.

From the points where this family of curves crosses the ordinate corresponding to the microphone diameter the correction curve given in Fig. 11 has been deduced. If, therefore, we multiply the sound pressure deduced from the Rayleigh disc calibration by the appropriate correction factor, we obtain a measure of the sound intensity which would obtain in the absence of the microphone.

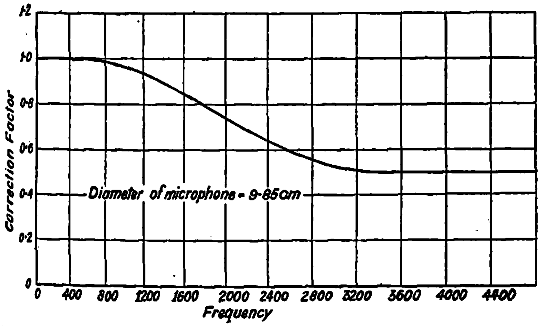

FIG. 11.—Microphone correction factor (to allow for finite dimensions).

(7) No. 2 APPARATUS.

(*a*) *Design.* — Having established an independent method of calibrating a microphone, it is no longer necessary to retain the mass-controlled type with its calculable performance, although it has been very useful in the development of the authors' technique of sound measurement. It is therefore possible to take any pressure-operated microphone with a plane reflecting diaphragm and permanent characteristics and calibrate it for use in conjunction with the rest of the measuring apparatus. However, owing to the strictly limited capacity of the amplifier power valves it is advisable to choose one having a sensitivity with frequency as uniform as possible. The questions of variation of sensitivity with sound amplitude and with everyday use must also be considered, particularly in moving-iron type instruments. The permissible impedance, having regard to the distance of the microphone from the amplifier, is very important and is bound up with the question of trouble due to stray e.m.f.'s being induced in the leads. In a works where a long lead connects the microphone on one of several testing departments to a central instrument room the maximum permissible impedance makes undesirable certain types of microphone such as the condenser type, which would have to be calibrated with the leads finally used. These considerations and others of convenience made it seem advisable to retain the moving-coil type of microphone in a modified form, giving greater average sensitivity and less variation with frequency. For other test conditions and for frequencies higher than 5 000 cycles per sec. the condenser microphone as developed by E. C. Wente * may be more suitable. Fig. 9 gives the sensitivity of No. 4 microphone with frequency, as measured by the Rayleigh disc method in the two resonant tubes. Excellent agreement between the results in the two tubes at frequencies from 500 to 1 900 cycles was obtained in this calibration except at 600 cycles, as noted previously, where the large disc was giving trouble due to resonance. Apart from these two frequencies where the difference amounts to 25 per cent, the agreement is within the limits of experimental error, viz. 2 per cent. The dotted curve gives the characteristic of an earlier microphone, which was deficient in sensitivity above 2 200 cycles.

For connecting the microphone to the amplifier, twisted leads in flexible metallic tubing are used for short distances and two twisted wires in lead covering for permanent connection from the testing departments to the central testing room. The twisting prevents inductive, and the metallic sheath capacitative, "pick-up" by the leads. To minimize stray "pick-up" on the microphone itself the magnet system is joined to the sheath of the connecting cable and earthed. The higher the impedance of the microphone the more difficult it becomes to provide an effective electrostatic screen and also the more effect the cable capacity has on the sensitivity as measured at the amplifier end of the cable. The effect of the connecting cables on all the microphones is inappreciable up to 5 000 cycles.

The amplifier, which is arranged for a.c. mains operation and for rapid calibration, is shown diagrammatically in Fig. 12. It consists of 3 resistance-capacity coupled stages employing 6-volt valves with voltage amplification factors of 30. With anode resistances of 200 000 ohms the actual amplification per stage is 20, giving a voltage amplification of approximately 8 000. The anode resistance of the second valve is arranged as a potentiometer so that the amplification can be varied down to 1/24th of the maximum value in steps of approximately $\sqrt{2}$. Each stage has a separate H.T. supply circuit to avoid resistance reaction effects. The now well-known connection of series resistance and condenser to a common source of 230 volts (d.c.) was adopted.

Two power valves are operated in parallel from the same common 230-volt d.c. source generated by a full-wave rectifier and transformer. The smoothing circuit is conventional and the anode choke is of large proportions to have an inductance of 100 H with a steady component of anode current of 36 mA.

The output transformer has a nickel-iron core to reduce the magnetizing current required at the low frequencies contemplated. The primary is fed through a large anode-feed condenser. The secondary has four windings for operating the oscillograph or the various ranges of the frequency analyser. These tappings are so proportioned relative to the load resistance which they feed that the primary impedance of the transformer is always equal to the impedance (3 000 ohms) of the power valves.

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* See Bibliography, (41).

The power transformer for supplying the H.T. current has three primary taps so that it can be connected to 110-, 220- or 440-volt mains, and the core section is such that frequencies down to 25 cycles can be used.

The whole amplifier, including the voltage stages and power valves, is enclosed in a copper-lined section of a box the remainder of which accommodates the two transformers, chokes, condensers and a panel carrying filament and H.T. voltmeters and an anode-current milliammeter.

An auxiliary 4-volt winding on the power transformer supplies the lamp of the reflecting galvanometer of the analyser and also feeds a calibrating potentiometer which applies known voltages of the power frequency to the amplifier for rapidly checking its amplification.

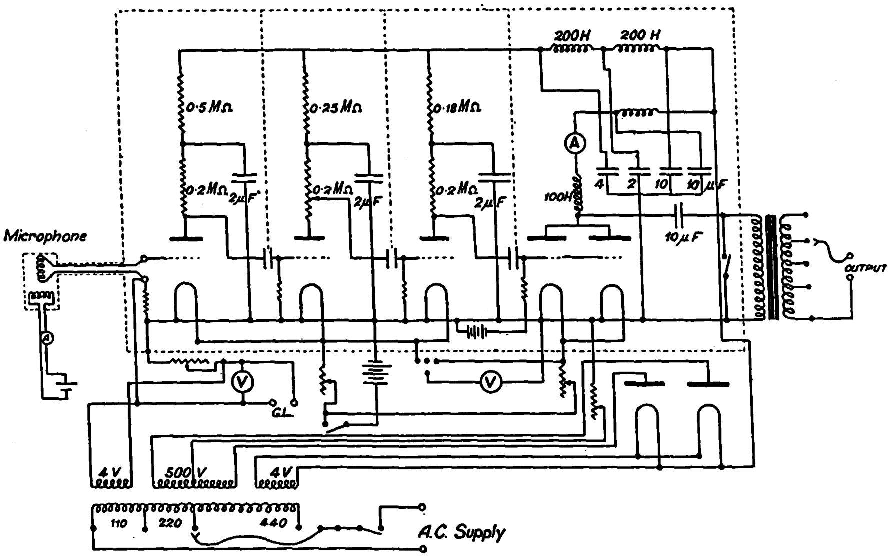


FIG. 12.—Amplifier unit.

In view of the complex sounds to be analysed, no definite selectivity requirements could be stated when designing the circuits of the analyser. Work with the first apparatus indicated that the more selectivity one had, without making the resonance curve too pointed, having regard to the variation of frequency encountered, the better. It was therefore decided to fix the width of the "flat top" of the resonance curve from considerations of possible frequency variations, and to make the selectivity comply with this limit. For this purpose the "flat top" of the resonance curve of the analyser is defined as the fractional change of frequency from the central resonant value to where the ordinate of the curve has decreased 2 per cent. If we denote this frequency change by x its value for a single tuned circuit is given by $x = R/(20\pi fL)$, where R and L are the resistance and inductance of the single circuit and f the resonant frequency. The value of x expressed in cycles is, of course, $R/(20\pi L)$.

For two similar "loosely coupled" circuits, the "flat top" of the resonance curve is given by $x' = R'/(28\pi fL')$ or, expressed in cycles, $R'/(28\pi L')$.

It follows, therefore, that for the same width of flat top the ratio of resistance to inductance is 1·4 times for two circuits what it is for a single circuit. Using these relative values of R/L it is easy to show that the frequency displacement from the central resonant value necessary to cause a reduction in circulating current to one-fifth of the maximum value is nearly twice as much for the single as for the double circuit. In other words, for the same immunity from trouble due to small frequency variations, the frequency spacing between two equal-amplitude components which can each be measured with not more than 2 per cent error in R.M.S. value due to the presence of the other is half as great for a two-circuit analyser as for one of the single-circuit type.

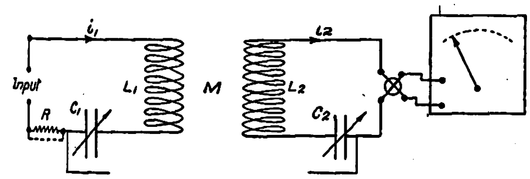
It was therefore decided to keep to the two-circuit type of analyser and so to adjust the values of R/L so that the "flat top" $x = 0\cdot2$ per cent. Since the value of x expressed in cycles is constant for a given value of R/L it is necessary to divide the frequency band to be covered into several narrow bands each with a suitable R/L value in order to prevent wide variations in the percentage selectivity. This is conveniently carried out by having several coils of suitable resistances and inductances so that in conjunction with two variable condensers the desired frequency band can be covered. A diagram of the analyser circuits is shown in Figs. 13 and 14. Four pairs of coils tuned by two 3-dial mica variable condensers of 1·11 μF capacity are used on the ranges 24–86, 86–310, 310–1 120 and 1 120–4 000 cycles. For x to be 0·2 per cent at the top of each range the corresponding values of R/L are respectively 15, 55, 200 and 700. Air-dielectric variable condensers of 0·001 μF bridge the gaps of the 3-dial condensers and make it possible to use the fourth pair of coils up to 16 000 cycles if necessary.

In operation, since both circuits are tuned to the frequency of the applied voltage, V_1, the primary current I_1 is equal to V_1/R_1, where R_1 is the total resistance of the primary circuits.

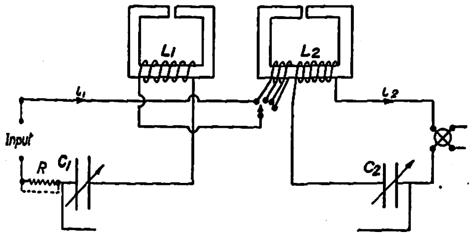
If M is the mutual inductance between the two circuits

$$I_2 = V_2/R_2 = \omega M I_1/R_2 = \frac{\omega M V}{R_1 R_2}$$

The voltage applied to the first circuit is therefore quite a simple function of the frequency, the coupling, the circuit resistances and the current flowing in the second circuit. However, as pointed out in connection with the calibration of the first apparatus, the effective resistance of circuit 1 includes a term $r_1 = (\omega M)^2/R_2$ due to the presence of circuit 2. Unless this term is negligible compared with R_1 the sensitivity of the analyser per unit coupling varies with M and makes an overall calibration difficult. If ωM does not exceed $0{\cdot}1\sqrt{(R_1 R_2)}$, then the transferred resistance is not greater than 1 per cent of the circuit resistance and can be neglected. The transferred inductance $L_1 = -(\omega M/Z)^2 L_2$ is also negligible if the above limit of coupling holds, so that the selectivity of the analyser can be estimated from the two circuits taken separately. In other words, if the given limit of coupling is not exceeded the sensitivity per unit coupling and the selectivity are independent of coupling. A rigorous mathematical investigation * of the problem upholds these conclusions. In passing, it might be added that greater values of M can be used, provided the total resistance of the primary circuit, including the transferred resistance, is determined either by measurement or by calculation and that it is understood that the selectivity for small frequency-changes is impaired. It is important, however, that the limit given by $\omega M = \sqrt{(R_1 R_2)}$ should not be passed, otherwise the tuning of one circuit will affect the other and "double humps" will appear in the resonance curves of the two circuits. The immunity from interference from a large component of widely different frequency may not be affected appreciably even when $\omega M = \sqrt{(R_1 R_2)}$, due to the large impedance of the secondary circuits at that frequency. The above point is of great assistance when using the analyser by itself for electrical wave-form analysis, a function for which it is eminently suitable. The resistance of the primary circuit, including any transferred resistance and the effective resistance of the source under test, is obtained by the added-resistance method, made convenient by the provision of a switch which inserts known non-inductive resistances in series with the rest of the circuit.



Coupled coils of equal inductance (air core for high frequencies).



Coupled coils of equal inductance (iron-nickel core for low frequencies).

FIG. 13.—Schematic diagram of electrical frequency analyser.

As regards the coils themselves, the two higher-frequency pairs are each wound on bakelite tubes in four sections to reduce self-capacity. One of each pair is made to rotate to vary the mutual inductance, which is calibrated in millihenrys. The two lower-frequency pairs of coils have cores of nickel-iron alloy to enable the requisite R/L values to be obtained in a small space and at a reasonable cost. Each core has an air-gap which alone controls the inductance of the coils, so that there is no appreciable variation of inductance with current amplitude. A small change in effective resistance with current is unavoidable and is made as small as possible by suitable proportions of core section and coil turns. The coupling between the two pairs of iron-cored coils is varied by having tappings on the secondary coils brought out to two stud switches so that a number of turns on the secondary coils can be connected in series with the primary coils.

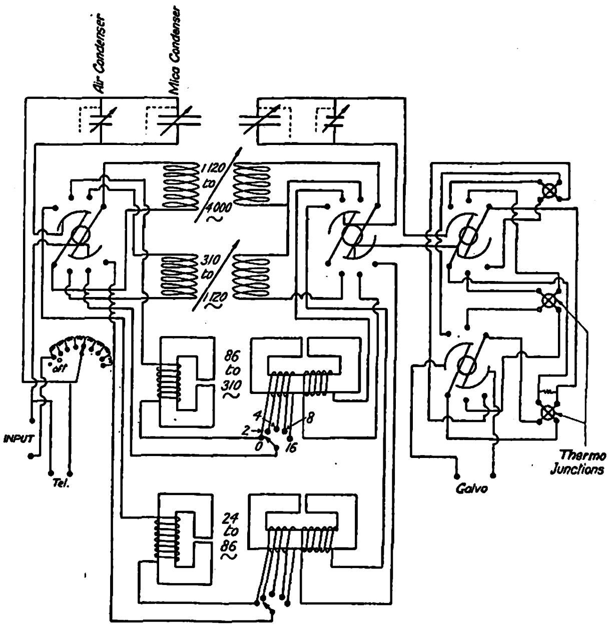


FIG. 14.—Diagram of connections of an electrical frequency analyser.

The secondary current is measured by one of three thermo-junctions and a portable reflecting galvanometer. Two double-pole coupled 3-position switches select a thermo-junction of suitable heater resistance, connect it in circuit and also connect its couple to the galvanometer.

This arrangement provides sufficient sensitivity for measuring sounds of the intensities met with in general

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* Due to Mr. J. D. Cockcroft.

engineering work. For tests in the laboratory on apparatus which emits relatively small intensities, a 5-fold increase in sensitivity is obtained by using a laboratory-type reflecting galvanometer. For testing apparatus which emits only the feeblest sounds a further increase in sensitivity is obtained by amplifying the current circulating in the secondary circuit of the frequency analyser before applying it to the thermo-junction galvanometer. This is carried out by a 3-stage resistance-coupled amplifier of conventional design which feeds the thermo-junction through a choke-condenser-transformer system. By means of this extra amplification it is possible to measure sounds below audibility level up to 500 cycles.

(*b*) *Performance.*—The performance of the No. 2 sound apparatus follows very closely that aimed at in the design. The sensitivity of the amplifier by itself is very little affected by frequency down to 24 cycles, the maximum reduction being 14 per cent. At frequencies above 2 000 cycles there is a gradual droop in the response curve, but this is of secondary importance to the apparatus as a whole since an overall calibration is required in any case and each component frequency is measured separately. The selectivity of the analyser has been sufficient for all the various uses to which it has been put. Curves have been prepared giving the resistance of the coils over the intended range of 24 to 4 000 cycles, with an extension of range (4) to 16 000 cycles.

The frequency calibration shows that the distributed capacity of the coils is negligible over the range for which they were designed, the curves of frequency against $1/\sqrt{C}$ being straight lines except above 6 000 cycles, where the curve for range (4) begins to bend.

The expression for the sound intensity in terms of the current (I) indicated by the analyser galvanometer is

$$p = \frac{I \times m \times 10^3}{F \times K_2 \times M \times S} \text{ R.M.S. dynes/cm}^2$$

where m = microphone correction factor,

K_2 = mA/mV/mH,

M = coupling between the two analyser coils, in mH,

S = microphone sensitivity, in mV per dyne per cm^2.

The factor F is dependent on the setting of the amplifier potentiometer. Its value is obtained from a table, as it varies very little with frequency.

Ranges (1) and (2) have a common thermo-junction, while (3) and (4) have one each. In reading off the current, therefore, the curve corresponding to the range in use should be consulted. Similarly the values of mA/mV/mH should be taken from the curve corresponding to the range in use, as the ranges overlap slightly.

The curves of microphone sensitivity and correction factor could be combined into one curve, but they have been kept separate to illustrate the effect of the dimensions of the microphone.

The ease with which the sensitivity of the amplifier and measuring apparatus can be checked is very useful. By turning a switch, various small voltages from 0·4 to 12 mV of the power-circuit frequency are applied to the amplifier, and the response on the oscillograph or analyser gives an indication of the consistency of the amplifier. The values obtained when the apparatus was calibrated can be read from the appropriate curve and a correction factor deduced. By this means the readings are consistent to ± 2 per cent.

In making measurements with this apparatus it is possible to save time by making a preliminary aural estimate of the various components in the noise to be analysed. As a result of experience the operator can say, for instance, that there is no need to try ranges (1) and (4) as all the components are between 100 and 1 000 cycles—a very common state of affairs. In any case the following few notes will indicate the method of making a complete analysis of a noise. The sequence of adjustments and the starting point in the frequency range are largely a matter of personal opinion, but the method described here is the result of the authors' experience in a large number of tests.

Having set the microphone in the desired position with respect to the noisy apparatus, the amplifier is connected to suitable a.c. mains and the valve filaments to a 6-volt battery. The filament and H.T. voltages are adjusted to the correct values by means of the controls provided, and the output transformer is connected to the input terminals of the analyser. The terminals of the output transformer should be chosen to correspond to the range in use.

A pair of 120-ohm telephones is connected in series with the primary circuit of the analyser, and shunts varying from 0 to 500 ohms can be connected in parallel to vary the sensitivity and selectivity. Starting with the highest frequency range and 500 ohms across the telephones it is probable that most of the high-frequency components will be heard more or less accentuated by the tuning of the circuit. The operator concentrates his attention on the highest-frequency component present and adjusts the primary condenser until this particular component is as loud as possible. The next step is to decrease the shunt across the telephones until the note is only just audible. It will now be found that the note is much more sensitive to adjustments of the condenser. The process of tuning and reducing the shunt is continued until finally the telephones are short-circuited. The secondary condenser is then made to correspond to the primary, and the coupling between the two circuits is increased until the galvanometer deflects. It is important, however, if maximum selectivity is to be retained, not to exceed the maximum linear coupling for the particular setting of the condenser and coil. Larger values, up to two or three times, can be used when selectivity is not a limitation. The value is obtained from a graph, but can be remembered after a little practice. Final adjustments are then made to the secondary and primary condenser, and the coupling is adjusted within the permissible limits to give a good deflection on the galvanometer. If necessary the sensitivity can be varied by the amplifier potentiometer. From the reading of the secondary condenser the frequency of the component is obtained from the calibration graph, and from the coupling and galvanometer deflection the sound pressure at the microphone is deduced from the overall calibration of the apparatus. Having obtained the necessary information, attention is turned to the next lower component. It frequently happens that, instead of a pure note, a band of frequencies is encountered. In this case it is obvious that the amplitude readings will have to be referred to the particular width of resonance curve employed. The usual procedure is to take readings of amplitude and frequency right through the band and to deduce the approximate width of the band from this spectrum. It is very seldom, however, that one is able to trace such a band of frequencies to its source, as, clearly, the component frequencies do not bear a simple relation to the speed (revs. per sec.) of the motor or turbine or whatever machine is being tested. With regard to the effect of temperature on the test conditions and apparatus, such effects can be ignored if temperature variations do not exceed ± 5 deg. C.

(8) TEST-CONDITIONS FOR GENERAL SOUND MEASUREMENTS.

A little consideration will make it clear that the sound intensity measured near a source is dependent on the presence of other bodies in the sound field. These bodies give rise to local reflection or absorption and hence modify the sound field to a degree depending on their dimensions and on their acoustical properties. It is therefore necessary to devote some space to the discussion of the conditions under which sound measurements on engineering apparatus are made, and to define the conditions necessary in order that the results may be susceptible of simple interpretation.

Broadly speaking, two cases arise in practice, viz. those in which the test-conditions are under control and those in which they are not. In Section (2) of this paper the ideal condition of infinite space, in which no other body than the sound source is present, is assumed. The nearest approximation to this condition is a large, open piece of ground free from buildings, trees or other objects which would cause reflection. Even so, there will be reflection from the ground. This may be minimized by working at a sufficient height above the ground. Many workers have experimented under these conditions. In the early stages of this investigation, a small part of the work was carried out in open space, the flat roof of a laboratory building being used. While a fairly satisfactory freedom from reflection was obtained, the disadvantages of rain, wind (which had a curious effect on the sound distribution) and extraneous noises were prohibitive. It was therefore necessary that efforts should be directed to obtaining satisfactory test-conditions in a building. The obvious difficulty of carrying out sound measurements in a building where other activities are going on, such as a factory building or even a laboratory building, is that of extraneous noise. It is clear that, if useful results are to be obtained, the intensity of extraneous noise must be small compared with the intensity of the sound under observation. In the measurement of feeble sounds this condition is the most exacting of those which have to be fulfilled. It was therefore decided to construct a special building for acoustical work, so that the greater part of the projected investigation of the subject could be carried out under sufficiently defined conditions. The building, which is described in detail later, performs three main functions, viz. the reduction of extraneous noise to a tolerable value, the provision of a testing space reasonably free from reflection and the provision of accommodation for the fundamental standards of sound measurement. Extraneous noise from inside the building is minimized by placing the apparatus under test and the detector element of the measuring apparatus in a soundproof room in the building, all other apparatus being excluded. The measuring and auxiliary apparatus, together with the observer, are located in adjacent rooms. Extraneous noises from outside the building are dealt with partly by the location of the building in relation to sources of extraneous noise and partly by adopting a suitable construction. The objection to reflection in a room in which sound measurements are being made arises in the following way. Suppose that the sound source under test is located in infinite space free from obstacles. Then, from Section (2) and equation (1), the sound pressure varies inversely as the distance from the source, and one observation at a known distance is sufficient to enable the intensity of a sound of a given frequency to be determined.

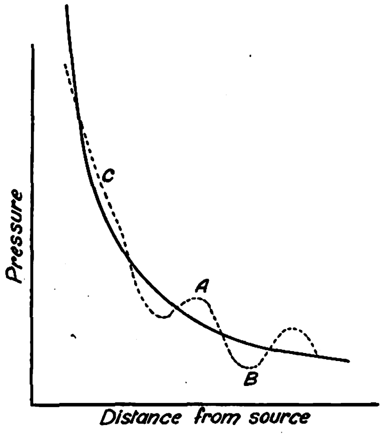

FIG. 15.

If reflection is not reduced to a negligible amount, the incident and reflected waves, travelling with equal and opposite velocities, produce an interference pattern. This gives rise to a pressure/distance relation such as that shown by the dotted line in Fig. 15, the full line showing the normal relation. When the interference effect is large, its presence may be detected by walking or moving the head slowly towards or away from the source, when points of maximum and minimum intensity will be noticed. Hence if reflection is present but unsuspected, observations with the detector at points such as A or B will be considerably in error. It is possible, of course, when reflection is suspected, to trace out a curve such as CAB and draw a mean curve through it, thus largely eliminating the effects of reflection. When, however, a machine is being tested which may emit half a dozen or more frequencies, and a pressure/distance curve has to be plotted instead of taking a single observation for each frequency, the advantage of making reflection effects negligible is obvious. Therefore, where it is practicable, measurements should be made in an enclosure designed for the purpose.

We have now to consider the case where, owing to circumstances not under control, measurements have to be made in a factory building, power station, substation or elsewhere. This usually occurs on account of the size of the machine to be tested. Although the walls of such buildings are highly reflecting, the interference trouble may not be prohibitive if the building is large and the machine is not close to a wall or switchboard or to another large machine. Where reflection is suspected, a pressure/distance curve should be taken. Extraneous noise, sometimes very loud, confused and variable, is the main difficulty. From the experimenter's point of view large machines fortunately make a large noise compared with small ones, so that the notes under observation may stand out clearly against the general background of noise. On the other hand, the detector must be placed at a distance not small compared with the dimensions of the machine, otherwise an exaggerated impression of the importance of certain components may be obtained. The necessity of placing the detector at an increased distance compared with that suitable for small machines somewhat discounts the contrast that would otherwise be obtained. It is here that the principle of dealing with each component of a complex sound in turn, rather than obtaining a simultaneous record of the whole sound, is particularly valuable. The relevant notes can often be quickly identified. If the machine under test can be shut down for a short time and the extraneous noise remains reasonably constant, the supposed irrelevance of certain notes can be checked. With small machines it may be remarked that attempts to make sound measurements on, say, a normal 10-h.p. motor on a factory test-bed, where several other machines are running and where the background of noise is large, are quite futile. It is not that the results may be inaccurate; they will probably be unintelligible.

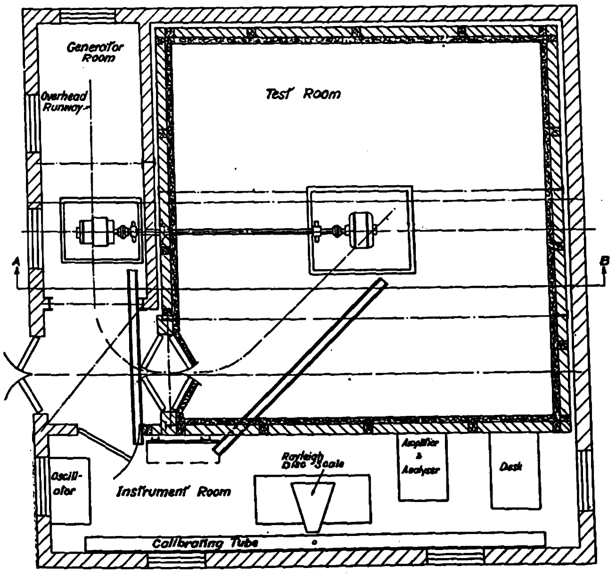

FIG. 16.

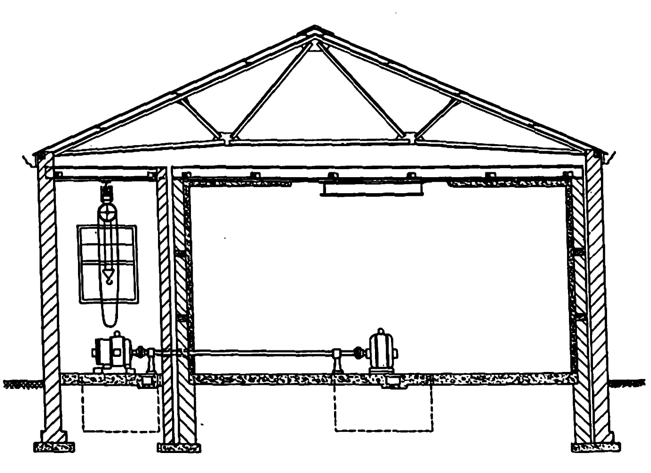

FIG. 17.

The authors' experience in testing machines of various kinds has shown that several other factors besides reflection and extraneous noise may have an important influence on the results obtained. For example, temporary test foundations may modify the magnitude and distribution of the sound considerably. Auxiliary test equipment, such as driving motors and loading brakes, may contribute no inconsiderable part of the total sound observed and must not be overlooked. Want of dynamic balance and want of alinement in a temporary set-up are also important factors. It is also necessary to guard against the direct transmission of vibration from the machine under test to the microphone, and electromagnetic or electrostatic "pick-up" from power circuits adjacent to the sound-measuring circuits. In this connection the electromagnet type of moving-coil microphone, compared with the permanent-magnet type, has the great advantage that the magnetic field may be temporarily switched off, thus facilitating the detection of "pick-up."

(9) LABORATORY FOR ACOUSTICAL WORK.

The laboratory, a plan and elevation of which are shown in Figs. 16 and 17, is a double-walled brick building resting on substantial concrete foundations. It consists of three rooms: the test room with non-reflecting walls, the instrument room in which is located the sound-measuring apparatus, and the generator room, which provides acoustical isolation for the generator used for a load in connection with the testing of motors.

The test room, which is formed by the inner shell of the building, is 20 ft. long, 20 ft. wide and 10 ft. high. Thus, when apparatus is placed in the centre of the floor for test, there is a minimum distance of 10 ft. to the walls and ceiling. The walls, floor and ceiling were first covered with a layer, 10 cm thick, of specially purified loosely packed cotton waste held in position by wire netting of coarse mesh. The cotton waste on the walls is prevented from slipping down by thin narrow shelves placed at intervals in the height of the walls. The walls of this room are of hollow brick 6 in. thick and are completely separated from the 9-in. solid brick outer wall by a 3-in. air space. The only point of connection between inner and outer walls is at the foundations, which are well below ground-level. Incorporated in the inner walls are steel stanchions, which carry girders for supporting a runway for a 1-ton block and tackle. The runway is arranged to pass over the centre of the test room, so that a motor or other apparatus to be tested can be lowered on to a bedplate to which it can be bolted during a test. The bedplate consists of a massive concrete block, the top of which is covered with a thick steel plate provided with suitable clamping arrangements. The block is let into the ground so that the top is level with the floor of the room. The sides of the pit containing the block are separated from the block by a 2-in. space to minimize the transmission of vibration from the block to the floor of the room.

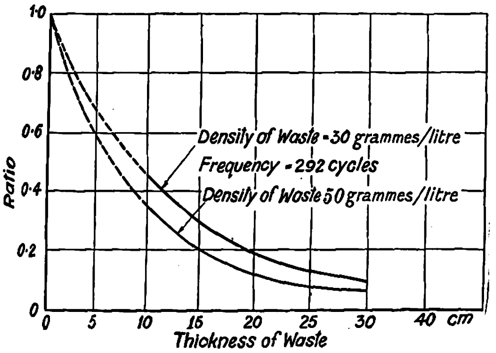

Fig. 18.—Curve of ratio (mean velocity with waste/mean velocity no waste).

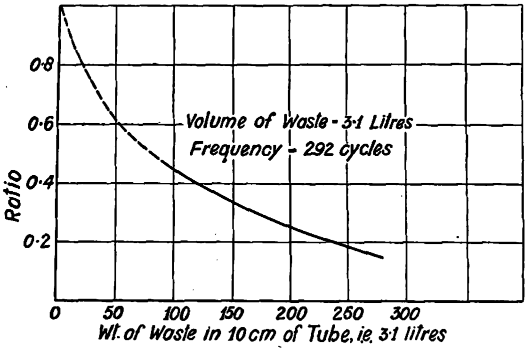

Fig. 19.—Curve of ratio (mean velocity with waste/mean velocity no waste).

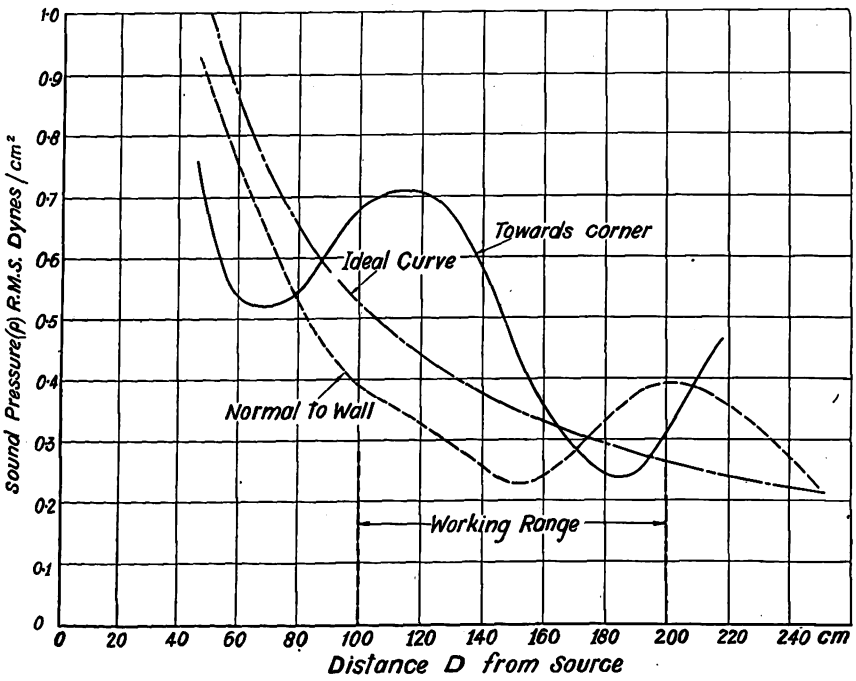

Fig. 20.—Pressure distribution curves in lined test room.

Frequency = 170 cycles per sec. Source at centre of room and 15 in. above floor-level.

The floor of the room is of concrete and the ceiling of wood. Double doors are provided, the inner sides of the inner doors being covered with cotton waste. The runway passes through those doors to a point opposite the main door of the building. It then curves round into the generator room. By this means, lifting facilities are available for handling apparatus coming in for test, and also for easily moving any apparatus in the generator room. To avoid the transmission of sound or vibration into the test room through the runway, a short gap is left in the latter near the test-room door. The test room is ventilated by suitable ducts and a fan which is

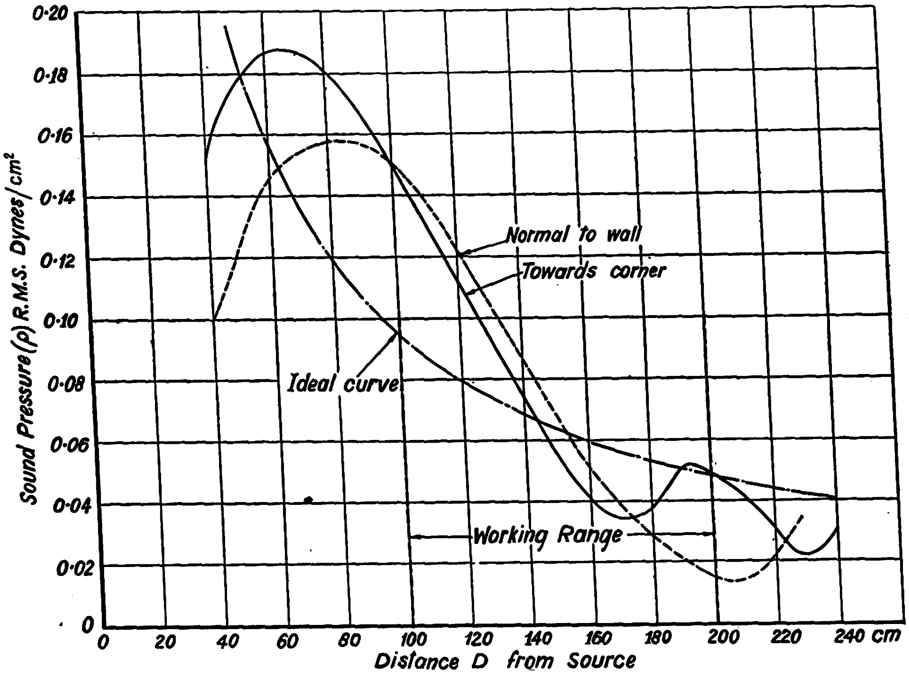

FIG. 21.—Pressure distribution curves in lined test room.

Frequency = 270 cycles per sec. Source at centre of room and 15 in. above floor-level.

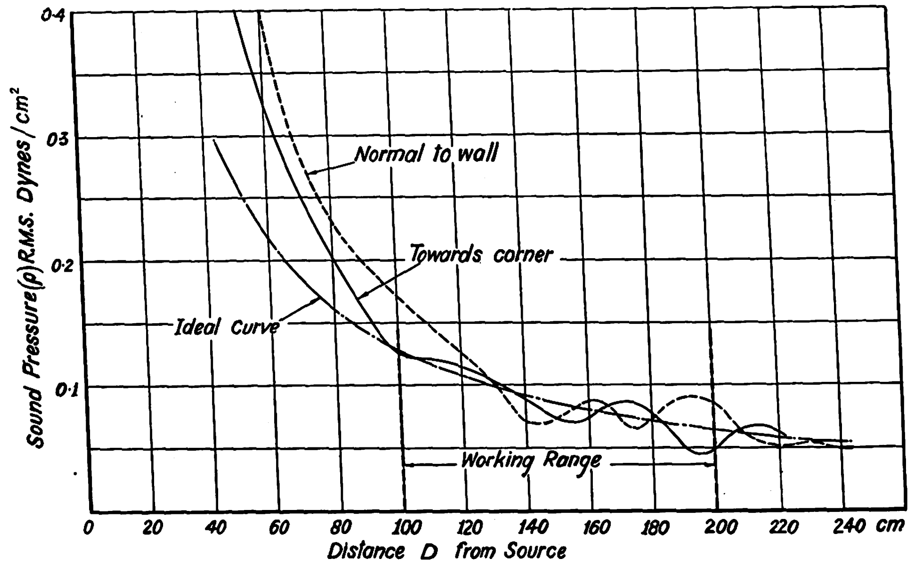

FIG. 22.—Pressure distribution curves in lined test room.

Frequency = 540 cycles per sec. Source at centre of room and 15 in. above floor-level.

located in the roof. If necessary, the noise of the fan can be eliminated by switching it off during a test. The generator room contains a separately excited d.c. generator mounted on a concrete block, and load resistances, so that suitable loads can be applied to a motor under test at speeds up to 3 000 r.p.m. The generator is coupled to the motor by a long shaft, mounted in ball bearings, passing through the double wall separating the test and generator rooms. The instrument room, the dimensions of which are 27 ft. 6 in. by 6 ft., provides accommodation for the sound-measuring apparatus (except the microphone), the control gear for the motor or other apparatus under test and for the loading generator. The fundamental standards for calibrating the measuring apparatus are also placed in this room. For heating this room the heaters are distributed in such a way as to avoid appreciable temperature gradients over the length of the Rayleigh disc tubes.

The site chosen for the building was a compromise between avoiding proximity to railway shunting sidings, factory buildings and a local substation containing a high-frequency alternator, and obtaining a conveniently central position. It was necessary to avoid not only acoustic disturbances but also electromagnetic disturbances from such apparatus as high-frequency induction furnaces and high-frequency oscillation generators and from the powerful oscillatory discharges associated with high-voltage testing.

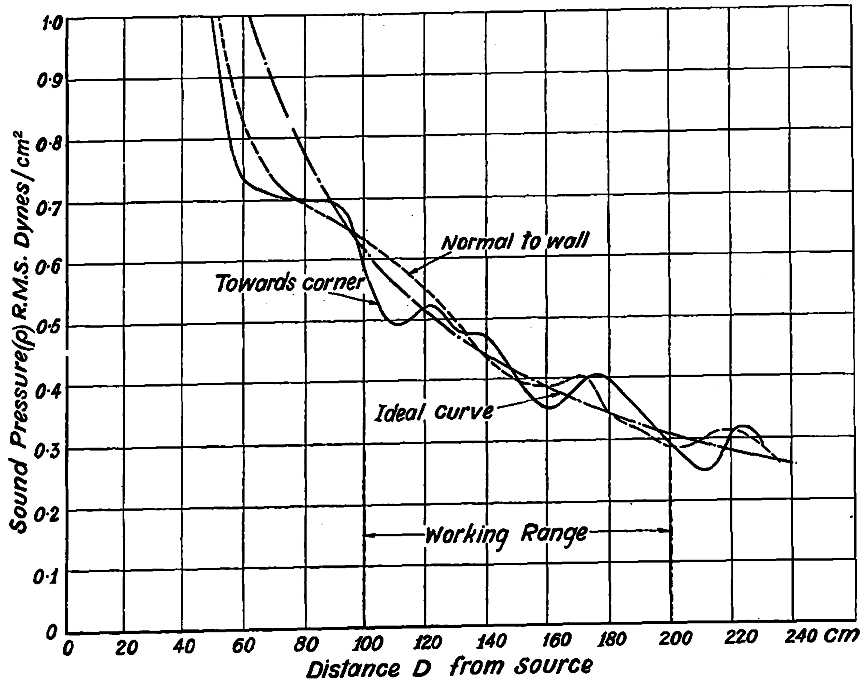

FIG. 23.—Pressure distribution curves in lined test room.
Frequency = 1 080 cycles per sec. Source at centre of room and 15 in. above floor-level.

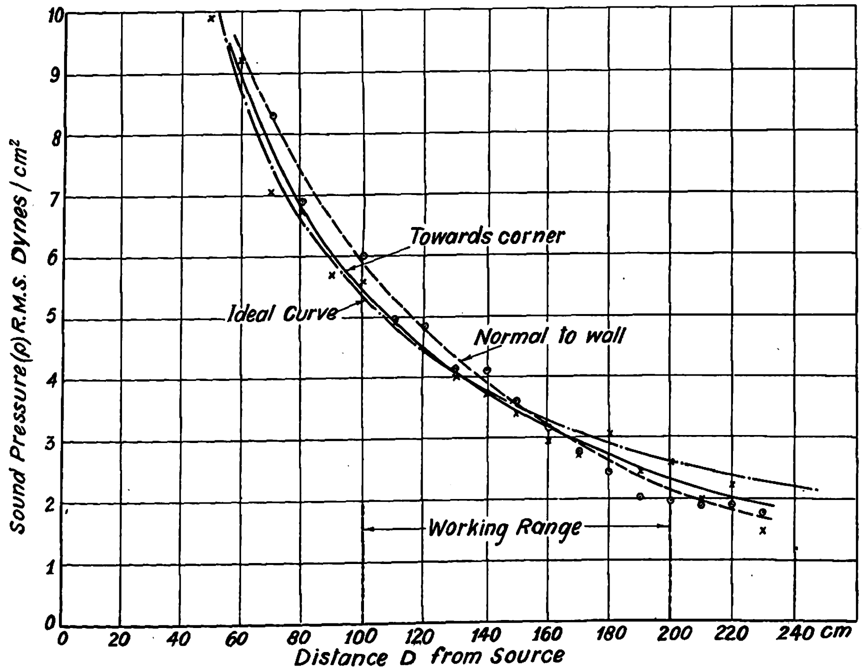

FIG. 24.—Pressure distribution curves in lined test room.
Frequency = 2 160 cycles per sec. Source at centre of room and 15 in. above floor-level.

The choice of a 10-cm lining of cotton waste for the test room was made as a result of Mallet and Dutton's work.* However, when the sound field due to a source hung in the centre of the room was explored it was immediately obvious that reflection effects were important, especially at low frequencies. An investigation into the reflection from different thicknesses of cotton waste was therefore commenced with a view to determining the best thickness to employ, having regard to economy and absorption. The Rayleigh disc and resonant-tube method seemed directly applicable to the problem, so it was chosen as the apparatus was all at hand. Tests were begun with a frequency of 292 cycles in the large calibrating tube with 2½ wavelengths between the reflecting pistons, one containing No. 4 microphone and the other the source exactly as in calibrating. The input to the source was measured and kept at that value throughout the tests. By taking preliminary readings of the Rayleigh disc and analyser galvanometer deflections, an incidental check was obtained on the microphone calibration and showed that it had not varied appreciably over a period of 6 months. The microphone and its piston were covered with a 10-cm layer of cotton waste, care being taken to keep the diaphragm free by a layer of copper gauze. It was found that the resonant frequency was unaltered, but the pressure and velocity deduced from the new readings were reduced in exactly the same ratio. Measurements were then made with 20 cm and 30 cm of waste and also with different densities of packing. In all cases the pressure and velocity readings agreed and the resonant frequency remained the same. In interpreting the results, which are given in Figs. 18 and 19, it is assumed that the initial wave from the source remains constant and that therefore the final pressure, which is the result of an infinite number of reflections from the pistons, is inversely proportional to the absorption in the tube.

In the first tests a constant density of 30 grammes per litre was kept while the thickness was varied up to a maximum of 30 cm. Fig. 18 shows how the ratio of the maximum velocity with the waste to that without varies with the thickness. The latter is necessarily rather indefinite but the graph indicates that 30 cm of such a packing would be necessary to reduce the oscillating velocity and pressure to 1/10th. The results of the tests on the tightness of packing are given in Fig. 19. They show that the absorption increases approximately with the density of the waste up to the limit of the tests, viz. 90 grammes per litre. This suggested a further test with thickness, using a higher density of 50 grammes per litre. The curve still indicates improvement up to the largest thickness.

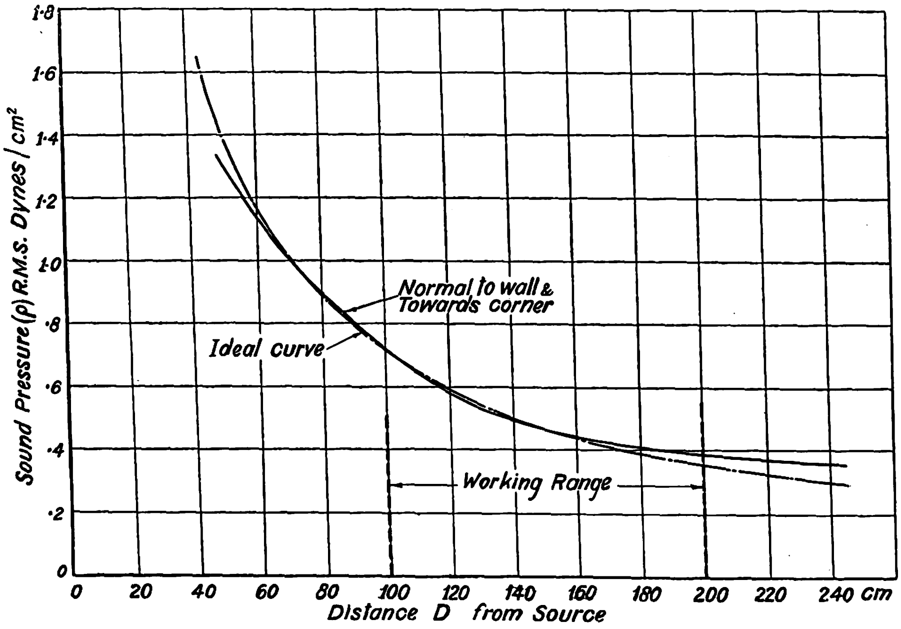

Fig. 25.—Pressure distribution curves in lined test room.

Frequency = 4 180 cycles per sec. Source at centre of room and 15 in. above floor-level.

It was obvious, therefore, that some compromise would have to be made, and finally a thickness of 20 cm was decided upon. A packing of approximately 50 grammes per litre made the total weight of waste nearly 1 ton; this figure was therefore adopted.

The packing on the walls and floor was first increased from 10 to 20 cm, that on the walls being pushed into the meshes of the wire netting so that when finished all the shelves and netting were covered with an unbroken layer of 10 cm of waste. On the floor several "stepping stones" of wood 15 cm thick were put where required to prevent the waste from being trampled down.

The work of plotting out the sound field due to a source suspended in the middle of the room was then repeated and a few typical pressure/distance curves are given in Figs. 20 to 25. These curves show that reflection effects have been largely eliminated at high frequencies but that they are still appreciable at low frequencies. Tests have usually been made at distances of 1 to 2 m, and as a result of these distribution curves a distance of 1·5 m has been standardized. All results, however, are referred to a standard distance of 1 m.

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* See Bibliography, (34).

(10) Examples of Test Results.

In order to illustrate the kind of result that may be obtained on various types of apparatus, a few examples are given below. These examples have been taken quite at random and should not be assumed to be representative of their respective classes.

Example (1). *Tests on a small motor.*—The following test illustrates those made on small motors in the non-reflecting test room. The example chosen is a 10-h.p. induction motor operating from the 420-volt, 3-phase, 50-cycle mains and running light. As one would expect, the distribution of sound round such a machine is by no means uniform in all directions, so it is necessary to take readings on all sides. Readings were also taken at several distances, viz. 1·0, 1·5 and 2·0 m, to verify the rate of falling-off of the pressure. In view of the smallness of the machine these distances were measured from the centre of the casing. Fig. 26 indicates the component frequencies with their respective amplitudes in the four directions.

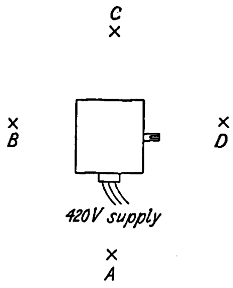

Fig. 26.—Diagram of sound field of a motor.

Readings taken at points A, B, C, D, all 1 m from centre of motor. The readings at A and B are almost identical, as also are those at B and D.

Readings at A		*Readings at D*	
Frequency (cycles per sec.)	Amplitude (R.M.S. dynes/cm²)	Frequency (cycles per sec.)	Amplitude (R.M.S. dynes/cm²)
225	0·625	100	0·07
360	0·37	225	0·235
524	0·18	310	0·27
590	0·18	394	0·35
670	0·18	590	0·12
1 640	0·10	1 120	0·12
		1 230	0·07
		1 640	0·06

Having obtained the components, the next step is to try to associate each one with some part of the machine. Since the sounds are peculiar to the rotation of the machine, each frequency is divided by the speed (revs. per sec.) of the rotor. A series of numbers is obtained which is very helpful in tracking the component sounds to their respective sources. For instance, in the case of this motor the following components are easily identified:—

Frequency of note	Frequency ÷ (revs./sec.)	Corresponding to
225	9	9 blades on fan
675	27	3rd harmonic of fan note
1 120	45	45 rotor slots
100	—	Vibration of punchings, twice supply frequency

As a check the fan was removed and another test taken. The 225- and 675-cycle components were absent.

Example (2). 1 000-*kW geared turbo-alternator set. Speed of turbine* 5 030 *r.p.m. Speed of generator* 1 000 *r.p.m. Distance of microphone from side of gear case,* 3·8 *m.*—Test carried out in large factory building in clear open space. Reflection effects were investigated and found to be not serious. The following values were obtained at full load and normal speed:—

Observation	Frequency (cycles per sec.)	Sound pressures (observed values)	R.M.S. dynes/cm² (aver. values; aver. corrected to 1 m)
A	2 710	2·37 to 2·75	2·56 to 9·7
B	1 610	1·04	1·04 to 3·9
	1 490	0·78	0·78 to 2·96
C	590	0·76	0·76 to 2·9
D	515	1·02	1·02 to 3·9
	474	1·25	1·25 to 4·7
E	360	1·17 to 1·4	1·28 to 4·9
F	240	2·94 to 7·6	5·28 to 20
G	190	0·7	0·7 to 2·6
	140	0·7	0·7 to 2·6

Observation A yielded a note of definite frequency, which slowly fluctuated in amplitude between the limits of 2·37 and 2·75. B consisted of a band of frequencies extending from approximately 1 610 to 1 490 cycles, the amplitudes corresponding to these frequencies being 1·04 and 0·78 respectively. C gave a definite and steady note, D gave another band of frequencies and E a definite frequency but slightly fluctuating amplitude. F was of considerable and variable amplitude but of low frequency, while G consisted of a general low-frequency rumble.

Example (3). *Test on a commercial horn-type loud-speaker.*—The sound-measuring apparatus and testing laboratory were developed primarily for tests on machines, but the present example illustrates the application of the methods and technique to another useful purpose. The comparison of loud-speakers in the past, as regards sensitivity and type of response curve, has been largely a matter of opinion. It is easy, with the apparatus described, to measure the response of any loud-speaker in a sensibly non-reflecting room at all important frequencies and to give the answer in absolute units. The curve of response against frequency, such as is given in Fig. 27 for the attracted-diaphragm type of loud-speaker tested, then provides a definite fundamental basis for comparison. There is very little doubt that, in a year or two when people have been educated to the sight of the utterly inadequate curves for their favourite loud-speakers, the makers of the better-class instruments will publish response curves just as the intervalve transformer manufacturers have done recently.

The fact that the loud-speaker tested would satisfy a large proportion of listeners is a striking testimony to the adaptability of the ear. Notes in the lower half of the piano range are heard largely as harmonics, the ear subconsciously supplying the diminished or absent fundamentals. It is also interesting to note that when this loud-speaker was supplied with 50-cycle currents no output at that frequency could be detected but, due to non-linearity, frequencies of 100 and 150 were generated and could be detected.

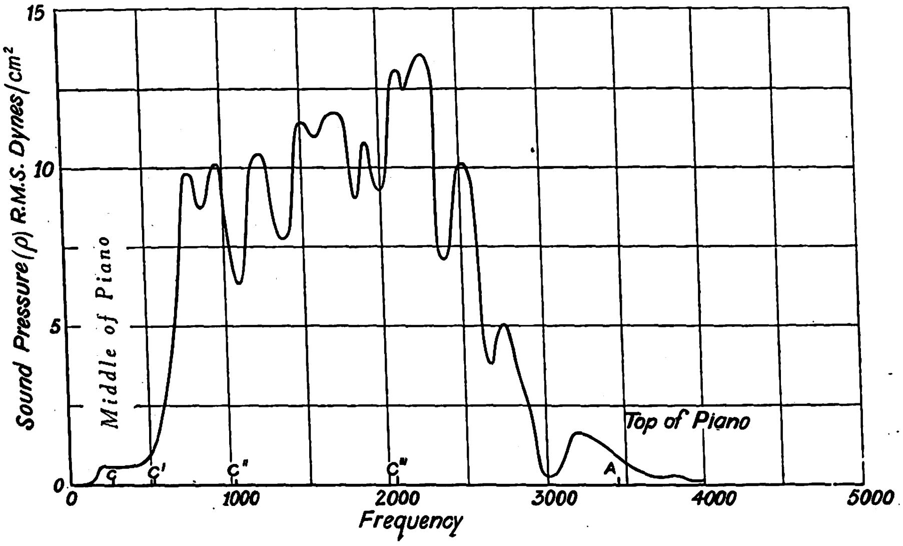

FIG. 27.—Response curve for a loud-speaker of attracted-diaphragm type.
Input current = 1·6 mA. Corrected for reflection from microphone. Measurements made at 1·5 m and reduced to 1 m.

If preferred, of course, the test could be made in conjunction with a particular loud-speaker valve, but in the present example a constant current of 1·6 mA was kept in the operating coils.

Fig. 28 shows the wave-form of sound emitted by a motor-generator set, and illustrates the complexity and non-periodic character of such waves.

(11) THE ASSESSMENT OF TOTAL NOISE.

It is generally accepted by psychologists that the ear adapts its sensitivity to the strength of the sound which acts on it. That is, for a loud sound the ear automatically de-sensitizes itself, afterwards regaining its sensitivity for small sounds. It must be very largely due to this self-preserving capacity that the ear has such a remarkable range of sound pressures to which it responds. At 1 500 cycles this compass of the ear is 5×10^6 in pressure units or 25×10^{12} in energy units.

Another consequence of this automatic regulation of the ear is to make equal geometric increments of sound energy appear like equal arithmetic increments in loudness. If, therefore, we take the logarithms of the intensities of two pure notes of the same frequency, then the difference between the logs is a measure, to some "sensation" scale, of the difference in loudness of the two notes. Further, if one of the notes happens to be on the threshold of audibility, then the difference between the logarithms of the two intensities can represent the absolute strength of the louder note on our arbitrary sensation scale.

In choosing suitable units for this new scale, telephone engineers have been guided by their previous standard, the "800-cycle standard mile." Instead, therefore, of taking just the logarithm to the base 10 of the sound energy, a unit 1/10th as large has been adopted and this corresponds roughly to the old standard. The name "decibel" has been given to the new unit to commemorate the inventor of the telephone, Graham Bell.

Since we work in sound pressures the difference in loudness between two pure notes of pressures p_1 and p_2 dynes/cm² is $20 \log_{10}(p_1/p_2)$ decibels.

Taking for p_2 the minimum audible pressure at the frequency considered, the loudness level of the pressure p is $20 \log_{10} (p_1/p_{min.})$ decibels.

Here we have a method of assessing the loudness of notes of different amplitudes but the same frequency. This latter restriction is important as the variation in minumum and maximum audible sound pressures at different frequencies is enormous.

In trying to compare the loudness of notes of different frequencies it seemed reasonable to the authors to make a sound corresponding to the maximum audible pressure at any frequency to be represented by 100 and a sound on the threshold of audibility by zero on the loudness scale. That is to say, they divided the range between minimum and maximum audibility into 100 equal ratio steps, calling these equal increments on a sensation scale.

The "relative loudness" or "nuisance" figure for a sound of pressure p dynes/cm^2 (R.M.S.) is therefore given by $100 \log_{10} (p/p_{min.}) \div \log_{10} (p_{max.}/p_{min.})$, where $p_{min.}$ and $p_{max.}$ are the minimum and maximum audible sound pressures taken from Fig. 1.

Since the ordinates of Fig. 1 are on a logarithmic scale, it is easy to get a rough idea of the loudness figure corresponding to a given pressure p at a frequency f by plotting the point (f, p) and noting into what proportions it divides the intercept between the two curves. If the point is half-way up the intercept the loudness figure is 50, if one-quarter of the way, 25, and so on. It is possible to mark the contours corresponding to loudness figures of, say, 60, 40 and 20 on Fig. 1 to facilitate this quick estimate.

Experience in testing a large number of machines of all sizes and types has given the authors a certain amount of confidence in this tentative loudness scale. A preliminary aural estimate of the most offending component of a noise is always confirmed by a high loudness figure where the results of an analysis are available.

Even if this loudness scale is accepted for the moment, the problem of assessing the total loudness of a number of components of different frequencies still remains. A solution of this problem has been proposed by J. E. Steinberg,* but the authors have not yet had an opportunity of judging how far his methods can be applied.

There is one case which does not lend itself to the above treatment. This exception is a band of frequencies such as is sometimes produced by windage. When analysing such a noise a continuous deflection is obtained over the whole band of frequencies, and the loudness figures deduced from the readings are much larger than one would expect. It is thought that this is due to the fact that the analyser is sensitive to a narrow band of frequencies, roughly 0·5 per cent wide, whereas the results are given just as if all the energy in that band were concentrated on the central frequency. The apparent energy density is therefore much greater than that which really exists at the central frequency. Any results given on such a band of frequencies are therefore peculiar to the resonance curve of the apparatus used, whereas measurements on pure tones and noises which can be analysed into distinct pure tones are independent of the apparatus used. Since writing the above the authors' attention has been drawn to an article by B. A. Kingsbury † in which he describes his experimental determination of comparative loudness. He deduces that the loudness of pure tones from 700 to 4 000 cycles is very well represented by the number of transmission units or decibels above the threshold value. For lower frequencies he found that the loudness increased faster than the transmission units or decibels above minimum audibility. These conclusions support the expression for loudness given by the authors, since the ratio of the maximum to the minimum audible sound pressures is nearly constant from 700 to 4 000 cycles and decreases rapidly at lower frequencies.

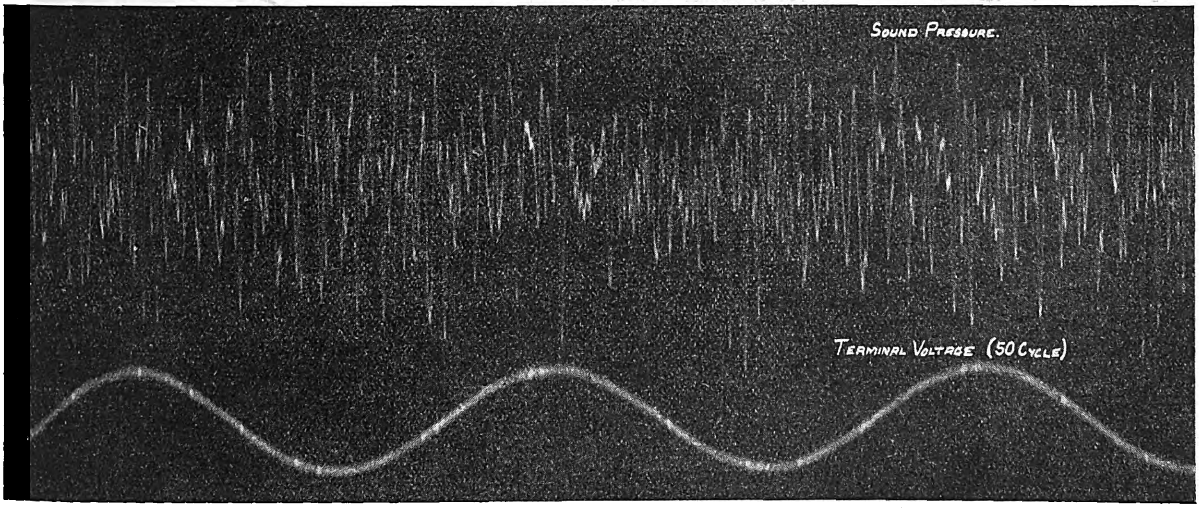

Fig. 28.—Wave-form of sound emitted by a motor-generator set.

It is evident that the assessment of the loudness of complex sounds is a subject of great importance and difficulty. It demands a knowledge not only of the physical qualities involved but also of the related physiological and psychological effects.

(12) Further Fields for Acoustical Measurements.

The experience gained by the authors in the testing of various machines has suggested that a modified form of sound-measuring apparatus might be employed to solve numerous other problems. A brief discussion of a few possible applications may therefore be of interest to those concerned.

The vexed question of "street noise" forms the subject of periodical attacks by the Press, but the difficulties in the way of fixing noise limits and enforcing them have prevented much progress from being made. To take a record of such noises the amplifier and oscillograph are directly applicable, but unfortunately there is the difficulty of analysing the oscillograms obtained.

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* See Bibliography, (24).

† *Ibid.*, (26).

A new apparatus of a more portable and self-contained type is therefore being designed and it is hoped that it will be possible to analyse a noise into all its components and measure their frequency and amplitude in approximately 1 minute. Motor vehicles and tramcars could be driven round a circular track at a constant speed with a central microphone always pointing towards the machine under test. In this way noise pass limits could be fixed and border-line cases judged on a definite quantitative basis. It is certain also that the information obtained would be of great help to the designers of such machines in producing quieter models. In view of the rapid advance in civil aviation it is more than probable that, sooner or later, similar methods will have to be applied to reduce the noise emitted by aeroplanes and airships.

The investigation of the sounds emitted by musical instruments constitutes a vast field for acoustical measurements. The excellence, from a tonal point of view, of English organs is known all over the world. This high standard has been gradually achieved by trial and error over a period of centuries. It is probable that the precise and detailed information that acoustical measurements can furnish would be of considerable assistance to organ builders. With an apparatus of the kind described in this paper the pitch and intensity of the fundamental tone and of the partials of an organ pipe could be measured with ease, and the effect of any modification in the structure of the pipe, the wind pressure or other condition immediately ascertained. The apparatus would not, of course, indicate tone quality from a musical point of view, of which the ear, in conjunction with a high degree of musical sensibility, must always be the judge. The measurements would, however, show quantitatively the physical constituents of any tone quality and would assist in the accurate reproduction of a given quality in pipes of the same nominal quality and pitch, and in preserving a uniform tone quality in a set of pipes covering a certain compass.

(13) Conclusions.

In order to keep the paper within a reasonable length, the authors have not attempted to deal with the whole subject of the noise emitted by machines but have confined themselves to a discussion of methods of measuring noise emitted by stationary machinery, which is a necessary preliminary to any systematic investigation of the subject. Since the paper was written, a wide experience has been gained in the interpretation of the results of measurements on machines of various types, their correlation with the design data of the machines and the measures which are effective in removing excessive noise. The discussion of these matters is beyond the scope of the present paper.

In conclusion, the authors wish to acknowledge their indebtedness to Mr. J. S. Peck and Mr. A. P. M. Fleming, C.B.E., for their interest and support throughout the research, to Mr. R. Johnson, to whom the inception of the work was due, and to Messrs. D. B. Hoseason and J. M. Newton for ready discussion and co-operation. They also wish to thank their colleagues of the Metropolitan-Vickers Research Department for assistance in the experimental work and in the construction of the measuring apparatus.

They also wish to acknowledge the permission of the Metropolitan-Vickers Electrical Co., Ltd., to publish the paper.

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DISCUSSION BEFORE THE INSTITUTION, 7TH NOVEMBER, 1929.

Prof. E. Mallett: Some years ago Dr. Dutton and I constructed a small sound chamber for use in measuring the overall efficiency of a telephone receiver. We were not troubled by sound reflection from the walls of our chamber, which were lined with cotton waste. The authors were guided by the results we obtained, and they did not get a satisfactory solution. We, however, were working at frequencies of from 700 to 900 cycles per sec., and from the authors' results it will be seen that we were fairly safe over that range. It is at lower frequencies that reflection troubles in the sound chamber become serious. The authors, by working down to 100 cycles and up to 4 000 or 5 000 cycles per sec. with one piece of apparatus, have carried out an important and difficult task. The use of the moving-coil movement of the loud-speaker as a microphone, instead of the more usual condenser microphone, is a bold step. At first glance one might think that the moving-coil movement was unsuitable; in America the condenser microphone is always used. It is interesting to note that the moving-coil system proved so successful. The amplifier presents no real difficulties, except that one must be very careful that the coupling condensers are of very high insulation resistance. If the insulation resistance of a condenser falls to 20 megohms, the next valve will probably cease to function correctly owing to the positive potential thus produced on the grid. The coupled-circuit method of overcoming difficulties due to the frequency variation of the machine under test is ingenious, and the authors are to be congratulated on it. Prof. Miles Walker made a suggestion for harmonic analysis, in which the machine itself was used to give the frequency of the auxiliary current necessary for measurement. That, one would have thought, would be a suitable method also, except that the authors have found frequencies which are not harmonic. There must be some sort of shock excitation of parts which vibrate at their natural frequencies, which are not necessarily harmonic. The influence of the size of the microphone on the proportion of the wave reflected and the correction to be applied to the pressure reading has for a long time required investigation, and the authors are to be congratulated on carrying out an opportune piece of work. Returning to the sound chamber, Figs. 18 and 19 can be arranged a little differently, so as to indicate the best density at which to use a given mass of cotton waste. Fig. A shows two curves, (i) reproduced from Fig. 19, showing the sound absorption with various weights of waste packed into 10 cm thickness, and (ii) the absorption for the same weights of material but at a thickness in each case giving a constant density of 30 grammes per litre. It is seen that the looser packing is the more effective. With 250 grammes of material the ratio with the loose packing is about half that with the tight packing. Since this clean cotton waste is expensive, this is an important consideration. These curves apply only to a frequency of 292 cycles per sec. It would be interesting to see similar data at other frequencies.

Mr. D. B. Hoseason: The paper deals with one particular method of measuring noise emitted by machinery. It may save other investigators a little time if mention is made of the work which had already been done before the assistance of the authors was obtained. There are two fairly well-known methods of assessing and comparing noise. First there is the shunted telephone method, referred to in the paper, which has been used both in Germany and in America with, we are told, a certain measure of success. This device was investigated fully, and the conclusion arrived at that it was not satisfactory on account of the periodic characteristics of the telephone. These make comparison of the results obtained from machines emitting noises of different frequencies quite useless. An alternative method which has been used in the United States is that of comparison with a standard machine. A selected machine is adopted as a standard and placed in a sound-proof room. The machine under test is placed in another sound-proof room, and the noise from each received in the two ear-pieces of a pair of headphones. The ear-piece corresponding to the machine under test is shunted to obtain the comparison. This method has the same defect as the first-mentioned scheme. Another alternative which was tried, and with which, again, we were not very successful, was to use a dictaphone. We endeavoured to take records of the sound emitted by various machines, with the idea of filing these and listening to the dictaphone records of a particular machine built, say, 2 years previously, and one which was on test in order to discover whether it was more noisy or less noisy than the previous machine. Eventually we sought the assistance of the authors, and in spite of the troubles that have been experienced the results embodied in the paper are, to say the least, highly satisfactory. A matter that intrigues me is the question of the influence of harmonics on the fundamental sound-wave—or what really seem to be not so much harmonics as a mixture of noises of several different frequencies. The authors refer to Knudsen's work and state that several tests have been made presumably by listening to a fundamental note and then adding known harmonics to it. Has Knudsen stated the amplitude of the harmonics and given any definite frequency relation between these and the fundamental? Some specific figures would be of assistance. Later in the paper reference is made to the work now being done by Steinberg, and it would be interesting to have details of his methods. The intermingling of notes of several different frequencies is at the present time the most urgent and difficult problem that we have to face in this matter.

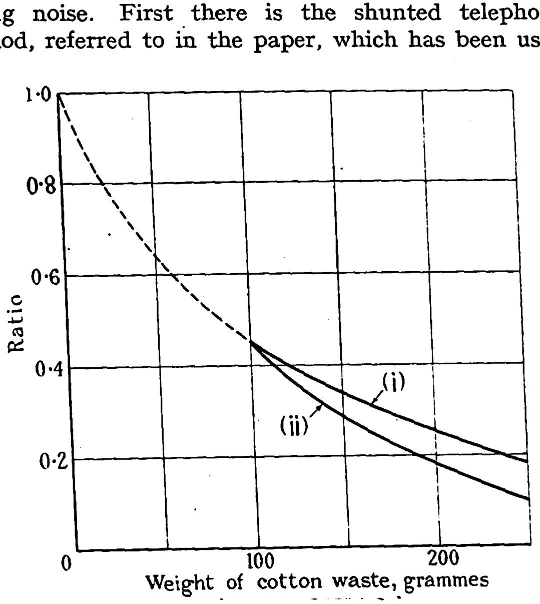

FIG. A.

Mr. A. J. Aldridge: This paper is an indication that at least one firm is at last making an attempt, on sound lines, to tackle the problem of noise and its elimination. It deals with matters on the border line of physics and engineering, and to many of us these border-line cases are more interesting than those dealing with purely engineering questions. I am particularly interested in the earlier part of the paper which deals with the measurement of sound. The authors have adopted an electromagnetic microphone to pick up the noises. An instrument of this pattern can be made fairly robust and this is an important consideration for a works instrument. It will, however, usually be of greater bulk than a condenser transmitter, and would, I expect, be rather difficult to screen when used near heavy-current machinery. Have the authors experienced any trouble due to this cause? On page 103, the authors state that they selected a microphone of this type because its performance could be calculated. They make this calculation and then proceed to check it by a direct calibration, and accept this method of calibration since the results of both methods agree reasonably. This appears to be "putting the cart before the horse." The calibration method is much superior to the calculation method. The method shown in Fig. 7 for calibrating microphones was first proposed in 1926 by Mr. W. West, of the Post Office Research Station, and has been largely used by us since then. We have several tubes in use designed for from 50 to 6 000 cycles per sec. Independent tests of this method against two others have shown it to be thoroughly reliable, and the only point to bear in mind is the fact that the "use" and "calibration" conditions are different. The authors deal with this matter on page 109 and subsequent pages. The authors do not give much information as to the results of their tests. It would be interesting to know if they have arrived at any values of permissible sound pressures for machinery for noises of various types, and also what measure of success they have reached in reducing the various noises when they have located their sources. It may be of interest to quote a few results recently obtained in connection with the noise in a city office. The occupant complained that it was impossible to work with the windows open and that even when they were shut the street noise was objectionable. Measurements were made with a calibrated condenser transmitter, the output of which was read for some hours on two microammeters in series, one being a slow-moving recording instrument, to average the results, and the other a quick-moving instrument, giving the peak values. It was found that the energy density was much the same in all parts of the room and with the windows open average figures of up to 0·5 dyne per cm^2 were recorded. (The pressures at the threshold of audibility vary from about 0·01 at 200 cycles per sec. to 0·005 at from 1 000 to 5 000 cycles per sec.) The fitting of a false ceiling of ½-in. felt 5 in. below the true ceiling reduced the pressures by about half. The noise was practically all found to occur at frequencies above 500, and as the ear reaches its maximum sensitivity just above this point, the improvement, as tested by ear, is greater than the figures indicate. Tests were also made in the modified room of the noise from a single typewriter. Values of up to about 0·5 dyne per cm^2 were found, the frequency of the noise being almost entirely above 2 000 cycles per sec.

Dr. L. E. C. Hughes: I am particularly interested in these specialized methods for the measurement of sound. When listening to a sound one hears the direct sound and the reverberation, and I should like to know if the authors considered a reverberation method, since noises usually reach us as reverberatory sound, and in any case it is the total sound radiated that is required in this measurement. Having decided to measure the direct sound, the authors would have saved considerable time by adopting the condenser transmitter, which, although expensive, is ideally suited for the desired measurement and has been extensively used in acoustic research for many years. The calibration of the condenser transmitter is performed with the thermophone, which generates a known excess pressure on the diaphragm. When placed in the open sound field, the excess pressure is, as indicated by the authors, augmented owing to the disturbance. I once thought that the unknown error might be circumvented by placing the condenser transmitter in the centre of a large baffle or wall. We then know that the excess pressure upon the diaphragm is exactly double that in the free wave for every frequency, and the thermophone calibration is applicable without correction. This wall would form one side of the sound chamber; reaction on to the source is negligible under these conditions. The best method using the condenser transmitter, or any other transmitter, is to compare its output when subjected to a sound with its output when a known electromotive force of the same frequency is injected into its earth lead. Not only is the calibration of a high-grade amplifier eliminated, but the circuit is exactly the same as that used in the thermophone calibration, and there can be no doubt in the interpretation of the measurements. The authors appear to have aimed at a high degree of accuracy in their sound intensity measurements; excess pressure measurement to within ± 10 per cent, corresponding to ± 1 decibel, is ample in this connection. Condenser transmitter calibrations are given to the nearest ½-decibel, which is adequate considering normal daily variations in such transmitters. With regard to the sound chamber, it is comparatively simple to measure the standing waves from one of the walls and compute the coefficient of reflection. In Prof. Mallett's 9-ft. cube lined with 4 in. of loose cotton waste on netting, I found the coefficient to be 6 per cent at 400 cycles per sec. and about 1 per cent above 800 cycles per sec., which is much less than for any other material. In the chamber described by the authors, a definite reduction in the reflection coefficient at low frequencies would result from the provision of a hollow space behind the cotton waste, in accordance with the principle that if cotton waste is to be used to absorb the motion of the air particles, it should be placed where the particles are moving, and not against a hard wall where the motion of the particles is practically nil. With regard to the curves in Figs. 20 to 23, it is stated that the source is 15 in. above the floor. Now it can be shown mathematically that on a line of symmetry towards a corner there is an augmentation of the apparent intensity due to reflection, but no wave-effect such as is exhibited by the curves. It seems, therefore, that the standing-wave effect is due to the wave reflected from the floor, and that better results would be obtained by locating the source at half the height of the ceiling. This observation applies also to the machines which are tested for noise.

Dr. A. H. Davis: At the National Physical Laboratory we have had to deal with various phases of noise recently; for instance, in assisting the Aeronautical Research Committee with the study of aircraft noise. Naturally, sound analysis is receiving attention, but I have also made several observations by ear, using a simple sort of noise meter which is proving, I think, to be of value. With this work in mind, the subject on which I wish to dwell for a few minutes is the assessment of noise, but I should first like to make a few comments regarding the instrumental side. The identification of sources of noise is, as the authors point out, facilitated by knowing the frequencies of the components, and so an analyser is necessary. Apparatus of a general type resembling that described by the authors has been used for several years in connection with the physical analysis of sound and noise, and, in addition to the papers mentioned by the authors, perhaps papers by Snook,* in 1925, and Firestone,† in 1926, on automobile-noise measurement may have some value for reference. A previous speaker has mentioned that the Americans have been investigating by a somewhat similar method the noise emitted by machinery; and Spooner and Foltz ‡ have recently published a paper dealing with tests on the noises in electrical apparatus, using somewhat similar apparatus, with certain differences of detail; in particular, they do not use double tuning. The method of Grutzmacher § is so promising that I should like to refer to it, though the authors will no doubt point out that it is inapplicable in certain cases. It enables each component of the noise to be studied in turn by heterodyning it with a pure exploring note of variable frequency. It is a somewhat indirect method, but its outstanding features are that it gives very sharp selectivity and in suitable circumstances is exceptionally convenient. For instance, the complex sound emitted from a loud-speaker when actuated by the ordinary 50-cycle a.c. supply mains, and adjusted so that the diaphragm rattled against the pole pieces, was analysed by Mr. Fleming and myself in a few minutes, some 30 definite overtones of the fundamental being observed. The method was adapted by Grutzmacher to be self-recording on a photographic drum, and a complete record giving the intensity and frequency of the component sounds can be obtained, he states, in a few seconds. The selectivity, of course, is marked. As the authors point out, where the noise is not of fixed pitch too great a sensitiveness to frequency reduces the value of the analyser; but recently Salinger has suggested improvements * which may be of assistance in this direction. The authors have dealt with this question of selectivity and, to meet the needs of their own work, have ingeniously adopted double tuning in order to obtain a flat-topped selectivity curve. Turning to the assessment of noise the position, as I see it, is as follows. We do not yet know how to infer the loudness of a complex sound from the analyser results. We know that the matter is complicated. The formula to which the authors refer, namely that advanced by Steinberg, was quite intricate, but I suspect that even this has not proved applicable outside the range of experiments on which it was based. It is 4 years since Steinberg's paper was published, and recently a member of the laboratory to which Steinberg belongs wrote: "Attempts to develop methods of calculating loudness which have a general application have not yet been successful." † The Steinberg formula is apparently being gradually abandoned. On the one hand, therefore, we feel that we must take physical measurements in order to obtain analyses which will be useful in tracing the sources of components, and which will give a permanent record; but on the other hand, since our knowledge is incomplete, I think that we ought sometimes to try to assess the loudness itself by instrumental means. From that point of view I do not agree with setting up a relative " loudness " or " nuisance " figure from the analyser at this stage, as the authors appear to suggest. I do not agree with the scale which they show; I think we know, even now, that pure tones with the same relative loudness figure on this scale would not be equally loud. Further, the authors themselves found their procedure somewhat troublesome when dealing with such sounds as the band frequencies which result from windage. In my opinion, for the present at any rate, the loudness or nuisance term should be left open for methods which attempt in some way to assess loudness itself. A method I have used, largely on aircraft work, with promising results is to produce a pure note of standard pitch in a telephone ear-piece, and to adjust its loudness until it appears to be as loud as the noise observed. That may seem troublesome, but in my experience different observers tend to get the same result, and over a period of some months I have found the method substantially consistent and useful. With such a method one can thus say that the noise appeared to be as loud as a pure note of standard pitch exerting a pressure of a certain number of dynes per cm^2 on the ear. This seems to be the tendency to-day in specifying loudness—to refer it to the loudness of a standard note. Alternatively, or, as I prefer, in addition, one can say that the noise was observed to drown this standard note when the intensity of the latter was at some lower figure. I think that both statements are useful. The equality method has been used by Barkhausen in Germany, while the masking method has received more attention in America. I suspect that the energy ratios of the test note in the equality method bear a more nearly linear relation to the energy ratios of the observed noise than is the case with the masking method, for with the latter method it is well known that a certain amount of sound is usually required before any appreciable masking appears at all. On the other hand, masking is not to be ignored, for it is used in everyday life to express loudness; people say "You could hear a pin drop" or "You could not hear yourself speak." Those are masking standards. With regard to this method of balancing a complex noise against a pure note, I set out quite prepared to abandon it, but I have been somewhat impressed by its usefulness in suitable cases. I feel, therefore, that observations of this kind are sometimes desirable to supplement analyses, and that one should drop the terms " relative loudness " or " nuisance " in connection with the percentage figures suggested in the paper, or at any rate defer them until the figures suggested have a better basis than they have at present.

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* *Journal of the Society of Automotive Engineers*, 1925, vol. 17, p. 1.
† *Ibid*, 1926, vol. 19, p. 461.
‡ *Journal of the American I.E.E.*, 1929, vol. 48, p. 199.
§ *Elektrische Nachrichten-Technik*, 1927, vol. 4, p. 533.

Mr. G. C. Marris: After reading the title I was a little disappointed to find that more than half of the paper consists of a rather detailed summary of matter relating to general acoustics of which a good deal has already been published, and it is not until two-thirds of the way through that there are some figures relating to actual results obtained on the machines. These results are certainly interesting as showing what may be expected in the future. The authors have given some results obtained on a turbo-generator. Can they give us an interpretation of these results? I think that the high frequencies are very important in connection with machine noise, especially in some of the smaller machines. I gather that the authors have concentrated on the lower frequencies. Above 3 000 cycles, however, noises which are important do seem to occur, especially as in that region the ear is still very sensitive. In the paper by Grutzmacher, to which Dr. Davis has referred, are some very interesting figures showing the spectrum of the noise from, I believe, some small domestic machinery, such as vacuum cleaners. The authors advocate the use of the moving-coil type of pick-up, but it certainly seems to me that it has drawbacks, and I do not feel convinced by their arguments. The calibration curve given in Fig. 9 is rather complicated to work to, and with such resonances and cut-off points it seems to me that the record of transient sounds must be rather distorted, though possibly these are not very important in every case. Early in the paper the authors state that the ear is not sensitive to phase displacement. That is true, but it applies only to the steady state; for the transient condition it would appear somewhat important to obtain a record, correct as to phase, through apparatus which has a linear frequency characteristic. If one assumes that an accurate analysis of sound is important in tracing the source of noise, and in studying the performance of acoustic apparatus generally, one would seem to require recording apparatus having a really straight frequency characteristic, and not an irregular one corrected by a calibration curve. As to the use of condenser transmitters, certainly our experience has not shown that there is difficulty in getting adequate sensitivity, or that low-capacity leads of a reasonable length cannot be used. It is possible to connect one stage of the amplifier right up against the microphone and to remove the rest of the amplifier to a distance. I was somewhat disappointed to find that the authors' moving-coil microphone had no greater sensitivity, judging by the figures given in the paper, than the condenser type. The authors state that they used specially purified cotton waste; it would be useful to know what form the purification took. I have not studied closely the analysis of the movement of the moving-coil microphone, but there appears to be no allowance for the "added mass" of air on the diaphragm. I am not clear whether, in the case with which the authors are dealing, that is actually of importance.

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* *Elektrische Nachrichten-Technik*, 1929, vol. 6, p. 293.

† "Speech and Hearing," p. 244 (Macmillan & Co., Ltd.).

Mr. W. West: Why do the curves in Fig. 10 not show proportionality between wavelength and diameter of baffle? For example, the 540-cycle curve reaches the ratio 2 for a 30-cm diameter baffle, while the 270-cycle curve reaches this ratio at 50 cm and not at 60 cm; the 1 080-cycle curve at 21 cm, not 15 cm, and so on. The authors' method of adding baffles to the microphone involves two considerations which are, I think, of interest, though probably not of importance in the present case. The addition of a baffle to the microphone may alter, first, the mechanical impedance of the diaphragm and, secondly, the rate of emission of sound energy from a source of constant strength. The first effect might be important only where there is resonance, when the mechanical reactance of the microphone is small, i.e. on the steep parts of the microphone curve (Fig. 9). The fractional change in the rate of emission of energy from a small source, distant x cm from a large baffle, is $(\sin 2kx)/2kx$: numerically, when $x = 150$ cm, this does not exceed 10 per cent at frequencies greater than 200 cycles per sec. The authors contemplate the investigation of transient sounds with their apparatus; are they satisfied with the characteristic of their microphone for this purpose? There appear to be somewhat undamped mechanical resonances which would blur the form of the transient by their free periods of vibration. The relative loudness figure is based on the threshold of audibility; this implies that the loudness is judged against a background of silence. I think it has already been established that the effective loudness of a sound will depend on the character as well as the magnitude of the background against which the sound actually is heard.

Messrs. B. A. G. Churcher and A. J. King (*in reply*): We are glad to have Prof. Mallett's confirmation that, in fixing the thickness of the cotton-waste lining to his testing chamber at 4 in., he only wished to ensure that reflection was negligible at frequencies of about 800 cycles per sec. and above. With regard to our use of the moving-coil type of microphone we are fully aware of the advantages of the condenser type, but we do not wish to be tied to any particular type of instrument. The calibration of the moving-coil instrument is very constant and when it is used with a frequency analyser, which is the case with practically all our work, the variation of response with frequency is no inconvenience. With regard to the possibility of low insulation-resistance in the amplifier coupling condensers, this contingency and any other which may affect the amplification is covered by the device, which is embodied in the amplifier, by means of which the amplification can be checked at any time in a few minutes. With regard to frequency analysers of the Miles Walker type, it must be remembered that we have set out to deal with a great variety of engineering apparatus, both electrical and mechanical. It cannot be assumed that a synchronous supply is available, and, moreover, many acoustical frequencies are observed which are not functions of any electrical or rotational frequency. As Prof. Mallett suggests, parts of machines vibrate at their natural frequencies by shock excitation, and these frequencies are not necessarily related to any electrical or rotational frequency. We are much interested in Prof. Mallett's rearrangement of our reflection curves for cotton waste, which demonstrates a very useful point regarding economy in the use of the waste. In arranging our test room we had to place a limit on the thickness of waste we could use and then obtain sufficient absorption by using as great a density as possible.

Mr. Hoseason has given a brief but interesting survey of comparatively simple methods of comparing noise. While attractive on account of their simplicity and cheapness, none of these methods attempts to analyse noise or give noise values in terms of any definite or reproducible standard. Both these requirements must be met before any serious study of noise problems can be undertaken. With regard to the effect of the addition of harmonics to fundamental tones in Knudsen's work, it appears from his paper that the amplitudes of the harmonics are small compared with that of the fundamental. With regard to the theoretical work of Steinberg on the assessment of total noise, we fear that the subject is too complex to be dealt with here. We fully agree that the placing of the assessment of total noise on an adequate experimental basis is a very urgent matter and we hope to give attention to it in the near future.

Mr. Aldridge's question about the screening of the moving-coil microphone is dealt with in the paper. The earthing of the magnet system provides electrostatic screening, and the switching off of the electromagnet field enables electromagnetically induced voltages to be detected. With the microphone 1·5 metres or more from the source, there is seldom any trouble from interference. Referring to calibration methods, we are not under any misapprehension regarding the relative accuracy of the Rayleigh disc method and the calculation of the response curve of a mass-controlled microphone. Our object in comparing the results of the two methods was to ensure that no large error was present in our procedure in using the Rayleigh disc; it was not to confirm the principle, which has been established beyond question. The subject of calibration is so important that an independent check, even if only a rough one, is of great value. We are interested to know that development work has been proceeding at the Post Office laboratories concurrently with our own on the use of the Rayleigh disc in a closed resonant tube. The only indication we have had of the Post Office work on these lines has been a brief reference to the use of tubes down to 50 cycles per sec. in Mr. West's paper* this year, which, of course, appeared long after the completion of our work, which was submitted to the Institution in December 1928. With regard to limits for permissible noise in machinery, the discussion of this matter is beyond the scope of the present paper. We are greatly interested in Mr. Aldridge's observations on the noise in an office due to street traffic. The results would be difficult to interpret in terms of loudness in the absence of more detailed information on the frequency spectrum.

In reply to Dr. Hughes, we feel that many of his remarks arise from a want of acquaintance with the practical limitations which arise in dealing with machinery. As our aim is to make our results of general application it is necessary to avoid any dependence upon the reflecting properties of a test room. As indicated in the paper, we wish our results to be equivalent to those which would be obtained in free space. Apart from the fact that reverberation involves reflection, we are unable to see how reverberation methods could be applied to the analysis of complex sounds emitted by steadily running machinery. With regard to the use of the condenser transmitter, the contention that this instrument is ideal for our purpose is debatable. We have found the moving-coil instrument very satisfactory for our conditions. The importation of a calibrated condenser instrument would not have avoided the problem of absolute calibration, as it was essential for us to be able to check the calibration of our apparatus at any time. When we started the work in 1926, the calibration methods of which descriptions had been published did not satisfy us and we decided to attack the problem on our own lines. The general experience gained, and the fact that the method of using the Rayleigh disc in a closed air-column has arisen out of the work together with the method of correcting for the effect of the microphone dimensions, have, we think, amply justified the course we have taken. In general testing, the deliberate exclusion of reflection rules out the use of a large reflecting baffle. Moreover, a few experiments in the early stages of the work showed that multiple reflections were set up between the baffle and the source, which is not, in general, of negligible dimensions. Referring to the method of avoiding complete calibration of the amplifier and frequency analyser by injecting a known e.m.f. into the microphone circuit after each observation, this may be " the best method " for some circumstances which Dr. Hughes has in mind; but for the conditions we have to meet it would greatly retard the taking of observations and is in fact totally unnecessary, as checks made from time to time have shown that the overall calibration of the amplifier and frequency analyser is constant to 2 per cent. The procedure of calibrating after every observation appears to amount to an admission of inability to construct a stable amplifier. With regard to the reflecting properties of the test room, we agree that there would be an improvement in the absorption for a limited range of frequency if the cotton waste were supported some distance from the walls. The maximum effect would probably be obtained when a region of high velocity is included within the thickness of the waste. However, the scheme would hardly be practicable where the wavelength is large, e.g. 10 ft. or more. With regard to the distance of the source from the floor in the reflection tests in the test room, it is clearly impracticable to carry out tests with a motor half-way between the floor and the ceiling. The reflection tests were carried out with the source at a distance from the floor corresponding to the position of the centre line of the average motor, viz. 15 in.

In reply to Dr. Davis's remarks, we appreciate the references he has given, some of which we had not seen. With regard to the paper of Spooner and Foltz* published in March 1929, attention may be drawn to the fact that our No. 1 apparatus, embodying all the essential features of present practice, was in use in April 1927, and the present paper was accepted by the Institution in December 1928. The heterodyne method described by Dr. Davis would no doubt be of great value for certain work. We imagine that it is essentially a laboratory method. With regard to Steinberg's theoretical work on the assessment of total noise, we are interested to hear that these ideas are being abandoned. We have looked in vain for some comprehensive experimental confirmation of them. We admit that the loudness scale used by us may be neither strictly correct nor the final solution of the matter, but it has been of great service to us. It has in all cases indicated that component of noise in a machine which requires most attention. We shall be quite ready to change over to a more accurate loudness scale when one is evolved. Perhaps the National Physical Laboratory can assist in this direction. We are interested to hear that Dr. Davis has been experimenting with the reference tone and masking methods of instrumentally measuring total noise. A few experiments which we have carried out in measuring the noise of a motor, using reference tones of 500 and 1 500 cycles per sec., have given us the impression that the method is very promising. We much appreciate Dr. Davis's valuable contribution to the discussion.

Mr. Marris asks for the interpretation of the results given for a turbo-generator. If Section (13) of the paper be referred to, it will be seen that the paper covers methods of noise analysis and measurement only, and that such subjects as the interpretation of results and the methods which are effective in reducing noise are beyond the scope of the paper. We find it difficult to see any reason for the criticism that we have "concentrated on the lower frequencies." The apparatus is at present calibrated up to 5 500 cycles per sec., but if higher frequencies were present they would be detected. The highest frequency which so far has been encountered on motors is 3 300 cycles per sec. We regret that Mr. Marris is "not convinced by our arguments" regarding the use of the moving-coil microphone ; we can only say that we have found the instrument entirely adequate for our purpose. The variation of the response with frequency causes no inconvenience when a frequency analyser is used by means of which each component frequency is dealt with individually. The oscillograph method is confined to the very few cases where a frequency analyser cannot be used. The variation of response with frequency both in the microphone and in the analyser will certainly distort the oscillograph record but, even so, much useful information can be obtained. We wish to make it clear that we hold no brief for the moving-coil instrument—we have simply found that it serves our purpose exceedingly well. We shall be quite ready to use any other type when there is a clear advantage in doing so. It is obvious that the sensitivity of the condenser instrument is much less variable with frequency than that of the moving-coil instrument, but in looking through the various publications on the subject we have been unable to find any reference to whether the maker's calibrations by the thermophone have been corrected for the effect of the dimensions of the microphone when used in free space. If this correction has not been made, the sensitivity in free space will begin to rise at about 1 200 cycles per sec., increasing to double the uncorrected values at frequencies of about 4 600 and over. Mr. Aldridge * has drawn attention to this and to other sources of error which may arise if a microphone intended for use in free space is calibrated by the thermophone and used without subsequent correction. In his paper, the calibration curve obtained from the thermophone shows the usual very small drop of response with frequency. However, the true response curve for free space shows a variation of 2·2 to 1 between 500 and 1 800 cycles per sec., and that the true response at 1 800 cycles per sec. is 3·3 times the thermophone calibration. It is surprising that quantitative information on so fundamental a point has not been more readily available.

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* W. West: "The Measurement of Sound Pressures on an Obstacle," *Journal I.E.E.*, 1929, vol. 67, p. 1137.

* *Journal of the American I.E.E.*, 1929, vol. 48, p. 199.

Dr. Hughes has already called attention to the day-to-day variations in the sensitivity of the condenser instrument, which are larger than any we have experienced with the moving-coil instrument. The absence of such variations is of great value, as it enables the effect of small changes made in the apparatus under test to be assessed. The condenser instrument and its associated apparatus are not, even in the most experienced hands, free from phase distortion. A curve given by Dr. Harvey Fletcher on page 28 of his book " Speech and Hearing " (O. van Nostrand Co., 1929) shows that the overall phase displacement of an oscillographic apparatus is nearly proportional to frequency and reaches a value of 80° at 4 500 cycles per sec. In calling attention to these points, we do not wish to belittle in any way the achievements of the condenser instrument, but we feel that criticism has been directed against our methods on the tacit assumption that the condenser microphone and everything connected with it is beyond criticism. In reference to the sensitivity of the moving-coil microphone, the fact that we are able to make measurements below the limit of audibility at all frequencies up to 800 cycles per sec. with a quite moderate amount of amplification is, we think, a sufficient answer. We have considered the added mass effect. For our particular conditions it is quite inappreciable.

We are very glad to have Mr. West's comments on the added baffle method of deducing the correction for the microphone dimensions. We think that the want of proportionality between the wavelength and baffle diameter may be due to our varying one dimension of the microphone, viz. the diameter, without varying the length. We think that this and other effects mentioned by Mr. West are covered by the continuous reduction, in small steps, of the baffle diameter until the diameter of the microphone alone is reached. The influence on the results of the conditions at large baffle diameters is very small. With regard to the detailed investigation of transient sounds, our apparatus would certainly require modification. An opportunity of going into this matter has not yet arisen, as the measurement of steady sounds has needed much more attention.

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* A. J. Aldridge: "The use of a Wente Condenser Transmitter to measure Sound Pressures in Absolute Terms," *Post Office Electrical Engineers' Journal*, 1928, vol. 21, p. 223.

ELECTRO-PHYSICS.*

By D. Owen, B.A., D.Sc.

Fundamental Theory.

In the past four years the main objective of physical investigation has been the further elucidation of the structure of the atom. The Rutherford-Bohr conception presented a simple picture of the atom with its minute massive central nucleus, and its orbital electrons whose number (the atomic number) determines almost entirely the physical and chemical properties of an element. The idea of "stationary states," when the electron moves in its orbit without radiating energy, and of the jumps of the electron from one stationary state to another of lower energy, attended by the emission of definite bundles of monochromatic radiation called quanta, gave a remarkably simple interpretation of the laws of series in optical and X-ray spectra, and indicated quite plainly the necessity for some system of mechanics other than the classical or Newtonian mechanics in dealing with actions within the province of the atom. Much in the first quantum mechanics was puzzling, and many gaps remained to be filled in. Great progress has been made recently in supplying these requirements, and the wave mechanics, the work of L. de Broglie, Heisenberg, Schrödinger and others, is the outcome. Not that an entirely new basis of physical theory was demanded—the laws of the conservation of energy and momentum remain as essential as before. Rather does the wave mechanics serve to supplement the mechanics of massive bodies in treating of the fine structure of matter, just as undulatory optics replaces geometrical optics in dealing with interference and diffraction phenomena. The new views have received startling confirmation from the experiments on electron waves carried out by G. P. Thomson in Britain and by Davisson and Germer in America. In these we see moving electrons possessed of properties usually associated with waves, capable of being diffracted according to optical laws as well as deflected by electric and magnetic fields. These new phenomena seem to place us well on the way to the resolution of the paradox of recent years, namely, of radiation behaving at once as a compact quantum and as an expanding uniform wave-front. Probability methods have been applied with much success in the development of wave mechanics, in both the Bose-Einstein and the Fermi-Dirac statistics. The general theory of quantum mechanics appears indeed to be almost complete, the difficulty encountered in specific problems being mainly that of obtaining exact mathematical solutions. The root idea of the quantum remains, and it is necessary to accept the existence in natural phenomena of an essential discontinuity symbolized by Planck's constant. The reality of the quantum has been emphasized by two important recent discoveries, the Compton and the Raman effects.

On the side of magnetism a definite advance in theory has been made in the introduction of the conception of the spinning electron, put forward by Goudsmit and Uhlenbeck in 1926. This spin confers on the electron a permanent magnetic moment, in addition to the magnetic moment arising from its orbital motion in the atom. It adds another degree of complexity to the structure of the electron, making magnetism one of its fundamental properties. Perhaps we have in the forces of attraction thus introduced between its parts an indication of the mode in which an electron is able to retain its compactness in spite of the disruptive tendency of the electrostatic forces present within it. L. V. King has worked out a view of the spinning electron on classical lines; this will be welcome in so far as it permits a simple picture of the electron to be retained.

Our knowledge of the nucleus of the atom is steadily growing. The simplest line of advance is due to F. W. Aston, who has designed and constructed a new mass spectrograph capable of an accuracy of 1 in 10 000 in the estimation of the mass of the atom. By these measurements the isotopic constitution of the elements, and the fundamental character of the whole-number law of atomic mass, have been established. No atom in the whole range from hydrogen to mercury has a mass diverging from an integer by as much as 0·1. The interpretation of the slight divergences in terms of the doctrine of the equivalence of energy and mass is of the greatest importance for the light it promises to throw on the stability of the elements.

The theory of relativity still holds a fundamental place in physical theory. All doubts as to the validity of the Michelson-Morley experiment, on which the relativity principle was first based, appear to have been completely dispelled by the repetition of the experiment in 1928 by Michelson over a greatly increased light-path—as before with completely negative results. In view of the importance assigned in this theory to c, the velocity of light in free space, as constituting a universal constant, Michelson has also recently made and completed a new determination of this quantity, the result found being 299 796 ± 1 km per sec.

Magnetism.

The desirability has long been felt of investigating the effects of intense magnetic fields on the properties of bodies. It was realized that little help in producing extremely strong fields was to be gained by the use of ferromagnetic materials. The notion of utilizing the great fall in resistance of conductors with temperature has been worked out, only to be rejected on the score of cost. Prof. Cotton at Paris has now constructed his electromagnet, which is expected to provide fields up to 100 000 gauss. Dr. Kapitza at Cambridge has aimed at producing electric currents of an intensity sufficient to maintain for a short time a field approaching 1 million gauss. The story of his work constitutes an epic page in recent scientific research. In his first tentative experiments in 1924 he succeeded, with accumulators as the source of current, in producing fields of 40 000 gauss with which experiments on the bending of α-rays were carried out; next he investigated the Zeeman effect with fields of 100 000 gauss. By 1927 he had succeeded, by the use of the current obtained by short-circuiting the armature of a specially designed alternator, in reaching a field of 320 000 gauss. A considerable series of investigations has been carried out in fields of this value, and by the development of the full power of the machine fields up to 700 000 gauss should be attained.

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* A review of progress. Reprints in pamphlet form, price 1s. each, can be obtained from the Secretary of the Institution.

A machine of 2 000-kW continuous rating was found to be necessary, and was constructed. Its weight is 13 tons, and a special laboratory has been built for it. By a special design of excitation windings a flat-topped current wave was obtained, so that the central part of the half cycle produced a steady current, and therefore a uniform field, in the central region of a small coil to which it was joined in series. The connection of this coil to the armature constitutes practically a short-circuit of the machine, the current for a field of 320 000 gauss within the coil rising to 72 000 amperes, and the power developed to 160 000 kW. To avoid heavy sparking the circuit is broken at the instant that the current passes through zero, the switching operation having therefore to be timed with an error not exceeding 0·0003 sec. In order to withstand the enormous stresses present in the experimental coil, this was surrounded with a bandage consisting of a ring of hardened and tempered steel. This steel ring had to sustain a total force over its periphery of 100 tons weight. One effect of the stresses is to increase the diameter of the coil, and to obviate breakage due to this a slipping contact was devised, with complete success. Towards the completion of this ambitious project help in design has been given by Prof. Miles Walker, H. T. Tizard and F. E. Smith. The undertaking has been financed throughout by the Department of Scientific and Industrial Research.

A brief account only can be given of the first results obtained with this plant. The effect of a magnetic field on the electrical conductivity of single crystals of bismuth was selected for first attention. Rods of bismuth 2 cm^3 in volume were required. These could not be turned from a large block of crystal owing to the destructive effect of such treatment on the homogeneity of the specimen. The problem of growing large crystals in the form of rods was faced and solved, and a thorough study was made of the effect of orientation of the crystal with respect to the direction of the current through it and to the direction of the applied magnetic field. A method was discovered of growing crystals having any required angle between the axis of the rod and the cleavage plane of the crystal. The test current through the crystal was about 3 amperes. This, as well as the fall of potential between two points on the rod, and the current in the surrounding magnetizing coil, was measured by a 3-circuit oscillograph. The electrodynamic force on the rod is not large, but the forces arising from the difference in the magnetic susceptibilities of bismuth and liquid oxygen in the low-temperature experiments amounted to from 1 to 5 kg, and the rod had to be tightly secured in position. The first effect of the magnetic field is to produce a temporary back e.m.f. in the rod (an effect previously observed by Seidler). Eliminating the effect of this in reducing his results, Kapitza finds that the effect of a magnetic field H on the electrical resistance R may be analysed into two parts: (1) in which $\Delta R/R_0 = \alpha H^2$, holding in fields up to 50 000 or 100 000 gauss, and (2) in which $\Delta R/R_0 = \beta H$, for all higher fields. The constant α depends on the orientation of the crystal; the constant β is the same for all orientations. The effect occurs only when H is transverse to the direction of the current in the crystal, there being no effect in longitudinal fields. The change of resistance increases very rapidly, according to an inverse fourth-power or fifth-power law, with fall of temperature. Experiments have been made on 35 other metals, which were obtained in a very pure state (at least 99·9 per cent), the general result found being that the same laws apply to all, with the exception of the ferromagnetic metals, which are clearly anomalous and are to be the subject of a further special study. The magnitude of the effect in the case of bismuth, antimony and arsenic is enormous. In the maximum field of 320 000 gauss, bismuth increases its resistance 50 times at ordinary temperature, and 1 360 times at the temperature of liquid air. The factors of increase for antimony and arsenic in the maximum field at the temperature of liquid air are 40 and 29 respectively; and the corresponding increases for certain metals are as follows: magnesium 300 per cent, zinc 100 per cent and copper 40 per cent. For iron the change under the same conditions is 5 per cent, and for nickel 4 per cent.

The correlation of the above results with theory is a matter of much importance. A treatment of the change of resistance of conductors under the influence of a magnetic field was first given in 1900 by Sir J. J. Thomson, and quite recently Sommerfeld has dealt with the question. But the amount of the change predicted on these theories is almost negligibly small compared with the results observed. Kapitza makes some suggestions based on the new data he has obtained. From the fact that the linear part of the curve connecting R and H is independent of orientation and of the degree of perfection of crystalline form of the material, he infers that the effect is an atomic phenomenon. He divides the total resistance of a metal into two parts: (1) an " ideal " resistance which falls to immeasurably small values with fall of temperature, and (2) an " additional " resistance dependent on the physical state. He thinks that by careful crystallization and by eliminating internal mechanical strain the condition of supra-conductivity may be produced in all metals. Non-metals and semi-conductors appear to fall into a separate category and to need different considerations.

Gyro-magnetic Effect.—According to a simple form of classical theory the magnetization of a body is due to electrons in rotation within the atoms. The rotating electron will possess angular momentum and magnetic moment, the ratio of these, called the gyro-magnetic ratio, being constant and equal to $2m/e$, where e is the charge and m the mass of the electron. On this view an iron rod spun about its axis should become magnetized; and conversely, as O. W. Richardson pointed out in 1908, a rod in the act of being magnetized should experience a rotational mechanical reaction. Both of these effects have been observed; but in each case the value of the gyromagnetic ratio deduced from the measurements turns out to be just half of that expected. The recent experiments of Sucksmith and Bates at Bristol prove this, as regards the converse effect, in the cases of iron, nickel, cobalt, the Heusler alloys and magnetite. Richardson has thus been led to the view, supported also very strongly by spectroscopic evidence, that the nucleus of the atom has also a quantized spin, possessing an angular momentum one-half the total value of that of the orbital electrons in the atom, but opposite in sign.

Perminvar.—To the list of iron alloys of high permeability, such as permalloy and mumetal, which have already proved their immense value in telephony, has now been added by Arnold and Elmen an alloy of iron, nickel and cobalt which has the interesting property of possessing, for fields below 1·7 gauss, a permeability of nearly 500, constant within 1 per cent over this range. To this material the name "perminvar" has appropriately been given. Within the same range of field the hysteresis loss is vanishingly small, being only 1/1 000th of that of permalloy, itself very small, as is well known, compared with the hysteresis loss in pure iron.

Solar Magnetism.—The sun's magnetism was detected 21 years ago by Hale. It is now known that the magnetic axis is inclined some 4° to the axis of rotation, and that the polarity is related to the direction of rotation exactly as in the case of the earth, so that the north magnetic pole is near the top of the sun as viewed from the earth's northern hemisphere. The intensity of the field at the poles is 50 gauss (the field at the earth's poles is 0·66 gauss). Superimposed on the general field are local fields, associated with sunspots, where the intensity may be as high as 3 000 gauss.

ELECTRON WAVES, AND THE WAVE MECHANICS.

The 25-year old problem of the reconciliation of the wave and the emission theories of electromagnetic radiation has now been attacked both theoretically and experimentally with startling success. In 1924 Louis de Broglie, combining the relativity and quantum theories, showed mathematically that a particle of mass m, moving with velocity v, is accompanied by a phase wave of frequency ν travelling with a velocity c^2/v. Associated with it is a wave group advancing with the same speed as the particle and (unlike the phase wave) carrying with it energy and momentum, the wavelength being equal to $h/(mv)$, that is, to Planck's constant divided by the momentum of the particle. Applying the theory to the case of the α-particle, we find it carries with it in its motion a group of waves of wavelength about $0{\cdot}5 \times 10^{-4}$ Å (Ångstrom units), equal, that is, to that of very short γ-rays. A hydrogen molecule moving at the mean translational speed corresponding to ordinary temperature carries to-and-fro a group of waves of wavelength 1·1 Å, which is that of ordinary X-rays. Greatest practical interest, however, attaches to the wave system accompanying a moving electron or cathode ray. If by the relation $eV = \frac{1}{2}mv^2$ we replace the speed v by the voltage V, falling through which the electron acquires its kinetic energy, we may write the de Broglie formula in the form $\lambda = 12{\cdot}24/\sqrt{V}$. Contrasting this with the formula for the limiting wavelength of X-rays, namely, $\lambda_x = 12\,350/V$, we see that moderately hard X-rays, generated by 10 000-volt electrons, are of about the same wavelength as the de Broglie waves carried by electrons which have fallen through 100 volts. Now if cathode rays or moving electrons are indeed associated with waves, diffraction effects should be observed when the electrons are reflected by a grating, or when they are transmitted through a very thin crystalline film. These phenomena have been brilliantly observed and measured, the former by Davisson and Germer, the latter by G. P. Thomson. Davisson and Germer allowed a narrow sheaf of cathode rays to fall at a definite angle of incidence upon a single crystal of nickel, and observed that the reflected rays pass through a series of maxima of intensity as the angle of reflection changes. They show, in fact, phenomena of the same character as the diffraction fringes exhibited by light when reflected from a ruled grating.

G. P. Thomson, using cathode rays of about 30 000 electron-volts, allowed a fine pencil of the rays to fall upon films of various metals. Owing to the strong absorption which they cause, the films have to be very thin, and Thomson has succeeded in producing spluttered films no thicker than 10^{-6} cm, free from holes and almost quite transparent to ordinary light. Such films contain crystals in all orientations, and it was expected that diffraction rings would be produced on a photographic plate on the other side of the film, similar in type to those produced by X-rays in the Hull-Debye-Scherrer method of analysis. These anticipations were fully realized, and from the measurement of the diameters of the successive rings the wavelength could be determined and compared with the value $h/(mv)$ indicated by de Broglie's theory. The agreement of theory and observation is complete. These waves differ from X-rays of the same wavelength by being associated with electrons, and therefore capable of being deflected by electric and magnetic fields.

Rupp has observed the diffraction of cathode rays by a ruled grating (of metal to avoid static charges), and has thus succeeded in measuring the wavelength of the electron waves in terms of the grating space.

We are thus in presence of a new phenomenon, in the possession by a moving electron of a duality of wave and corpuscular properties, exactly parallel with the peculiarity shown by light in possessing at the same time the properties of quanta and of a continuous wave-front. The development of the wave mechanics is due chiefly to Heisenberg and Schrödinger. It has the advantage over the first quantum mechanics of Bohr of disclosing the presence of waves associated with the electron as it moves in its atomic orbit, of a frequency identical with that of the radiation emitted in one of its transitions. By combining the formula $\lambda = h/(mv)$ with the Bohr expression $nh/(2\pi a)$ for the momentum in a circular orbit of radius a, it is seen that $\lambda = 2\pi a/n$, so that the number of waves in a complete electronic orbit is an integer, one for the innermost orbit, two for the next, and so on. The wave mechanics has also been applied with great success by O. W. Richardson and others to the interpretation of band spectra, now known to be phenomena of the molecule as line spectra are phenomena of the atom.

X-RAYS.

For many years the range of X-rays has been comprised between about 10 Å and 0·1 Å. It has by now been extended both on the long-wave and the short-wave sides. Using the formula $\lambda = 12\,350/V$ for the shortest wavelength generated by a voltage V, it is seen that to extend the range on the long-wave side a fall of potential of less than 1 000 volts across the X-ray tube must be used. To avoid space-charge effects at such low voltages the electrodes must be placed close together. The absorption of soft X-rays by a metal is very great, and the rays are consequently generated only in a very thin layer of the surface of the anti-cathode. This layer, for a given metal, may be obtained by using that metal as the material of the cathode filament, or by placing it on the hot filament which is composed of a metal of much higher melting point. Volatilization occurs, followed by condensation on the anti-cathode, which may be of some neutral metal such as iron. Hot filaments of large diameter have to be used to permit of sufficient current through the tube to provide the intensity of X-rays required.

At such large values of λ the Bragg spectrometer method fails, since, according to the formula $n\lambda = 2d \sin\theta$, even with a spacing constant as high as 21 Å (using cane-sugar) the highest value of λ measurable must fall below 42 Å. Now A. H. Compton in 1925 suggested a new method of producing X-ray spectra by reflecting them from an ordinary optical diffraction grating at very nearly grazing incidence. The dispersive power of a grating is greatly improved by using small glancing angles; furthermore, owing to the fact that the refractive index of X-rays is less than unity, there is a critical glancing angle below which the rays are totally reflected. By working at angles below this critical value, which at $\lambda = 1{\cdot}6$ Å is under 25′ of arc, it was found possible to obtain sufficient intensity in the reflected beam to affect a photographic plate with comparatively short exposures. In 1927 Thibaud perfected the technique of the method and succeeded in obtaining very sharply defined photographs of characteristic X-ray spectra down to long wavelengths. He finds that glass gratings are preferable to metal, and for the long waves uses a grating of either 11 000 or 22 000 lines per cm, of the type produced at the National Physical Laboratory. He has obtained photographs of the K-series of certain light elements (O, N, C, B), the N-series of some heavy elements (Pt, W, Ta, Au), and the O-series of thorium, this last including a line at 68·1 Å. The method applies also in the ultra-violet and the extreme ultra-violet parts of the spectrum, and Thibaud, using glass gratings of 2 000 lines per cm, has succeeded in registering the whole spectrum from 6 000 Å (in the visible region) to 140 Å (the longest wavelength of the Millikan region) on the same photographic plate. Hoag, using a concave grating, has also succeeded in obtaining beautifully defined spectra of the elements C, O and N between 200 and 1 650 Å.

The use of the ruled grating in the province of X-rays has an added importance as promising a new basis for the accurate determination of the electronic charge e. The wavelength of a spectral line as determined by the grating depends only upon the number of lines in the grating and the angular measurements. The wavelength value determined by using the crystal depends on the spacing between the crystal planes, the estimation of which involves the knowledge of e. Usually Millikan's value $4{\cdot}774 \times 10^{-10}$ electrostatic units is assumed, and this value has hitherto been regarded as probably correct to 1 part in 1 000. But if the absolute wavelength of some spectral line be found by the ruled grating, it becomes possible from the data of measurement with the same spectral line by the crystal method to calculate the crystal spacing, and to proceed thence to a determination of e. Already Bäcklin, working in Siegbahn's laboratory, has arrived at a value $e = 4{\cdot}793 \times 10^{-10}$ electrostatic units, estimated correct to 3 parts in 1 000. Greater precision of measurement, and an assured foundation for the formulæ used in the calculations, have, however, yet to be acquired to permit of the possibilities of this method being adequately realized. The position is of interest also in relation to a recent mathematical theory of Eddington's, based on considerations of wave mechanics which would require the quantity $hc/(2\pi e^2)$ to be an exact integer, namely 136, in place of the value 137·1 found on substituting the hitherto usually accepted values for e, h and c.*

On the side of short wavelengths Thibaud and Frilley have succeeded in getting down to a wavelength of 0·016 Å. Coolidge, by using three discharge tubes in series, has produced cathode rays and X-rays corresponding to a total fall of potential of 900 000 volts, in stages of 300 000 volts each. The limit of voltage per stage is set by the emergence of the "cold electron" discharge (dealt with at further length in this Report), which sets in at voltages of about 300 000. The fine jets of electrons thereby produced impinge on the glass walls of the tube, causing local heating leading to puncture; whilst if they happen to fall on the anode the local heating sets up an arc discharge. The results obtained by Coolidge appear to be very striking. Intense luminous effects are produced if the cathode rays are allowed to emerge through a thin metallic window, while the X-rays are said to be of such intensity as to produce luminosity on a fluorescent screen held 100 ft. away. Their frequency falls within the range of γ-rays, though far short of that of the most penetrating γ-rays, which possess a quantum energy of 3 to 4 million electron-volts.

Compton Effect.—In 1923 A. H. Compton proposed a quantum theory of the scattering of X-rays by electrons. The classical theory requires scattering without change of wavelength, whereas the theory of Compton involves an increase of wavelength as shown by the formula $\Delta\lambda = (1 - \cos\theta)h/(mc) = 0{\cdot}0242(1 - \cos\theta)$ Å, where θ represents the angle of scattering. The increase of wavelength postulated is independent of the initial wavelength. It varies from zero up to a maximum of 0·048 Å according to the value of θ, the maximum change occurring when the scattered ray travels in the reverse direction to the incident ray. The existence of the new effect is now well established. Both types of scattering occur, but within the visible spectrum the intensity of the Compton scattering is inappreciable. At X-ray frequencies, however, the Compton effect is quite marked, and for short γ-rays becomes of preponderating importance.

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* Eddington has recently (*Nature*, 1929, vol. 124, p. 840) given reasons for revising his conclusion in favour of the integer 137.

The effect constitues a striking testimony to the reality of quanta of radiation. If the frequency of the incident beam is ν, the quantum of energy is $h\nu$, its momentum is $h\nu/c$, and its mass $h\nu/c^2$. When the quantum impinges on a free electron it shares its energy and momentum with the electron, in conformity with the laws of conservation of energy and momentum. At low frequencies the mass of the quantum is small compared with the mass of the electron, and the degradation of frequency is of little consequence. At an incident wavelength of 0·048 Å the frequency of the scattered quantum for direct incidence is exactly halved, and the energy is shared equally between the scattered quantum and the electron. At much higher frequencies the mass of the quantum far exceeds that of the electron at rest, and most of its energy is transferred to the electron.

The Compton effect has an interesting application to the highly penetrating or "cosmic" rays discovered by Millikan and Kolhörster. Sir James Jeans has suggested that these rays owe their origin to the union of a proton with an electron, with mutual annihilation of charge and attended by the production of a quantum of radiation of the same energy, namely, 920 000 electron-volts. The collision of such quanta with electrons would raise the speed of the electrons to within a few parts in a million of that of light, and so confer on them a mass almost equal to that of the proton at rest. The wavelength of the cosmic rays can only be inferred from their measured absorption coefficient. The results of Millikan and Cameron inserted in the Klein-Mishina absorption formula, which is based on wave mechanical principles, lead to a wavelength agreeing very closely with Jeans's hypothesis.

Electric Conduction in Metals.

In 1928 Sommerfeld applied wave mechanics and the Fermi-Dirac statistics to the doctrine of free electrons in metals, with the result of eliminating many of the discrepancies between the early theory and observation. According to Sommerfeld's theory there is one free electron per atom of a metal, and the contribution of these to the specific heat is less than 1 per cent of that postulated on the old theory, so that the difficulty in regard to the specific-heat value disappears. As in the older theory, the ratio of the thermal and electrical conductivities comes out proportional to the absolute temperature. In regard to thermo-electric phenomena, the experimental data are in good accord with the Sommerfeld theory. However, as already pointed out, the enormous effect of magnetic fields on the resistance of metals is too great to be accounted for on either the new or the old theory. Kapitza's suggestions, and his conclusions in regard to supra-conductivity, are stated above. It may be noted that tantalum and thorium have now been added to the list of supra-conductors. Like those previously discovered, these metals are of high atomic number.

The passage of electricity through solids of very low conductivity has been studied by Joffé, Pohl and Gudden, and others. An immediate simplification, from the point of view of theory, is evidently effected by working with single crystals, owing to our present fairly complete knowledge of the structure of the crystalline lattice. The brothers Curie were the first to make measurements of the electrical conductivity of crystals, and Joffé has continued and perfected their methods. When a steady electromotive force is applied to a crystal, say rock salt or quartz, polarization phenomena manifest themselves and the current slowly falls with time. Joffé has shown how to measure this polarization e.m.f., and on allowing for it he finds that the conduction obeys Ohm's law, so that the crystal has a true conductivity. With different specimens of the same substance, however, he found widely divergent values for the conductivity. This he has traced to the presence of impurities, and by repeated re-crystallization he has been able to show that this variation disappears. With crystals of the cubic system, like $NaNO_3$, NaCl, etc., he found the conductivity σ to be independent of the orientation of the crystal. In crystals belonging to other systems the conductivity varies greatly in different directions, far more so than the thermal conductivity. In quartz, for example, σ is many thousands of times greater along the optic axis than perpendicular to it, whilst the thermal conductivities differ only by 20 to 80 per cent.

The formula $\sigma = \sigma_0 e^{-a/T}$ represents the relation between conductivity and temperature, the constant a being practically the same for all heteropolar crystals, namely, between $1{\cdot}0 \times 10^{-4}$ and $1{\cdot}15 \times 10^{-4}$. The temperature coefficient of electrical conductivity of pure dielectric crystals is thus very high, a rise of 1 deg. C. causing an increase of from 10 to 20 per cent. This is in sharp contrast with the dielectric constant, the value of which is almost independent of the temperature.

The mechanism of conduction in crystals appears to be of two types. Normally it is of the electrolytic type; but, if the crystal is illuminated, electrons are liberated in the interior and act as carriers of the current. The first type involves a movement of ions, matter being transferred in accordance with Faraday's laws and deposited at the electrodes. The conduction differs, however, from that in liquid electrolytes in that practically only one kind of ion is mobile. In most of the halides the positive is the mobile ion: for example, Na + in the case of rock salt. In general, the conductivities in question are extremely small, the value for ammonium alum, for instance, being given as 20×10^{-16} ohm^{-1} cm^{-1}, and the number of free ions per cubic centimetre is very small at temperatures far removed from the melting point. For quartz the number of free ions is about 1 per 10^{13} of those present in the lattice, and the calculated mobility is 5×10^{-7} cm/sec. for 1 volt/cm. As conduction proceeds and fresh ions are removed from the lattice the crystal breaks down, and holes have sometimes been observed to develop.

If, however, the transparent crystal is illuminated, electronic conduction occurs. The action of the light appears to be enormously increased by previous irradiation with X-rays, although the direct effect of these rays in increasing the conductivity appears to be but small. This "activation" by X-rays is attributed to the production of neutral atoms or groups of atoms in the lattice, and at the same time the liberation of electrons: it being easier to set these free in the interior than to expel them through the free surface of the material. At liquid-air temperatures the ionic or electrolytic conduction becomes vanishingly small, whilst the electronic conduction persists and can therefore under these conditions be more easily studied. Pohl and Gudden have worked with diamond, zinc sulphide and selenium, which belong to a class of substances in which no previous activation with X-rays is necessary. In these cases, in contrast with rock salt for instance, a complete saturation current can be observed, and from the value of this the number of electrons per cubic centimetre can be deduced. Their observations lead to the conclusion that one free electron is produced within the crystal for each quantum of light absorbed. This work is of great interest in its bearing on the selenium cell.

ELECTRIC CONDUCTION AT THE SURFACE OF A SOLID.

Lee du Bridge has made measurements of the photo-electric and the thermionic work-functions of platinum, taking the utmost care to eliminate that serious source of error in all such work, namely, the presence of gas films at the surface. As "outgassing" proceeded, the photo-electric threshold was observed to shift steadily towards the shorter wavelengths, reaching after prolonged treatment in the highest attainable vacua the limiting value 1926 Å, equivalent to 6·30.electron-volts. Similarly the thermionic work-function, that is, the coefficient w in the equation $i = AT^2e^{-w/(RT)}$, was found to increase under a like treatment and to reach the limit of 6·35 electron-volts (± 1 per cent). The coefficient A reaches a corresponding limit of 14 000. This demonstration appears to be a final confirmation of the theoretical conclusion, reached by O. W. Richardson some years ago, that these work functions are identical. As the form of the thermionic equation shows, the value of the thermionic emission at any given temperature is enormously sensitive to changes in w or $\phi_0(w = e\phi_0)$. Thus in the case of tungsten, coating the surface with oxygen raises ϕ_0 from 4·5 to 9·2 volts; whilst coating it with thoria lowers it to 2·68 volts, and with cæsium to only 0·715 volt. The application to the properties of the dull-emitter filament is obvious.

The phenomenon of the extraction of electrons from cold metals under intense electric fields has received careful experimental investigation at the hands of R. A. Millikan in America and of B. S. Gossling in England. These currents, obtained in the highest vacua, were apparently first observed by Lilienfeld in 1921 in X-ray tubes, and have been variously designated as auto-electronic currents, or field currents, or under the name "aeona effect." Much earlier Earhart and others, working with minute spark-gaps in gases, claimed to have observed sparks at potentials below the minimum sparking potential of the gas. The values of electric field reached in their experiments were at least as high as those used in the experiments now to be described, but an uncertainty remained as to whether actual contact between the electrodes occurred owing to the electrostatic pull between them. Both Millikan and Gossling removed all doubt on this score by working with distances of the order of 1 cm between the electrodes. Using a fine wire along the axis of a cylindrical sheet of metal an intense field can be obtained at the surface of the wire by the use of quite moderate voltages. Thus with a tungsten wire of diameter 0·0012 cm along the axis of a copper cylinder of diameter 1·62 cm a field of over 1 million volts/cm is present with 4 800 volts between them.

The initial gradient at which a detectable current begins to flow is about 500 000 volts/cm. The current increases rapidly with the field F according to the exponential law $i = Ce^{-b/F}$, where C and b are constants, and currents up to several milliamperes may be observed. The discharge is not uniform, but usually occurs from a few points or only one point of the cathode, narrow pencils of current shooting out and producing corresponding hot points where they impinge on the anode. The strength of current is independent of the temperature of the metal up to about 600° C. At higher temperatures the usual saturation thermionic current becomes augmented in such intense electric fields, but this is an effect to be distinguished from the auto-electronic current when cold conductors are used.

Schottky has proposed a theory of the effect—as also of the effect of intense fields on thermionic emission—according to which the external field reduces the work function. The electric field opposing the escape of an electron may be regarded as arising from an attraction between the electron (when already outside the geometrical boundary of the metal) and its electrical image in the surface. Assuming, for example, that the electron will get clear if it is 10^{-8} cm outside the surface, a simple calculation shows that the work function is 3·6 electron-volts. To do this amount of work on the electron a uniform electric field of $3{\cdot}6 \times 10^8$ volts/cm would be required. This is, however, of the order of 100 times the field at which currents may be observed, assuming that the field is perfectly uniform. The existence of sharp points, or possibly (as Richardson suggests) the presence of local weak spots on the surface, may account for the difference.

It is the existence of this effect which explains the necessity of placing several cathode-ray or X-ray tubes in cascade when high voltages of a million or over are to be applied.

OTHER LINES OF ADVANCE.

In 1928 Sir C. V. Raman announced the discovery of a new effect when radiation is scattered by a transparent body. As in the case of the Compton effect, we have to do with a change of wavelength in the returning radiation. But whilst in the Compton effect there is an increase of wavelength varying in extent from zero to a fixed maximum independent of the incident radiation, in the effect discovered by Raman the incident radiation suffers definite and sharp changes of frequency which are determined by certain frequencies characteristic of the irradiated material. These changes of frequency are, in fact, found to be identical with the various rotational or vibrational frequencies of the molecule. Many of these characteristic vibrations, which are of comparatively low frequency, were already well known from the work of Rubens on residual rays, and have been the subject of recent investigation by Sir Robert Robertson and others in the infra-red spectrum. The Raman effect manifests the existence of these, and of many other lines previously unobserved. In the case of quartz, for instance, characteristic vibrations corresponding to lines at 118, 94, 78, 48·5, 37·4 and 21·5 μ have been discovered, all save the last of these being new. If N denotes the incident frequency, and n a frequency characteristic of the molecule, then lines of the frequencies $N \pm n$ will be found in the scattered radiation. It is of great interest that the lines occur in pairs, one being of enhanced frequency, though of much feebler intensity than the line of lowered frequency. The occurrence of lines of enhanced frequency is not in itself a new phenomenon. According to Stokes's law the light emitted by fluorescent bodies is lower in frequency than the exciting light; but it is now known that this law is by no means general. The presence of the lines in pairs, and the simplicity of the frequency relations, are facts readily interpreted on the quantum theory, and constitute a striking evidence of the reality of quanta. The effect promises to be of the highest importance in the elucidation of molecular structure.

A solution has at last been found to the question of the origin of the green auroral line 5 577·35 Å, which has been shown by McLennan to be emitted by atomic oxygen. Lord Rayleigh has observed that this ray may be seen not only in auroral regions, but also, though very faintly, over the whole of the night sky. The auroral spectrum also contains bands due to nitrogen, but the general illumination shows only the one green line, on a faint continuous background. The phenomenon is of interest in regard to the question of ionization within the Heaviside layer.

Debye has recently published in book form an account of his work on the influence of polar molecules, or dipoles, on dielectric constant and electrical conductivity. The presence of dipoles affects the rate of variation of these properties with temperature and with frequency. The values of the electric moment of such molecules can be determined by several methods, and their values have been tabulated for a considerable number of liquids.

Many investigations continue to be carried out on piezo-electric crystals. To name only a few, Dye has published an important theoretical and experimental investigation of the fundamental piezo-electric properties of quartz, and has later been engaged on a detailed study of the complex of vibrations present in the excited crystal. Pierce and others have applied the effect to the determination of the velocity and the properties of sound waves at supersonic frequencies. Pierce and Vincent have also investigated the production of high-frequency oscillatory currents by use of the magnetostriction effect in nichrome rods. Frequencies as high as ½ million per sec. may thus be attained, and it will be of interest to observe whether oscillators of this type prove of service in stabilizing radio frequencies. On the side of the relation between piezo-electric quality and crystal structure a valuable contribution has been made in papers by Sir William Bragg and R. E. Gibbs. Ordinary or "low" quartz changes its crystalline form at 575° C., passing into "high" quartz, the structure of which has been determined completely by X-ray analysis. The slight difference in structure due to the passage from the first form to the second, small as it is, is attended by a complete loss of piezo-electric properties. From the slight degree of asymmetry possessed by low quartz, Gibbs has calculated a value for the piezo-electric constant which comes out of the same order as the observed value.

A concluding reference will be made to the passing of H. A. Lorentz, the great mathematical physicist. He showed with eminent success how to combine Maxwell's theory with the later theory of electrons, and made valuable contributions to most branches of electrical theory during the past 50 years. He was also a great expositor, and the charm of his presence at scientific assemblies will be gratefully remembered by all who enjoyed the privilege of hearing him.

ELECTRICAL PLANT AND MACHINERY, INCLUDING MARINE APPLICATIONS.*

By A. R. EVEREST, Member.

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(1) GENERATORS AND MOTORS.

(a) DIRECT-CURRENT MACHINES.

Much advance has recently been made both in the standardization of manufacture and in the scope of application.

Constructional.—Dealing first with constructional developments, the main feature to be noted is the extended substitution of "built-up steel" structures for castings. Beginning with the simpler forms, such as baseplates, the development has extended to cover complete magnet-frames with feet, end-shields, pedestals and other details. Elaborate wooden patterns, with the accompanying delays and costs, are eliminated, the material is more homogeneous, stocks can be reduced and cheapened, and production is accelerated. The welded joints are found to compare well, as regards strength, with the rest of the structure.

The use of ball and roller bearings is now very general on small sizes, while on larger sizes (above $3\frac{1}{2}$ in. diameter) their adoption is extending and the employment of roller bearings on machines for heavy duty, such as crane and traction work, has proved successful.

The several alternative types of enclosures of machines are being reduced and simplified; louvred covers for drip-proofing are becoming more general, while for totally enclosed motors two methods in particular are being employed to an increasing extent, both in England and on the Continent. The first and simpler, though less effective, method is to propel (by means of an external fan) and guide cool air over the outer surface of the frame (whether smooth or ribbed); while the second method consists in utilizing an internal fan for circulating the hot air through cooling tubes, an external fan providing cooling air on the outside of these tubes.

Electrical Design.—Electrical design may almost be said to be standardized on small and medium-size motors; but for large machines, with difficult commutating properties, special compensating windings and tapered air-gaps are employed, in addition to commutating poles, to improve the commutation. These developments, together with improvements in the mechanical design, have enabled high-power high-speed motors to be built for blowers, ventilators and other similar purposes.

The modern increased demand for machines in which the stable range of voltage or speed is wider than that hitherto provided has been met by the more general application of a long-known principle, viz. the introduction of points of high saturation into the magnetic circuits.

Applications.—The application of electrical energy to industrial mechanism is practically unlimited in its scope, and there are but few branches to which the electric motor has not been adapted. For general machine-tool purposes great headway in the use of electrical drive has been made, as indicated in both the British Industries Fair and the Leipzig Fair during recent years; but great diversity in practice is still to be found as regards the building in or attachment of the electrical unit to the machine-tool proper. In many cases the driving end-shield of the motor is provided with a bracket for bolting to the tool; in other instances the motor frame is furnished with a flange for this purpose, while in still other cases the motor is built into the tool housing.

The development and adoption of ball and roller bearings have enabled much higher speeds to be attained, thus permitting direct electric drive for such purposes as wood-working machinery running at 6 000 r.p.m. or higher speeds.

For the driving of winches and hoists, and the operation of navvies, dredgers, excavators, and similar duties, the Ward-Leonard system has been employed for many years. This system is based on the control of each motor or group of motors by a separate generator; variations in speed are obtained by variations in the generator voltage, both motor and generator being excited from a separate source.

It is, however, in some cases desirable to adopt a system possessing torque characteristics similar to those of a steam-driven set. These can be very closely obtained by the adoption of the scheme known as the "constant current" system, and considerable attention has been paid to this during the last few years. In this scheme the windings on the generator are so proportioned as to produce a characteristic giving practically constant current output over a large range of voltage. A number of motors can be driven by one generator; these are connected in series, their fields being separately excited; the desired variations in torque and speed are produced by varying the field excitation. If the torque exerted by any one motor varies owing to alteration in the mechanical loading, the resultant adjustment of current and counter-e.m.f. is immediately accompanied by a rapid compensating change in the generator voltage; it is, therefore, clear that, with any given excitation, the torque of the motor will remain constant over a wide range of impressed voltage. Any tendency of the motors to race when load is thrown off, due to an excessive rise of impressed voltage, is counteracted by a suitably arranged automatic reduction of the field strength. The motor characteristics can be varied considerably, by field adjustments, to produce accelerating and braking torques as required.

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* A review of progress. Reprints in pamphlet form, price 1s. each, can be obtained from the Secretary of the Institution.

In electric railway service, train-lighting sets operating without the use of batteries have been developed with characteristics such that even with a considerable variation in the supply voltage (amounting to as much as a drop of 50 per cent) the alteration in the secondary voltage is maintained within satisfactorily close limits.

Another branch of growing importance is the electrical equipment of public laundries, the electric drive being eminently suited to the great diversity of types of machines in this class of work, e.g., washing and drying machines requiring frequent reversals, with, in certain cases, dynamic braking, and "inching"; ironing machines needing considerable speed variation; extractors requiring very high accelerating but small running torque; marking machines and belt conveyors; all of which apparatus generally requires to be capable of running in a steamy atmosphere.

The talking-film development in the cinema industry has brought in its train a demand for small rotary convertors or motor-generator sets; the generators of the latter are of a fixed output and voltage, while the motors are varied to suit the changing local supply conditions.

High-Voltage D.C. Generators.—With the development and rapid spread of wireless transmission has come a demand for high-tension direct-current generators for the purpose of energizing the anodes of transmitting valves. At first, various voltages were adopted as considered desirable in each individual case, but the present tendency seems to indicate 12 000 volts as being the most suitable value.

The actual type of design has not yet settled down to any definite standard, as some firms advocate the 2-pole design, giving a comparatively low voltage per commutator bar, while others prefer the multi-polar type, in spite of the resultant higher voltage per bar, in order to avoid the difficulties of insulation met with in bi-polar armature end-windings using conductors of small section. Some, again, build the field structure of the normal salient-pole type, while others resort to a completely compensating distributing winding. The commutating-pole winding is generally arranged on both sides of the armature to act as a protection against voltage surges.

(*b*) Alternating-Current Machines.

Induction Motors.—In the many applications associated with the modern rapid development of electric power there has been a marked tendency to prefer the squirrel-cage type of induction motor on account of its simplicity, ruggedness and low cost; but for services demanding high starting torque this type of motor has been generally inadequate, and for such purposes it has been necessary to employ the slip-ring motor, notwithstanding its increased complication and inherent lower efficiency and power factor. Recent improvements in design have resulted in the evolution of motors of the squirrel-cage type capable of completely replacing the slip-ring motor.

For applications in which the duty comprises chiefly starting and accelerating, as in many cases of lift work, the squirrel-cage motor with high-resistance rotor in conjunction with a special speed-change stator winding has proved successful. The ordinary change-pole stator winding is limited to a speed ratio of 2 : 1, but by providing two separate change-pole stator windings the speed is successively stepped up in the ratios 2 : 1, 3 : 1, 4 : 1 and 6 : 1.

For more general applications, providing for continuous running at a definite speed in addition to high starting torque, various means for producing the necessary high rotor resistance at start have been tried, and of these the double-squirrelcage rotor, originally proposed by Boucherot 25 years ago, has recently been brought to full development.

In this type of motor, the rotor has two squirrel-cage windings one above the other; the upper squirrel-cage is of high resistance, while the lower squirrel-cage is of low resistance, but on account of the position of the bars in the slots it has high reactance. In consequence, at starting, when the rotor frequency is the same as that of the stator, the lower winding, on account of its high reactance, takes little current, while the upper squirrel-cage is active and the motor starts with the high torque and low starting-current characteristics of a high-resistance rotor. When run up to speed, the low slip-frequency allows the lower squirrel-cage to become effective, and its lower resistance largely determines the running characteristics.

A motor of this type, intended for crane and elevator drive, will give gradually increasing torque from full speed to standstill, with low starting current. The efficiency of the double-squirrelcage rotor is generally but slightly less than that of a motor with the ordinary single-squirrelcage rotor. The double-cage construction has the disadvantage of slightly decreasing the power factor, which, however, is still superior to that of the slip-ring motor.

Squirrel-cage construction favours the elimination of the objectionable humming noise usually associated with slip-ring motors, and designers have given this point special attention.

If fine speed-adjustment under running conditions is desired it is readily obtained by resistance control in series with the stator windings.

Single-Phase Induction Motors.—The single-phase induction motor, consisting of a squirrel-cage rotor and a polyphase stator winding fed from a single-phase supply through a phase-splitting device, is well known. In the past the phase-splitting starting device has usually consisted of resistance and reactance, but in an improved form recently developed, and known as the capacitor motor or condenser motor, a condenser is employed in place of the reactance. The starting torque of the motor is thereby much improved, and the operating efficiency and power factor are high, particularly if the condenser is kept in circuit while running. Unfortunately, the cost of the condensers limits the application of this design to small sizes of motors.

Speed Control of Induction Motors.—For the speed control of large induction motors the well known Kramer and Scherbius auxiliary machines continue to be employed, but for smaller power units the a.c. commutator motor described below affords the most satisfactory solution.

A.C. Commutator Motors.—While the a.c. commutator motor is not new, general appreciation of the advantages to be obtained from the improved modern designs appears to be quite recent.

Variable-Speed A.C. Commutator Motor (*Shunt Characteristic*).—While speed variation can be obtained with the slip-ring type of induction motor, such a machine is not economical on varying-speed drives, because speed variation produced in this way involves power wasted in the resistances. It is not applicable where the speed to which it is adjusted is required to remain constant with changing loads, because, where resistance control is used, for any particular setting the speed varies with the current flowing through the resistance, and consequently with the load. The variable-speed a.c. commutator motor has been perfected to satisfy these conditions, being readily adjusted to any desired speed over a wide range, the speed so selected remaining constant with varying load, while the motor operates with high efficiency and high power factor.

Starting and speed control are simple, as the speed control is obtained by moving the brushes, whereas with the ordinary slip-ring induction motor a multi-contact switch and resistance are required, the switch having a number of control contacts corresponding to the number of speeds required.

The modern tendency to adopt the variable-speed a.c. commutator motor in connection with paper-making machinery and for newspaper printing-press service is due to these special characteristics.

Structurally, it is an induction motor in which the rotor carries the primary winding, fed through slip-rings, and also carries a second winding, known as the regulating winding, connected to a commutator. Two sets of brushes bearing on this commutator are connected to the starting and finishing ends respectively of the three phases of the secondary winding which is wound on the stator.

Thus the commutator winding impresses in the secondary circuits a voltage which is varied to obtain the desired speed adjustment by varying the angular separation of the two sets of brushes, while suitable movement of the two sets of brushes together round the commutator controls the power factor. For lift operation the brushes are moved automatically as the speed changes.

Simplified Forms of the Type.—For applications in which the foregoing characteristics are not all required, the following simplified forms of motor are provided:—

A.C. Commutator Motor for Power-Factor Correction.—When only power-factor correction is required without speed variation, one set of brushes is omitted and the commutator reduced in size. Power factor is then controlled by the remaining set of brushes. The motor can be provided to work at unity or with leading power factor up to practically zero (leading). The speed characteristic of this motor is similar to that of the ordinary induction motor. If speed regulation is required, it can be obtained by inserting resistances in the secondary circuit, as with the slip-ring motor.

Alternative types of this machine are available; with some, the high power factor is maintained throughout the range of load, while with other makes it is maintained only at the higher loads.

Intermediate-Speed Motor.—The ordinary induction motor operates at certain definite speeds determined by the number of poles and the supply frequency. For operation at a speed intermediate between these induction motor speeds, a special form of a.c. commutator motor is available; such machines are particularly useful when replacing d.c. by a.c. drive. As speed variation is not here required, the construction becomes simplified while providing operation at an exact speed with good efficiency and power factor.

Motor with Series Characteristic.—For certain duties in which the load is practically constant for any particular speed, as with fans and centrifugal pumps, a simplified form of motor is provided in which one rotor winding is omitted, the stator and rotor being coupled in series through a transformer. Different speeds may be obtained by brush shifting; sometimes a number of transformer tappings are provided to increase the range.

Single-Phase Commutator Motors.—The ordinary "repulsion" motor has been known for many years both in the plain and reversing types. This motor has a characteristic similar to the ordinary d.c. series motor, that is, the speed varies considerably with the load. The constant-speed characteristics of the shunt-type motor have been obtained by an improvement which consists in embedding a squirrel-cage winding below the commutator windings in the rotor. The effect of this squirrel-cage winding is to give almost constant speed from no load to full load; the large starting torque of the repulsion-type of motor is retained, commutation is improved, and the motor operates with a high power factor. Reversing is accomplished, as in the repulsion motor, by reversing the connections to one section of the stator winding.

This motor has proved particularly suitable for the operation of lifts, cranes and hoists, owing to its large starting torque and small drop in speed between no load and full load.

Synchronous Motors.—While the ordinary salient-pole type of synchronous motor is very successful in the majority of cases, there are certain applications requiring a starting torque higher than that obtainable from this type of machine with reasonable starting current. For such duty the new form, known as the synchronous induction motor or auto-synchronous motor, is available. Structurally, this is similar to the induction motor with wound rotor, slip-rings and external variable resistance, but with a d.c. exciter provided in addition. The machine is started as a resistance-controlled slip-ring motor. When it has gathered speed, d.c. excitation fed to the rotor windings brings the motor into synchronism, after which it continues to operate as a synchronous motor.

High-Frequency A.C. Generators.—While machines of this type for the power supply of radio stations are now almost entirely superseded by valve generators, a new demand for high-frequency alternators has developed in connection with the rapidly extending use of high-frequency induction furnaces, special applications, requiring the use of high-speed motors, the production of ozone, and other electrical processes. Both the salient-pole and the inductor types of field are employed in high-frequency alternators now provided for these purposes.

Constructional Improvements.—The modern improvements in constructional features and in methods of cooling discussed above under direct-current machines apply equally to alternating-current machines.

(c) STARTING AND CONTROL GEAR.

Startors and Regulators.—For moderate and large sizes of motors, both d.c. and a.c., and for medium voltages, the drum type of startor is becoming more generally used with non-reversing motors, starting infrequently, where formerly the face-plate type of switch was used. The modern form of startor consists of a drum-type switch for cutting out the resistance, and electrically operated contactors for closing the line circuit, the arrangement being such that the circuit is not broken on the resistance switch-contacts but always on the contactor, which is specially designed for the purpose. The result is that there is very little wear on the resistance switch-contacts.

There are signs of a tendency to use overload relays of the thermal type in place of those of the coil type, or in addition to the coil type, for motor startors. By this means the overload device has a characteristic more like that of the machine than can be provided by the coil-type overload relay.

Two alternative forms of protection may be used. In one the thermal overload relay only is used in the startor and a short-circuit protection is provided in the coil overload of a group switch. This is particularly suitable where a number of switches of very small capacity are used, and where unnecessary expense would be incurred in making each one suitable for rupturing the maximum capacity of the circuit. In the other case, where the switch is capable of rupturing the maximum capacity, a thermal overload relay is used to protect against relatively small overloads of long duration, and a coil trip set for high overloads is provided for tripping under short-circuit conditions.

(2) POWER TRANSFORMERS.

Size of Unit.—The outstanding progress in England is in the increase in the kVA capacity of the units which British manufacturers are able to build for transport over British railways through our small tunnels, and complete in their own tanks except for such external parts as bushings and radiators. Whereas in 1926 this limit of size was estimated to be about 30 000 kVA at 66 000 volts, units are now being built up to and including 75 000 kVA to operate on the national 132 000-volt network. The transport of the largest units is opening up new problems for the railway companies, who are actively engaged in designing entirely new types of vehicles for this service.

Method of Cooling.—These large units are oil-immersed and self-cooled up to about half rating, i.e. 30 000 kVA, forced cooling being adopted at full rating and the auxiliary cooling being automatically started by devices which are controlled by the internal temperature of the windings. (It is now recognized that internal temperatures of windings are of more vital importance than oil temperatures.) The auxiliary cooling sometimes employs a forced oil circulation through separate oil coolers, in which case the preferred cooling medium is now generally an air blast (except on hydro-electric schemes), rendering the installations independent of water supply. A more popular scheme, however, is that by which air jets are directed upon the transformer radiators; this facilitates the provision of self-cooled rating amounting to a large proportion of the full rating.

Air-blast cooling without oil immersion is now confined chiefly to extensions of existing plant. Objection to oil immersion as a fire risk is now seldom raised, but where it is, objection is taken, quite reasonably, to air blast also.

High Efficiency.—Many operators are now demanding self-cooled designs for the largest ratings, not merely in order to save the running cost of auxiliary plant, but because in their opinion the increased capital cost is more than offset by the gain in efficiency. As a corollary, the high efficiency demanded results sometimes in a design in which forced cooling shows no capital economy. The demand for high efficiency has caused designers to study in more detail the causes and accurate estimation of stray losses.

Three-Phase versus Single-Phase Units.—It is of interest to note that the two biggest transformer units yet built in the world are both 3-phase units, viz. a 50-cycle, 100 000-kVA unit in the short-circuit testing laboratory of a large Continental firm, and a 25-cycle, 83 333-kVA auto-transformer supplied to Buffalo, U.S.A. In this latter transformer, the high-voltage winding was in two independent sections connected to separate bus-bars in order to reduce the magnitude of possible short-circuits on the system.

British practice, like Continental, is distinctly in favour of 3-phase as against single-phase units, even for the largest capacities. The saving in space and switch-gear is considered to be particularly important.

In the Dominions, owing to their greater distance from the manufacturers, and to the inferior transportation facilities and the need to carry more spares at minimum cost, there is an equally decided preference for single-phase units. While these arguments will not apply to the United States, the industry there also prefers single-phase units.

Earthing.—Continental practice has crystallized in the use of a high reactance between system neutral points and earth. The reactance is adjusted to balance the line capacity under conditions of fault on one line, with the object of (1) stopping the fault current immediately if it is merely an arc-over, and (2) permitting operation with one line earthed if the fault is more serious.

American and British practice, on the other hand, favours solid earthing of the neutral through a minimum impedance, with the object of switching out immediately any line on which a fault occurs. On the higher-voltage systems, solid earthing without any impedance has been employed, but on the larger systems in the United States it has been found that, simultaneously with system faults, telephone exchange operators have received severe acoustic shocks, and some change in practice may be necessary.

Surge-resisting Design.—The prevalence in the United States of single-phase units combined with solid earthing of the neutral has resulted in the development of a "non-resonating transformer," characterized by uniform stress distribution throughout under transient voltage conditions, rendering possible the elimination of end-turn reinforcement, one of the bugbears of general transformer design.

High-Voltage Testing Transformers.—Similar principles have been independently applied, with great success in England and on the Continent, to high-voltage testing transformers up to 500 000 volts in one tank, and in a single-tank unit now under construction for 1 000 000 volts to earth. A 3-unit testing set giving 1 000 000 volts to earth has been installed at the National Physical Laboratory. An American University has a 6-unit equipment giving, at 50 cycles, 2 100 000 volts with centre point earthed; and the General Electric Co., Pittsfield, U.S.A., have made impulse tests at 5 000 000 volts.

Transients.—Considerable research is in progress on the propagation of transients over transmission lines and through transformer windings, and much attention is being paid to the correlation of the insulation throughout systems so that no parts are unduly weak in comparison, or others of unnecessary cost or dimensions. It is recognized that where overhead lines are employed and traverse districts subject to lightning, transient voltages must be considered as well as rated operating voltage. Allied with this has been the adoption, notably in Sweden and the United States, of an ultimate safety protective discharge-gap adjacent to expensive apparatus such as transformers, to act as a final relief to the system if abnormal voltages occur.

Tap Changing.—Tap changing under load is now a common feature of large transformers. The range required is often such as seriously to complicate the design, and special arrangements of windings are developed to ensure a minimum of mechanical forces while meeting requirements as regards reactance and high efficiency.

Separate boosters are almost inevitable when there are added the complications of "three windings" transformers with two output windings and definite reactance requirements for each to be simultaneously met under different loading conditions, or, again, when the lower-voltage winding is 125 000 volts or more.

General Construction.—Improvement in manufacturing methods has rendered possible the production of windings in which the shrinkage is completed before final assembly, thus in many cases permitting the elimination of adjustable coil-clamps.

Paper-covered wire is now almost universal, and cotton coverings are restricted to low voltage and small outputs.

The internal temperatures of cores have been studied, and methods of construction adopted giving improved results both from mechanical and thermal viewpoints.

Drying Out.—It is now common practice to transport transformers to site in oil in their own tanks after drying out at the makers' works; by this means long periods of drying out on site are replaced by a speedy conditioning or merely a check of condition. Varnish impregnation of the insulated windings is claimed by some makers to facilitate this, while others use oil impregnation also.

Oil.—Due to the general use of oil complying with the British Standard Specification, and to the general adoption of the conservator type of transformer in large sizes, oil sludging is no longer a serious problem.

Transformer Protection.—Attention has been given on the Continent to the development of means for detecting an incipient fault in the transformer by means of the gas produced thereby, this gas being made either to operate a float or to displace oil in an upper vessel and operate a photo-electric relay. These devices have found little favour in Great Britain and the United States, reliance still being placed on the well-known systems of balanced-relay protection.

(3) CONVERTORS AND RECTIFIERS.

(*a*) ROTARY CONVERTORS.

Rating.—The average size unit demanded has increased. Typical sizes representing modern practice would be:—

4500-kW 187·5-r.p.m., 1 500-volt, 3 000-amp., 25-cycle rotary convertors for heavy traction work, these machines having the normal overloads for such service.

3000-kW, 333-r.p.m., 440-volt, 6 800-amp., 50-cycle rotary convertors for power and lighting.

2500-kW, 300-r.p.m., 250-volt, 10 000-amp., 40-cycle rotary convertors for electrolytic work.

Voltage Regulation.—Voltage regulation by reactance control has been used on the bulk of the machines installed. Where the range in voltage was larger than could be conveniently and economically controlled by this method, induction regulators, rather than boosters, have been used for the purpose of giving the larger range required. This method has the advantage that the commutation of the machine is not disturbed when varying the voltage delivered by the rotary convertor at the d.c. end.

Starting.—The greater proportion of machines installed have been provided with starting induction motors, and arranged for self-synchronizing rather than starting by taps from the main transformer. This method has the advantage of low starting current, no sparking at the commutator during the starting period, and simplification of the main transformer design by the omission of taps. It also has the added advantage that, should the commutator or slip-rings require grinding, the starting motor is available for this service.

Efficiency.—The efficiencies of rotary-convertor plant have been so maintained that they still remain the most efficient method of converting alternating to direct current for voltages up to 600 volts on load factors even as low as 33 per cent. Machines of 1 000 kW capacity, and larger, have been installed with efficiencies, including the transformer, of 95 per cent on full load, this efficiency including all load losses. The efficiency of 500-volt to 1 500-volt rotary convertors on full load, including transformer and including load losses, may be taken as 94 per cent, this figure representing average good design.

1 500-*volt Rotary Convertors*.—Several large schemes, involving generation of direct current at 1 500 volts by 50-cycle rotary convertors, have been installed. Where the size of unit has been 1 500 kW and above, two 750-volt machines in series have been installed. Where the size of unit has been below 1 500 kW, single-armature machines for this duty have been constructed.

The majority of machines for 1 500-volt service have been constructed without the use of commutator lugs, and with a fan to produce a blast of air over the commutator surface. Machines constructed along these lines have proved that 1 500 volts can be obtained from 50-cycle rotary convertors with an exceedingly low cost of maintenance.

The contract for one recent railway electrification scheme at 1 500 volts (d.c.) covers the installation of twenty-six 2 500-kW units generating at 1 500 volts, each unit consisting of two 1 250-kW, 750-volt convertors in series, these machines having overloads of 75 per cent for 1 hour, and 3 times full load for 5 minutes. These machines were constructed for reversible operation to take care of regeneration on the trains.

(*b*) MOTOR CONVERTORS.

The proportion of converting plant in the form of motor convertors has increased during the last few years, mainly owing to important detail improvements.

The speed of motor convertors was for a long time limited because the current per brush arm was restricted to from 800 to 1 000 amps. If attempts were made to increase the current per brush arm beyond this figure, commutation became delicate and difficult.

Armature windings have now been developed which have considerably raised this limit without reducing the robustness and reliability of the earlier machines. This has resulted in cost and efficiency becoming more comparable with those of the rotary convertor. In fact, motor convertors have been installed with efficiencies as high as the highest-efficiency 50-cycle rotary convertor equipment.

Motor convertors having the following rating have been manufactured: 3 000-kW, 428 r.p.m., 460 volts d.c., 6 000 volts a.c., with normal temperature-rise. A 3 000-kW, 500-r.p.m., 490-volt d.c., 6 750-volt a.c., maximum rated motor convertor is also under construction.

It is possible with machines designed along these lines to obtain greater output per sq. ft. of floor space than with any other type of converting machinery.

General.—Material detail improvements in windings, brush-gear and brushes have been effected, so that operating engineers should no longer be worried by any form of marking of commutators.

While the speed of machines for a given output has increased, a good deal of research work has been done with regard to noise, with the result that there has been a marked reduction in the noise emitted from rotating machines, even though speeds have materially increased. Manufacturers who have studied this problem appear to be acquiring almost complete control of this aspect of design. Also, in line with this, steps are being taken to render substations more noise-proof. Many of the more important stations are also fitted with filtering equipment for the purification of the incoming air.

Automatic Operation.—There has been a material increase in the number and size of automatic equipments. More protective devices are usually provided for the machines in those unattended substations which are automatically started by remote control than in the attended substations, and a fault is more quickly removed from a machine by this automatic means than in an attended substation.

In order to provide equivalent protection in an attended substation the cost of the equipment would be nearly as high as for an unattended substation, so that the logical tendency is to make the substation entirely automatic and save the cost of the attendant. Such stations may be controlled by pilot wires from the nearest manually operated substation, or a group of such automatic substations may be controlled from a central office.

(*c*) MERCURY-ARC RECTIFIERS.

The steel-clad type of mercury-arc rectifier has made little advance in this country. Progress has been made abroad, particularly in details giving improved reliability of operation.

An electrified German railway has a 1 200-volt automatic-rectifier substation provided with mercury-arc rectifiers, each of 450 kW continuous capacity and able to handle peak loads up to 850 kW.

There has been considerable activity in connection with the glass-bulb type of rectifier, particularly in the extension of its application to automatically controlled plant.

(*d*) HIGH-VACUUM THERMIONIC RECTIFIERS.

The application of this type for the generation of high-voltage d.c. anode supply in wireless transmitting stations has become general. It is also now extensively employed for rectifying the anode supply from a.c. mains in broadcast receiving sets.

(*e*) HOT-CATHODE MERCURY-VAPOUR RECTIFIERS.

These are a new development which may ultimately supersede the high-vacuum type thermionic rectifier in high-voltage wireless transmitting stations; they also promise to become an active competitor of the mercury-arc rectifier in other fields of high-voltage work.

(*f*) COPPER-OXIDE DRY RECTIFIERS.

These have proved remarkably successful for low-voltage battery charging from a.c. mains. An alternative form is the copper-sulphide dry rectifier, the use of which is extending.

(4) POWER-FACTOR CORRECTORS.

The chief advance in power-factor improvement is the rapidly extending utilization of compensated induction motors and synchronous motors of both the salient-pole and synchronous induction types discussed above under a.c. motors. Apart from this, several alternative means are employed to improve load power factor, chiefly static condensers, synchronous motors or synchronous condensers, and phase advancers (used in conjunction with large induction motors).

Static condensers are either directly connected to groups of motors or are employed in banks operating on the supply busbars or feeders. In the latter case they have usually been brought into and out of service by means of time switches, but an improved method is to employ relays controlled by the magnitude of the busbar or feeder load current.

Synchronous condensers hold their own limited field in connection with large plants.

The practice of compensating individual large induction motors by means of auxiliary phase advancers, generally of the Scherbius type, is steadily growing.

An interesting recent development in the United States is the "series capacitor," consisting of a bank of oil-immersed static condensers connected directly in series with the line and compensating for transformer and line reactance at all loads. Automatic protective devices by-pass the condenser under short-circuit conditions.

Experience indicates that the series capacitor increases the stability as well as the power-carrying capacity of long lines, and improves the voltage regulation and the division of load between parallel lines.

(5) MARINE APPLICATIONS OF ELECTRICITY.

The application of electricity on board ship has now reached the stage when its reliability is accepted and unquestioned.

This statement is proved by the success of recent vessels equipped with electric drive and also by the fact that practically all vessels, whether propelled by steam or internal-combustion engines, depend on the reliability of electric machinery for operating vital parts such as steering gear, scavenger blowers, and circulating and lubricating pumps.

Diesel-Electric Drive.

The flexibility of the power distributing system and the availability of the current wholly or in part either for one or for several simultaneous duties are of major importance in certain classes of vessels. The oil tanker uses the Diesel-engine-driven generators for propulsion at sea and for driving the heavy oil pumping equipment in port. The system also applies with equal advantage to ships which have extensive deck-unloading equipment, or to fire-boats, salvage boats and dredges in which a large amount of power is required for other than propulsion purposes.

On tugboats, ferries, tankers, cargo vessels, cutters, submarine depot ships, cement carriers, yachts and dredges, the economy and convenience of the system are very pronounced.

An example of the Diesel-electric drive is that of the oil tanker "Brunswick," completed in 1928 and owned by the Atlantic Refining Co. This ship is propelled by a single-screw d.c. motor of 2 800 s.h.p., to which power is supplied by four 600-kW Diesel-driven d.c. generators connected in series. Each of the four Diesel engines is direct-coupled to one 600-kW generator and one overhung 75-kW d.c. auxiliary generator which supplies power for various auxiliary purposes, or, alternatively, for exciting the various field circuits of the several machines.

The speed of the propeller is varied by alteration of the generator voltage by means of a potentiometer rheostat, and the direction of rotation is changed by reversing the generator voltage. The potentiometer rheostat can be operated either in the engine-room or, by remote control, from the navigating bridge. The latter consists of a follow-up device, so that the navigating officer merely moves a lever which is in the form of the usual bridge telegraph, and the rheostat automatically, and at a predetermined rate, takes up a position which gives the desired propeller speed. Means are usually provided to prevent power being applied to the propeller too rapidly, so that the engines and generators do not become overloaded during manœuvring.

If it is required to run for long periods at reduced speed—for example, during a fog, or when running to a schedule or effecting repairs or adjustments on the Diesel engines—one or more of the generators may be cut out of circuit and the engine stopped. This is accomplished by de-energizing the generator field and short-circuiting its armature, so as to maintain the circuit of the propeller motor intact. The generator can then be disconnected by opening the switches. These operations can be performed without stopping the propeller, and in a similar manner extra generators can be brought into service. All switches are interlocked to render them mistake-proof.

The system is usually earthed through a circuit-breaker and resistance at one point, with alarm devices to give warning should an accidental earth occur elsewhere.

The "Brunswick" has proved the reliability and economy of electric drive to the satisfaction of the owners; this is further emphasized by the fact that two more identical tankers have been ordered.

Turbo-Electric Drive.

This form of drive can claim advantages such as silent running, reliability, economy, and quick response to orders from the bridge. It is only by actually taking a voyage on a turbo-electric vessel that the silent running and absolute comfort can be realized.

An example of turbo-electric drive is the well-known "Viceroy of India," which started her maiden voyage in March, 1929, and is owned by the Peninsular and Oriental Steam Navigation Co.

The main propelling machinery consists of two separate turbo-alternators, each with its own condensing plant and auxiliaries, supplying current to two 8 500-h.p., 109-r.p.m., 3 000-volt synchronous motors which are direct-coupled to twin propeller shafts. The propeller motors have a squirrel-cage winding embedded in the pole-face of the rotors for starting purposes.

A contactor cubicle, including air-break reversing contactors for effecting the necessary phase reversal for changing direction of rotation of the propeller motors, is provided to control the power from one or both alternators to both motors. With synchronous motors it is also necessary to have contactors to break the alternator and motor fields.

All manœuvring, i.e., starting and reversing, takes place at approximately one-fifth of full speed. The reversing contactors and field contactors are operated by levers interlocked with a third lever for varying the speed of the turbine. When starting from rest, the reversing lever is first placed in the direction required and the manœuvring lever is moved to the first starting position. This energizes the alternator field at a field current in excess of the normal running value. The propeller motor functions as an asynchronous machine and accelerates almost up to synchronous speed. The field of the motor is then energized and the motor pulls into synchronism, when the alternator field is reduced to normal. The control gear is fully interlocked to avoid mishandling and to prevent access to the high-tension switchgear without first isolating the supply. Various temperature and earth alarms are also provided.

At reduced powers one turbo-alternator only is required for supplying current to both motors: thus maximum economy in fuel, both at full and reduced power, is obtained, and this is a great advantage in a vessel which does part of its voyage at less than the maximum speed and power. The reserve power can be quickly brought into use when required, for example, if the ship is delayed by heavy weather or fog.

The trial results, the results in service and the minimum amount of time this vessel has been in port clearly indicate the many advantages the electric drive can offer.

It is beyond the scope of this paper to discuss the economies of electrical propulsion. In general, the question as to whether electrical drive is used depends upon the purpose for which the vessels are intended, and also upon the enterprise of the chief superintendent engineers of the various shipping companies.

AUXILIARY ELECTRIC DRIVE.

The application of electricity has come to the assistance of some of our large vessels driven by reciprocating engines, and great strides have been made with this form of auxiliary drive.

The exhaust from the reciprocating engine is led into a turbine, and useful work is done by further expansion of the steam. The turbine is coupled, either direct or by means of mechanical gears, to an electrical machine, and, if required, a generator suitable for supplying auxiliary power and lighting can be connected in tandem.

The electrical machine supplies current to a motor on the main propelling shafting, and by this means the reciprocating engines are assisted in turning the propeller. Approximately 25 per cent of the total indicated horse-power of the existing engines can be fed back to the propeller shaft.

In the case of a twin-screw vessel, this drive has an additional advantage over the well-known mechanical auxiliary drive, in that only one turbo-alternator need be fitted and the power divided equally between the two screws by a motor connected in each propeller shafting.

AUXILIARY MACHINERY.

All kinds of machinery, such as winches, windlass, steering gear, pumps of all descriptions, scavenger blowers, fans, compressors and refrigerating machinery, are driven electrically, and electric cooking and heating are now quite common on modern liners.

On the "Viceroy of India" the winches, windlass, capstans, engine-room pumps, refrigerating machines and forced-draught fans are electrically driven on the constant-current system. Another application of the constant-current motor is for driving the winch which operates the life-boats. Recently many orders have been placed for this type of motor. The use of this new system is increasing rapidly, and in the next few years considerable use of this system for the above-mentioned duties is anticipated. Even for main propulsion it is ideal in some specific cases.

GENERAL.

It is of interest to note that, at the present moment, 4 large turbo-electric liners, 2 ferries and 2 yachts using turbo-electric drive, and 1 tanker, 3 tugs and 3 ferry-boats using Diesel-electric drive, are being built by a well-known company in America. In this country, orders for 3 turbo-electric vessels, 2 Diesel-electric vessels, and 3 auxiliary turbo-electric equipments have been placed with a well-known electrical company. The placing of so many orders, some of which are repeat orders, clearly indicates the path which many shipowners have until recently hesitated to follow.

(6) ACCUMULATORS.

(a) LEAD-ACID BATTERIES.

The old-established makes show progressive improvement in quality without any radical departures, except perhaps the perfection of the so-called solid electrolyte—a gelatinous substance saturated with acid which is now extensively used in portable cells.

In a new make a special process is employed which is claimed to give extremely low internal resistance and to obviate the tendency to formation of sulphate. The makers claim that these new batteries can be short-circuited with impunity and left in a discharged state for any length of time without impairing their capacity and efficiency. Severe independent tests by responsible laboratories and individuals appear to substantiate these claims.

(b) IRON-NICKEL-ALKALI BATTERIES.

The recognized features of batteries of this type are their light weight for a given output, robust construction, resistance to vibration, absence of acid fumes, freedom from sulphating or kindred troubles associated with standing idle, immunity from damage by overloading, short-circuiting or reversed charging.

These properties have led to their extensive adoption for special purposes, such as train and car lighting, aircraft lighting, life-boat wireless equipment, and other occasional emergency services.

Recent improvements in this type have been in the direction of improving the length of life and reducing the weight, volume and cost for a given output. The makers now claim to have overcome the difficulty of inactivity at low temperatures.

DOMESTIC APPLICATIONS OF ELECTRICITY.[*]

By C. G. Morley New, Member.

Dr. Ferranti, whose views are always regarded with more than ordinary interest, has stated: "We have learnt that electricity is before all things the greatest labour saver, and a little investigation shows that in the application of electricity to the requirements of the home we have open to us a field almost unimaginably wide."[†]

The great potentialities in this field have been fully recognized in recent years and, almost without exception, supply undertakings have been concentrating on this development. Undertakings which for many years have been associated more particularly with the development of supplies for power purposes are to-day equally active in the field of domestic supplies. The growing importance of these supplies has been commented on by the Electricity Commissioners in their Annual Reports,[‡] from which the following figures have been taken:—

Private Lighting and Domestic Supplies.

	1924–5	1925–6	1926–7
Increase, in millions of units	—	206·9	198·9
Percentage of total sales ..	20·3	22·2	24·6
Revenue as a percentage of total revenue ..	49·0	51·4	49·7

When it is borne in mind that a relatively large amount of labour and material in the way of cables, service and installation accessories and domestic appliances is required to obtain this additional output, compared with that in other directions, the importance of this development to the manufacturing and contracting branches of the industry will be appreciated.

It is pleasing to record that reliable and efficient domestic apparatus of all descriptions is now manufactured in this country and that the resources in this connection have been considerably increased in recent years.

Statistical information regarding the total amount of domestic apparatus in use is not available, but the *Electrical Times* has from time to time published details of progress made by individual undertakings. The following figures are obtained by summarizing the particulars given in 1927 and 1928 of 35 undertakings.

	1927	1928	Increase	Percentage increase
No. of cookers ..	22 442	29 147	6 705	29·9
Cooker connections, kW	129 474	172 048	42 574	32·9
Apparatus other than cookers, kW	315 036	395 956	80 920	25·7

Returns which are now being published show that this percentage increase is being maintained.

Popularizing the Domestic Use of Electricity.

During the winter season of 1926–27 the British Electrical Development Association conducted a campaign directed to better lighting in the home, and this was followed in 1927–28 by schemes to popularize the domestic applications of electricity. It was reported that 122 demonstration houses, exhibitions and special electrical demonstrations were organized, mainly through local committees, and that an attendance of approximately 1 200 000 persons was secured. An interesting and satisfactory feature of this campaign was the enrolment of nearly 250 volunteer lecturers, resulting in 274 lecture engagements being reported. The Association again in 1928–29 directed its energies to domestic apparatus, by a scheme of national advertising linked up with a monthly programme for local activities such as posters, showroom window-dressing suggestions and publicity leaflets. Co-operation in a scheme of this sort meant that numerous parts of the country were giving publicity to a particular item of domestic electrification at one and the same time. The outlet campaign referred to below is the subject of the Association's special activities for 1929–30.

The Electrical Association for Women is firmly established and is doing excellent work in assisting development in the domestic field. In addition to the usual lecture programme the first national campaign was carried out in 1928, having for its object the provision of more electrical outlets in the home. A number of meetings were held throughout the country to discuss a draft specification issued by the Association. At these meetings there were, in addition to those connected with the electrical industry, representative architects and builders, and considerable publicity was thus obtained. There is further definite evidence, not necessarily arising entirely out of this particular campaign, that speculative builders in most districts are now providing more adequate facilities for the use of sundry electrical apparatus throughout the house, where hitherto at the most a 5-ampere plug and socket was provided in the hall and on the bedroom landing. The Association has 20 branches and over 3 000 members, and publishes an interesting and instructive monthly journal, now in its second year, entitled *The Electrical Age for Women.*

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[*] A review of progress. Reprints in pamphlet form, price 1s. each, can be obtained from the Secretary of the Institution.

[†] *Journal I.E.E.*, 1928, vol. 66, p. 127.

[‡] "Engineering and Financial Statistics," 1926–7, vol. 4, p. xiii, par. 39; also p. xxiv, pars. 84 and 85.

Facilities for Instruction in Schools.

The Electrical Association for Women is making a survey of the kind of domestic electrical apparatus that exists in girls' schools and domestic science centres. The Association feels that, with the exception of a few progressive centres, the equipment is out of date.

This is part of an endeavour to induce educational authorities to provide facilities for senior scholars and teachers to obtain some simple instruction on electrical matters. Generally, educational authorities still regard electrical equipment in the nature of a luxury, but the town of Barnsley is an outstanding example of progressiveness in this connection. The Corporation, having during recent years brought into operation schemes for hired wiring, and electric cookers and hire-purchase of domestic apparatus, has through its education authority equipped 8 elementary schools with 12 electric cookers, 15 wash boilers and 130 irons, for the purpose of practical instruction in the care and use of apparatus similar to that already installed in a large number of working-class homes.

As a result of a committee (Headmistresses' Employment) set up by the Ministry of Labour, two special courses of training in electrical housecraft have been started at Chelsea and Battersea Polytechnics.

Installation Accessories.

The increased use of bakelite and similar synthetic resins for installation accessories in place of wood, porcelain and metal has been most marked. Switch-covers, ceiling roses, lampholders and galleries are available, and the majority of plug tops and socket covers are made of this material.

The more general adoption of plugs and sockets to the British Standard Specification, and the policy of some supply engineers, have resulted in 15 amperes being the size now generally used for heating and domestic power circuits. The sales of 3-pin sockets and plugs have been increasing slowly, more particularly in the larger sizes, but earthing is to a large extent ignored where plug points are used for reading lamps and small appliances. It cannot be said that there is any definite movement towards a settlement of the debatable question of earthing, as the increased sales of 3-pin plugs and sockets probably only represent between 5 and 10 per cent of the total number of both types installed.

Lighting.

The cost of electric lighting is probably as low to-day as it has ever been. Improved manufacturing methods have provided the user with cheaper electric lamps, and the efficiency of these has been improved by some 3 to 5 per cent. A small preference in price is being given to 230-volt lamps, in order to encourage the adoption of this standard pressure. Lamps suitable for domestic use have been reduced to five sizes, 15- and 25-watt vacuum type and 40-, 60- and 100-watt gas-filled type.

To-day there is a definite tendency for manufacturers to concentrate on the sale of glareless lamps at prices that are in many cases lower than those for clear lamps, and this should result in the near future in the replacement of all clear lamps by obscured lamps for domestic purposes. This movement will go far towards establishing better lighting conditions in the home and assist in the important national problem of eyesight preservation.

Light as a decorative medium in the home is being more and more appreciated, and new materials have been produced which give lighting fittings still greater utilitarian and decorative value. The more general adoption on the part of supply undertakings of the two-part tariff enables the householder to use electricity lavishly for lighting purposes.

Public interest in residential lighting during the period under review has been greatly stimulated by the fitting up by the Electrical Development Association and other organizations of all-electric homes in various parts of the country, the dominant feature of the furnishing being the electric lighting effects.

The new architectural lighting, in which the lighting is built into the fabric of the interior, has not so far been applied to any great extent in the home, but a definite tendency to adopt lighting fittings of a modern type has been noticeable, the units being generally constructed of flat sheets of glass built up into simple geometric forms and supported in light metal frames. The new styles have emanated from the Continent, and an attempt to interest British decorative artists and designers in this development is being made by a prominent electrical manufacturing firm in co-operation with the organizers of the Ideal Homes Exhibition to be held in the spring of 1930 at Olympia, London, by offering prizes to the value of £1 000 in connection with the lighting and decoration of a suite of six rooms.

In general it may be safely stated that a much greater public appreciation of the possibilities of electric lighting is apparent, but the ordinary householder is still considerably hampered in the adoption of many home lighting conveniences by the scarcity of plug points.

Cooking.

Progress in electric cooking is being fully maintained, the business generally being obtained by hiring the apparatus. At least two towns have over 5 000 cookers installed, five between 2 000 and 4 000, and 10 between 1 000 and 2 000.

Considerable improvement has been effected in recent years, both in general appearance and finish—appealing to the public—and in those details that make for reliability and lower maintenance costs—appealing to the supply undertakings. Obsolescence has been a serious factor, and the improvements in design appear to have delayed the downward trend of prices expected from increased business. The general design is, however, settling down, and an effort is being made by the Incorporated Municipal Electrical Association with the assistance of supply company representatives, in conjunction with a group of manufacturers, to standardize certain details based on the considered opinions of the majority of purchasers.

With regard to improvements, vitreous enamelled hobs have proved a boon to user and hirer and are now standard with all makers. Hot cupboards are now general, except for small cookers. The freer use of vitreous enamel, and the avoidance of sharp edges and corners both externally and internally, are noticeable in recent models. A tendency to revert to the fully-enclosed boiling plate was reported in the last review.* The insistent demand of supply engineers for greater reliability has resulted in many manufacturers adopting the fully-enclosed cement-insulated type of boiling plate, which is usually guaranteed for 2 years. In order to obtain the best results, greater attention has to be given to the utensils for use with this type of plate. Aluminium utensils with turned bottoms and guaranteed against distortion are now available. The desire for quicker boiling brought a transformer-operated boiling-plate on the market in 1928, and, as the resistor runs at a red heat, no special utensils are necessary to ensure good results. Its comparatively high first cost has militated against its more general adoption. In order to get a lower input for simmering than can be obtained with heavily-loaded boiling-plates fitted with the usual series-parallel control, an arrangement for inserting an external resistance in series with the boiling-plate has been put forward. In place of fragile and expensive mercurial thermometers on ovens, an all-metal temperature indicator marked in terms familiar to the housewife, instead of temperature, is being fitted by some makers. The question of the disposal of the oven elements, i.e. as to whether these should be arranged for top and bottom heating, side, or side and bottom heating, is still a debatable one amongst supply engineers and manufacturers, although the majority appear to favour the two latter methods. Those who contend that side heating will do all that is required, would probably not object to a little bottom heating, and should a standard method be considered desirable the solution seems to be in this direction.

The development of electric cooking in the United States of America is understood to be ahead of that in this country. It is, however, estimated that 3½ million devices for cooking were sold in that country in 1927, of which only 120 000 (3·4 per cent) were electric. These figures show the possibilities of expansion in this field.

It is usual to supply a self-contained electric kettle with cookers on hire, and it has been found essential in practice to provide an automatic device to prevent damage due to overheating. Considerable attention has been given to this detail, and much ingenuity shown; although many of the early devices proved unreliable, effective and satisfactory ones are now available.

HEATING.

The electric fire still forms the principal application of electricity in the home. The portable type with fireclay fire-bar is very popular and in greatest demand. The imitation coal fire with and without a flame effect is also freely sold. Manufacturers have been giving increased attention to improving the general appearance of comparatively cheap mass-production models. Enamelling has improved considerably and excellent examples with a choice of colours are sold by most makers. Chromium plating has been introduced for reflectors and framework, also cellulose finish, giving unique and attractive colour effects. There is a slight demand for heaters which can be placed in the centre of the room instead of in the fireplace. Fixed fires, more particularly rectangular-shaped, are available for fixing in chimney breasts in place of the open grate. It is not unusual with fixed fires to place the controlling switches at hand-level on the wall, instead of on the apparatus itself.

Domestic heating by electrical means has generally been looked upon as occasional heating with a good diversity factor, the living rooms being heated during winter months by the usual coal fire. This view may have to be modified where a two-part tariff with low secondary unit charge is available. In any case, exceptional climatic conditions are likely to embarass supply engineers where this load is well developed. Extremely cold weather was experienced in this country during the week ending the 18th February, 1929, and a number of undertakings experienced heavy loads and increased outputs, particularly those in residential areas. Increases of up to 120 per cent in output and 85 per cent in maximum load over the corresponding week of the previous year were reported.

Low-temperature heating in one form or another has made tremendous headway in offices, schools, theatres, picture houses, etc., but in the home it has been introduced to only a very small extent. The advantage over central heating of being able to heat individual rooms and control the temperature easily and, if necessary, automatically, is being appreciated. The tubular type, loaded to about 60 watts per foot run and working at a surface temperature of about 180° F., appears to be popular. There are nearly 100 schools, with individual installations up to 130 kW, heated by this system, whereas 3 years ago there were probably not six. At that date the system was experimental and it was not unusual to provide heating chambers and fans in case of failure, but to-day there are cases of new buildings being designed for electric heating only. The first cost of this system is less than that of low-pressure hot-water systems if regard is given to the omission of flues, etc., and the running costs appear to be comparable, with energy at ¾d. per unit. Thermostatic control is necessary to ensure economy.

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* *Journal I.E.E.*, 1927, vol. 65, p. 360.

An interesting departure from the tubular and panel or plate heaters as commonly known, which operate at comparatively high temperatures, is an electric warming panel which, on account of its low working temperature, readily admits of easy and safe incorporation in the building structure. These panels are designed for a maximum surface temperature of 120–125° F. when fixed horizontally on a ceiling and operated in still air. With automatic temperature control, the temperature averages 85–90° F., if adequate surface is installed in relation to the heat loss. The loading averages 40 watts per sq. ft. of active surface, or 400 watts for a standard panel of 12 sq. ft. The panels are intended, wherever possible, to be sunk into the ceiling, and the finished surface of the ceiling is left flat so that convection currents and " dusting " are eliminated. This embedded type of panel consists of a slab of cork secured to an asbestos-cement board, and to the cork is attached the insulated electric warming element embedded in a rough-faced plastic composition. With the finishing coat of plaster after erection, the total thickness is about 2 in. The makers state that the most economical and efficient method of operating this system is to keep the installation continuously in circuit during the heating season, 24 hours per day and 7 days per week, with thermostatic control, and to install an ample area of surface at the outset. As an alternative to making full provision for occasional spells of extreme cold weather, the system can be installed as a basic warming method for average conditions, being boosted by other means as and when required. The wattage to be installed varies not only with the temperature-rise required but with the amount of glass surface, thickness of walls, amount of exposed surface, and other details. As a rough guide, average figures show a variation from 0·57 watt per cub. ft. and a temperature-rise of 15 deg. F., for such places as garages and store rooms, to 1·67 watts per cub. ft. and a temperature-rise of 45 deg. F. for occupied rooms. These latter figures would meet extreme cold-weather conditions.

In order to take advantage of low off-peak rates, thermal-storage systems using either oil or water as the medium have been introduced. A notable installation is that at the new headquarters of the London Underground Railways, designed to store 16 million B.Th.U. to cover two 4-hour periods. There are four 4 000-gallon cylinders installed (one spare) fitted with immersion heaters having a total loading of 1 344 kW. Heating is carried out by hot-water panels embedded in the concrete of the ceilings. The whole system is fully automatic, the storage cylinders releasing hot water when the temperature of the water in circulation falls below a predetermined figure.*

Another large thermal-storage installation is that at the Polytechnic extension in Great Portland Street, London. In this case, instead of low-tension immersion heaters, a high-tension electrode water-boiler is employed, delivering the hot water to three thermal-storage tanks each 8 ft. 3 in. diameter and 28 ft. long. A 3-phase supply at 6 600 volts, 50 cycles, is taken direct to electrodes immersed in the water space of the boiler. The full capacity of the boiler is 1 800 kW, the present loading being 1 200 kW, and regulation is effected by raising or lowering insulating cylinders surrounding the electrodes. This type of installation has emanated from the Continent and is designed to take advantage of low rates offered for night supplies, in this case 0·27d. per kWh. A relay is provided to put the boiler out of commission should any appreciable current pass to earth.*

WATER-HEATING.

There is increased interest in, and demand for, electrical means of providing hot water, more particularly for use during summer months. The instantaneous geyser type has a limited application, and, although small self-contained storage cylinders (usually lightly loaded) are most useful over sinks and in bathrooms, they are expensive in first cost and should be hired out if much headway is to be made. Immersion heaters fitted in the existing central cylinder connected up with the kitchen range, although a somewhat inefficient arrangement, appeal generally to the public because they are easily applied and work in with existing domestic facilities, such as airing cupboards and points where hot water is required. This arrangement, with thermostatic control and working in conjunction with the kitchen range, is convenient and popular. Efforts are being made by some undertakings to encourage water heating at night, and rates as low as ½d. per unit are offered. Instead of time-switch control, a novel scheme of relays controlled by a street-lighting switching conductor has been adopted by the Ashford Urban District Council for storage heaters; this arrangement ensures that heaters are out of circuit when street lamps are lighted between dusk and 11 p.m. As the heaters are fitted with thermostats, a night load may be expected from this arrangement.

ASSISTED WIRING SCHEMES, AND SHOWROOMS.

Full advantage is being taken of the general powers given by the recent legislation† enabling local authority undertakings (in whose hands is the supply to most of the urban areas) to sell apparatus and fittings. About 270 undertakings have in operation assisted wiring schemes, and these fall broadly into two classes. One provides for limited installations in small tenanted properties, on terms enabling supplies to be obtained without any initial outlay on the part of the consumer, and the other covers any installation of reasonable size and/or apparatus on a straight hire-purchase or deferred-payment scheme, with payments spread over, say, 1, 2 or 3 years. A popular and successful method of operating the scheme for small houses is to recover the installation costs by charging a higher rate per unit through slot meters.

There are some 306 undertakings with 350 showrooms; the majority of these sell apparatus, either direct or through contractors, in addition to carrying out the usual demonstration work. Undertakings acting as distributors over large areas find it necessary to have several showrooms, and a new and interesting feature is the introduction of travelling demonstration vans, complete with their own electricity supply, so that propaganda work can be carried on in scattered areas and before public supplies are made available.

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* *Electrical Review*, 1929, vol. 105, p. 468.

* *Electrical Times*, 1929, vol. 76, p. 711.

† Electricity (Supply) Act, 1926, Section 48.

"ALL-ELECTRIC" HOUSES.

Additional all-electric and one-coal-fire houses, mostly municipally owned, are reported from time to time. An experiment carried out in Birmingham with three houses built by direct labour to the same plan and specification, except in so far as details were affected by the installation of electricity, showed a saving on the cost of £555 for the ordinary house, of £30 in the case of the one-coal-fire house, and £76 for the all-electric house.*

Details of Typical Installations.

Barnes.—57 small houses, one coal fire in kitchen. Apparatus installed:—Cooker and kettle, wash boiler, 2-kW fire, small bowl fire and flat-iron, all hired for 10s. per quarter. Rateable-value tariff. Maximum annual consumption 6 480 units, costing £25 6s. 7d. Average revenue per house £9 14s. 7d.; average price 0·99d. per kWh (or 1·25d. inclusive of hire of apparatus). Total consumption 106 228 kWh per annum (54 812 in two summer quarters).

Epsom.—120 houses. Apparatus installed:—Cooker and kettle, 10-gallon wash boiler, flat-iron, one 2-kW and one 1-kW fire; total cost, including lighting installation, £4 925. Tariff £2 per annum, plus £1 13s. 8d. per annum for hire of apparatus, plus 1¼d. per kWh through prepayment meters, the fixed charges being collected with the house rent. Annual consumption 142 397 kWh. Total revenue £1 178; average per consumer £9 16s. 4d.; average price 1·99d. per kWh.

SUNDRY APPLICATIONS.

It is most difficult for supply undertakings to keep reliable statistics of domestic apparatus connected, and the following list specially prepared by the borough electrical engineer of Ilford and relating to that undertaking is therefore of great interest as showing the relative development of the different appliances.

Apparatus	Number connected	Load
		kW
Radiators	6 557	11 960
Irons	4 597	1 868
Kettles	1 440	1 440
Cookers	938	4 931
Vacuum cleaners	912	106
Immersion heaters ..	381	737
Sundry apparatus ..	171	273
Charging boards	124	186
Washers	117	232
Boiling-plates and grillers	104	137
Toasters	91	52
Fans	85	15
Hair-dryers	54	30
Geysers	28	141
Total	15 599	22 108

DOMESTIC ELECTRIFICATION IN THE UNITED STATES.

The National Electric Light Association have compiled statistics which show that, at the end of 1928, 19 077 000 homes in America were wired for electricity, this number representing about two-thirds of the total. Approximate figures of some of the electrical appliances in use are as follows:—

Irons	14 500 000
Vacuum cleaners	5 800 000
Washing machines	5 000 000
Fans	4 900 000
Toasters	4 540 000
Coffee percolators	3 500 000
Refrigerators	755 000
Sewing-machine motors	700 000

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* *Journal I.E.E.*, 1928, vol. 66, p. 747.

ELECTRICITY SUPPLY TARIFFS AND METHODS OF CHARGE.[*]

By J. W. Beauchamp, Member.

General

The last report on this subject appeared in the *Journal* about three years ago.[†] Since that time no basic change has been made in methods of charging for domestic supply. The perfect tariff for this purpose is still to seek, but the movement—then noted as important—towards tariffs of the composite type (periodic subscription plus charge per unit of energy consumed) has greatly increased, and the older flat-rate scales have in many cases been modified to imitate the effect of this more modern method of charging.

In framing domestic tariffs there is also a movement towards greater simplicity, with reliance on average results rather than on meticulous care as to the cost in individual cases. In calculating the basis of power tariffs as well as of domestic tariffs, the earlier tendency to regard consumer's load factor as the prime, almost the exclusive, consideration has been modified a good deal, and it is recognized that the receipt of a certain minimum payment per annum per consumer is the first consideration and, once secured, permits a good deal of variation in load factor, time of use, and amount of annual consumption.

The demand for electricity no longer calls for such careful nurture as in the early days; sowing its own seed, namely the satisfaction of the user, it now realizes to almost any supplier costs of a character which do not show so rapid a decline in relation to extended hours of use as in the earlier stages of expansion beyond the use of electricity merely for lighting.

Limits of Consumption.

The use of electricity for domestic purposes as practised to-day in the more advanced areas can result in a consumption of the following order:

Houses of Small and Medium Size.

	Units per annum, average per head	
Lighting	100 – 300	A possible range of 100 to 300 units, up to say 3 000 to 15 000, the figure per head being about one-fifth of these amounts.
Heating (partial)	500–5 000	
Cooking	1 000–3 000	
Refrigeration, power ventilation, etc.	100–1 000	
Water-heating	1 000–5 000	

This range of values excludes the largest houses, where method and cost of working are of small interest to the occupiers and electricity is likely to be used largely for reasons of luxury and beauty rather than for its utility and economy—and also excludes the vast number of homes of people with small purchasing-power to whom full electrification can perhaps offer the greatest comfort and improvement, but can only follow elaborate and costly schemes for the free provision of wiring, apparatus and maintenance.

Between those limits, however, the field is large, and the resultant consumption of energy can have a very marked effect on all branches of the electrical industry and make it necessary for the tariff systems on which the supply is based to be such that almost indefinite expansion of the business can be contemplated with safety.

Cost Determinants.

The attainment of the lowest cost for energy delivered to the consumer depends largely upon a particular mixture or proportion of different classes of load—industrial with domestic, and power with light. Where an undertaking operates successfully in a particular class of business, there may exist temptation to encourage another class for the benefit of the combined load factors and differently timed demands, the sought business being supplied with energy which is, in a sense, a by-product of the existing production. By-product terms can, however, only be applied with safety when the supplier has the power to check output at his will—a condition which does not apply where a tariff is offered in a market which may be almost unlimited.

For these reasons very low tariffs free from all restrictions may stimulate such a demand as would lead to embarrassment, only to be overcome by price advances, probably resented by those who had expended money in adopting new methods on the strength of the low rates at the time offered to them.

Tariffs and Character of Districts.

In rural areas and good-class residential areas of a semi-rural character, the much smaller number of dwelling houses per acre or route-mile and the relative absence of works and shops result in a lower density of demand and less diversity of use, making the cost of distribution a very heavy item. In quite rural areas, even if prosperous, there is also much less demand for light and the consumer has a different outlook on the value of expenditure for reducing labour and inconvenience, in short, an undeveloped convenience consciousness, largely impervious to the advertising which has done so much to sell equipment and service in city areas. Not only do costs vary widely with the district, character and magnitude of business done by the supplier, but the value to the consumer also depends a good deal upon his surroundings—the transformation value of electricity to light, heat and power, is constant, the benefit to the user is variable with his circumstances and habits, and the cost of delivery to him varies very widely in different districts.

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[*] A review of progress. Reprints in pamphlet form, price 1s. each, can be obtained from the Secretary of the Institution.

[†] *Journal I.E.E.*, 1927, vol. 65, p. 361.

To develop such places is not so much a question of how low a price can be charged, but of how much help, equipment and service can be included for a comparatively high price.

Cost of delivery accounts for much of the variation in tariffs, in different districts, as, for example, between a town area, a " dormitory " suburb, and a purely rural district; whilst the towns again vary widely in cost of generation, business and habits of the people.

Greater uniformity in the charges made for electricity is desirable, since notable differences between the rates and forms of tariff of different suppliers cause dissatisfaction to the users, particularly where areas using widely different rates adjoin.

Probably some unification of policy must precede any widespread similarity of charges. The modern tendency to amalgamate undertakings under a common financial interest will help to bring this about, as will also the derivation, in many cases, of bulk supplies of electricity from or under the control of the Central Electricity Board with its unified system of generation and accounting, which may in time be followed by some amalgamation of distribution interests over large areas.

FORMS OF DOMESTIC TARIFF.

However, progress has been made and, to-day, in any district where the supply of electricity amounts to anything more than an exiguous service of lighting the domestic user need no longer be content with a flat-rate tariff, and if an alternative is not offered he should ask for a method of charging which will enable him to lengthen his hours of lighting and progressively adopt electricity for every other purpose in the home.

In most cases improved domestic tariffs are optional and alternative to flat rates, but it is now competent for electricity suppliers to seek official approval for tariffs of other types and to make them compulsory. The special tariffs generally offered vary, but in essence they amount to the collection of a fixed sum per annum per consumer and, in addition, a flat rate per unit for the energy metered.

The annual fixed charge may be divided into regular monthly or quarterly parts, or be greater in winter than in the summer months. It is assessed on:

(1) Capacity of apparatus connected, or some proportion of it.

(2) Maximum load measured by an instrument, at any time, or at a particular time.

(3) Rent or assessment value of house.

(4) Floor area.

(5) Number of rooms.

(6) An " allowed " maximum load, the supply being interrupted or a warning given if that load is increased.

(7) In some cases the fixed charge (for which no supply is given) is replaced by flat rates in a block tariff, the first annual block of units being charged at the usual lighting rate per unit and the number of units in this block representing the supplier's estimate or experience of a normal lighting supply to the particular house for a year—all further units used in the same year being charged at the low, or heat and power, rate. This is an old method, but simple and acceptable to many who object to any charge which does not cover a certain quantity of electricity.

In some of the multi-part tariffs offered, in addition to the fixed charge a certain block of units has to be used and paid for at an intermediate rate before the low or final unit rate becomes operative. This allows a higher intermediate rate to be collected on the use of small accessories—flat irons and vacuum cleaners, for example —before the lowest rate (needed for heating and cooking) comes into operation. This method has the advantage of helping a small undertaking to introduce a multi-part tariff without making the fixed charge unduly high, and to offer a progressive encouragement to the consumer as the latter gradually electrifies his home. Each of these methods has some disadvantages, but all of them are superior to the older system with separate rates and metering for different use of the supply to the house.

In comparing methods, local conditions must be considered, and, provided that a fair measure of equity as between consumers is achieved and that the tariff enables the supplier to contemplate large resulting extensions with safety, there can be no doubt that the method which is the simplest for the supplier's staff to operate and for the consumer to understand is the best.

Although method (7) above has been in use in but a few undertakings, it has stood the test of experience, and its recent adoption in a slightly modified form by a very large and progressive company seems likely to direct attention again to its great simplicity and appeal to the user.

The perfect multi-part tariff for domestic use should record the consumer's maximum demand, the time of occurrence in relation to the undertaking's station and local peak-load, and the diversity of his demand in relation to that of other consumers—an impossibly complicated task which, if achieved, would still leave the consumer uncertain, in advance, of his fixed charge.

The practical alternative, namely, to assess by some simple standard a reasonable annual charge, is sufficiently accurate, but if it is to result in increased domestic business and an improved load factor the amount of the fixed charge must be limited to the annual cost, at the local rate, of normal lighting (less only the cost of normal lighting units at the low unit rate), this fixed charge becoming, if desired, a minimum annual payment. It may then (*a*) be followed by a limited number of units at some price intermediate between the lighting and the heating or power rate, or (*b*) be associated with a single low rate per unit for all purposes. It is better to use method (*a*) than to employ (*b*) with too high a fixed charge, as in this case the tariff may attract the large user, whereas it should offer a progressive attraction to all directly the limit of " normal lighting " is exceeded. Many of these multi-part tariffs have, for this very reason, failed to bring about any notable increase in domestic electrification, often, indeed, entailing to the meagre user a higher average cost than the alternative flat rates. In this respect tariffs of class (7) have the real advantage that the consumers who venture to adopt them cannot pay more than the standard flat rate for lighting, the minimum payment per annum being usually only the statutory minimum in force in the district; yet the consumers are offered the fullest encouragement to electrify their homes in a progressive way.

PREPAYMENT METHODS.

Prepayment Meters.—Re-housing and the demand amongst the working-class population for better home conditions have opened up to the electricity supplier a very large class of customer of small purchasing power and unaccustomed to any periodic payments. The supply of electricity to such property must be on a cash basis, and the prepayment meter, which would be regarded as a nuisance by people better situated, is actually welcomed by the poorer consumers. Unfortunately, with these meters it is difficult to charge on anything but a single flat rate; the separate collection of a fixed charge is as difficult as the collection of the whole account in that way and, although in some cases a fixed charge has been collected with the rent, leaving the slot meters only to collect the unit charges, no great progress has been made in offering the prepayment consumer a chance of using electricity for all purposes and yet of paying the whole of his account through a simple meter and in advance.

This problem is the more important, since the smallest consumer can be satisfied with so little energy for lighting (50 to 100 units per annum) that the business is hardly remunerative, especially if the installation is connected to an underground network and is associated with some form of "assisted" wiring, as is often the case.

Prepayment meters are now available which will collect a periodic fixed charge in relation to the electricity supply and/or on the hired wiring or apparatus and, in addition, will deliver units against further payments by coins in the slot. There are also types which rely on a time-registering mechanism and need the insertion of a coin at fixed intervals (e.g. once a week) to keep the switch closed and, in addition, of coins to cover the electricity used.

The technical difficulty of collecting a multi-part tariff through the medium of prepayment meters has to some extent been overcome, and such meters are already in use; for the moment, the difficulty lies in their relatively high cost and the need, in the case of small consumers, generally to provide wiring and apparatus on easy hire or hire-purchase terms.

NON-METERED SUPPLIES.

When this very small business was first catered for, there was little prospect of a heating and cooking demand from this class of user and the difficulties were met to some extent by the "contract" system of charging. In this a fixed charge is collected at regular intervals with the rent, or otherwise, and a certain number of lamps of definite size could then be used without a meter by the consumer, who undertook to avoid wasteful use and not to increase the number or size of his lamps. The success of this method varied greatly, in some districts leading to waste and abuse and in others giving fair satisfaction. There appears to be no tendency for it to extend, the limitations of such supplies to lighting, and the ease with which electricity can be used over abnormal hours or for other purposes, making it unpopular with progressive suppliers, particularly when the supply is derived from coal. On hydro-electric systems the disadvantages are not so immediately apparent.

Even where "demand limiting" devices are used, abuse is not entirely checked, whilst progressive electrification is, and some of the conveniences of electricity have to be sacrificed, so marking the method down as a cheap or inferior supply in the minds of the users.

It may be argued that those who can buy only in small instalments and for cash can never buy well, but the total amount paid in the year by small householders for light and heat of all kinds is considerable and worth collecting, whilst the increase in comfort arising from the use of electricity is even greater in the homes of the poor than in those of the well-to-do.

RELATION BETWEEN ALTERNATIVE TARIFFS.

As in most cases the multi-part or subscription tariff is optional to the consumer and is alternative to flat rates, it is desirable that these flat rates should not be unduly low. The consumer seldom starts with an all-electric house but, under an encouraging tariff, progressively electrifies his home methods.

In some cases progress with good and simple multi-part tariffs has been hampered by too low a flat rate for lighting, with the result that the consumer has little incentive to change over unless he puts into use a considerable amount of electrical equipment. Very low lighting rates are seldom justified and may hamper progress by dissipating a surplus of revenue, which could better be employed in developing distribution and consumers' equipment facilities to enable a much wider use to be made of the supply. A commercially-minded management will remember that the value of electric lighting is always increasing, the demand is always for more light, and the tendency is to use it as a luxury and a decorative feature and not merely to regard electric light as a substitute for some other light.

LOAD LEVELLERS.

In the delivery of energy to many small users over an extensive area, minimum cost can only be reached when every user's demand is steady and continuous over all the hours of the year; in this case the distribution investment and other costs have the benefit of division by a load factor of 100 per cent. Failing this, a similar condition is approached where there is a high diversity in the times of use of energy as between one consumer and another, the increased load factor then applying to the generating plant and to a greater or less degree along the distribution network.

Where a fixed charge is made per kilowatt-year, as in the case of some hydro-electric supplies, there is a strong tendency for the consumer's load curve to approach in shape the desirable rectangle. Cases are even reported where the electricity supply secured under these conditions is treated by the consumer as a constant or "base load" of heat energy, extreme needs being met by the use of oil or other fuel, and this regular demand for electricity being achieved by alternatively switching it to lighting, water-heating, food-cooking or warming of the house.

Some attempts have been made in this country to effect the same object by interconnection of cooker elements, water heaters and lamps, so that any combination can be used, but not exceeding a certain capacity in watts at any time.

Recently, also, devices known as "load levellers" have been introduced to offer the same facilities automatically, storage water heaters being generally employed to take up in varying steps the difference between the kW demand allowed under the tariff and the actual demand at any time for light, power or cooking.

For the latter purposes the consumer's need must be met as it arises, whilst the heating of water under a storage system can be carried out, within limits, at any time during the night or day.

A fixed charge per kilowatt, or a limit to the number of kilowatts of demand, having been arranged, it is the duty of the load-levelling apparatus to switch on to or out of the heat-storage tanks such proportion of the demand agreed as is not, from time to time, being used for other purposes.

Similar in object is the system referred to as the "dispensable circuit." In this the heat storage is connected to a special circuit and the amount of energy it can consume is regulated by the use of all the other household appliances which are on the "indispensable circuit"; in practice the former endeavours so far as possible to fill in the gaps in demand produced in the latter, resulting in a consumer's load curve which approximates to a rectangle or the ideal 100 per cent load factor.

HEAT STORAGE.

The storage of electrical energy in the form of heat, viz. as hot water for use as such or for space heating, or as hot oil or refractory material for space heating, has made considerable progress already and offers great possibilities of increasing the load factor on plant and on local networks (often quite as important in reducing the cost of supply). Space heating of this class has, however, none of the advantages and attraction of the radiant electric fire, and although more suitable and efficient for certain situations and uses, by that reason finds itself in direct competition with low-temperature hot-water systems, i.e. is only possible on a large scale and at quite low rates for energy consumed.

INFLUENCE OF BULK-SUPPLY COSTS.

In recent times no less attention has been given to the important subject of power tariffs and, although outside the scope of this review, it must be remembered that consideration of power tariffs may have an increasing influence on the rates and charges for domestic supplies. Under the ægis of the Central Electricity Board the authorized distributors will buy or have their own supplies charged to them in bulk on a maximum demand tariff, a condition which may compel a closer inspection of the effect of new load on their overall load factor.

Although in some of the domestic applications there is a large diversity factor, short-period uses of electricity being spread over a long period of the day, yet some of the more important uses—cooking and water-heating, for example—are required by most people at the same time of the day as dictated by routine. The water-heating problem will probably be solved by heat storage and off-peak supplies. Space heating and room heating at rates low enough to compete with gas and coal may come to be used over long hours and so present no great difficulty, at least in urban areas, but as used to-day, mostly for occasional heating and as a supplement to fires, electric heating already presents problems of some difficulty to the tariff maker, providing on occasions a demand on the plant and distribution out of all proportion to the annual revenue resulting from it.

GENERAL CONSIDERATIONS.

The more extensive use of electricity in homes of all classes is a subject to which great attention has been given in recent years by all sections of the industry. In certain urban areas very great success has attended this phase of development and to-day the conditions for it are understood.

The wiring of buildings has been simplified, accessories and fittings have reached some degree of standardization, the apparatus for heating, cooking and labour-saving exists in great variety, of British make and reliable to a degree unknown a few years ago, whilst in the realm of lighting there is an entirely new and growing movement toward efficiency and beauty in a branch of electrical work which many regarded only a few years ago as capable of but little further advance.

The study of domestic electrification and the establishment of hire and hire-purchase methods to enable householders to enjoy the advantages of the cheaper electric power now available in most places has had the serious encouragement of the Electricity Commissioners* and has been fostered by the work of the British Electrical Development Association, the Electrical Association for Women and the great trade organizations promoting the interests of the makers of electrical plant and apparatus, cables and lamps, and also the wholesalers and contractors for installation work.

These efforts have awakened the public to the possibilities of electricity in their homes. A real demand exists and, if it is welcomed with a simple tariff and a commercial policy on the part of the authorities responsible for the distribution of electric power, the householders of this country may, in the course of a few years, consume as much electrical energy in a year as is at present supplied annually by all the statutory undertakings in this country.

The form in which tariffs and charges are presented to the public, and the conditions under which electricity is supplied or apparatus hired, should be as simple as is consistent with accuracy and the safety of the supplier.

The electrical industry has frequently been at fault in this respect, passing on to the uninstructed public in its printed forms the work of legal or technical minds, bristling with expressions which arouse suspicion, or decimals which are not understood. For success in this department of the supply industry the scientific or legal basis of the work needs to be concealed under the language and arithmetic which the housewife encounters in her business with the butcher and the baker.

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* A Committee appointed by the Electricity Commissioners under Section 4 of the 1919 Act produced a report on method of charging for domestic supplies. This report is obtainable from H.M. Stationery Office and is of interest to students of this subject.

THE ELECTRICAL EQUIPMENT OF AUTOMOBILES.*

By Professor S. **Parker Smith**, D.Sc., Member.

The electrical equipment of the automobile has followed a course of progressive development from an accessory which, in the first instance, was added to the car after purchase, to its present position in which it forms an integral part of the equipment and is built into the chassis by the manufacturer. Electric ignition was the earliest application, and its adoption is now universal. Likewise electric lighting, bringing freedom from mess and smells, and the ability to light the lamps in a gale, gradually ousted the popular, and originally more powerful, acetylene lamp. With lighting, the battery was introduced, unless one was already installed for coil ignition. The next stage, namely the introduction of the charging dynamo, was inevitable; and, with the battery and dynamo installed, further applications became possible. The relatively large battery required to control the 3-brush dynamo assisted the application of the starting motor, now universal on most private vehicles and widely adopted on certain commercial types. The later introduction of other electrical accessories, such as the electric horn, windscreen wiper, fuel pump, signalling devices, etc., whether as extras or as part of the standard equipment, was both simple and natural.

Table 1.

Standard Dimensions and Data for Electrical Equipment of Automobiles.

S.M.M. and T. Provisional Standard No.	I.A.E.† Data Sheet No.	Date	Subject	Corresponding B.E.S.A. Report No.
6 R	104 R	1929	Lamps	Under revision
9	107	1924	Magneto switch	—
15	114	1924	Dynamos	5031/3—1925
16	115	1924	Distributor mountings	
17	116	1924	Starting motors	
18 R	117 R	1928	Dynamotor	Under revision
19	118	1924	Small couplings	—
23 R	123 R	1928	Batteries	—
24	124	1925	Impulse startor couplings	—
35	135	1926	Magneto contactor parts	—
36	136	1926	Magneto brushes	5039/40—1928
47	147	1927	Dynamo and motor brushes	
			Flexibles and terminal tags	
			Lighting and startor cables	5002—1924
			Standard nomenclature	5012—1927
			Sparking plugs	45—1928 ‡
			Magnetos	5027—1924
58	158	1929	Dynamos (commercial vehicles)	—
61	161	1929	Wiring colour code	—

† Institution of Automobile Engineers. ‡ British Standard Specification.

Almost without exception, every piece of electric equipment for automobiles had to be specially developed. This development was generally associated with strong competition from non-electrical alternatives, and a critical, if not hostile, attitude of car manufacturers towards electrical equipment. The competition between automobile makers was also keenly felt by electrical firms, though doubtless improved performance and reduced weight and cost were the response to many such difficulties.

As in most other industries, early progress produced a multitudinous variety of equipment and wiring diagrams. This stage of development now appears to be passing and signs of standardization are already apparent. Among certain British manufacturers determined attempts have been made to ensure interchangeability wherever possible. Table 1 shows the activities of the Society of Motor Manufacturers and Traders (S.M.M. and T.) and of the British Engineering Standards Association (B.E.S.A.) in this connection, while in Tables 2–10 data concerning batteries, cables, brushes and lamps are given. It is satisfactory to note that, in general, these specifications are well observed by many manufacturers, particularly in new designs.

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* A review of progress. Reprints in pamphlet form, price 1s. each, can be obtained from the Secretary of the Institution.

In this review the progress of the several parts of the electrical equipment of automobiles is dealt with in the following order: Wiring systems; Batteries; Lighting; Charging dynamos; Starting motors; Dynamotors; Brushes; Miscellaneous; Ignition systems.

WIRING SYSTEMS.

Distinction must be made between the high-voltage ignition system and the low-voltage system used for all other electrical services.

Low-Voltage Systems.—Low-voltage wiring systems may have an insulated or an earth return, the earth part of the circuit being formed by the chassis. Two voltages have become standardized: 6 volts and 12 volts. The 6-volt system is almost universally employed on American cars, while the 12-volt system is mainly used in Europe. The 6-volt system is still met with on certain British cars, though generally only on earlier models. For the same percentage voltage-drop, four times as much copper is needed in the 6-volt as in the 12-volt system. This relation also exists between the insulated-return and the earth-return system. In 12-volt systems, the drop in the lighting cables is usually about 0·5 to 0·75 volt, and somewhat less in 6-volt systems. Omnibuses and lorries are mostly wired with an insulated return. The earth return is used more widely on private cars.

Types of Low-Voltage Automobile Cables.—Experience of automobile wiring soon revealed that ordinary protective compounded braiding over the vulcanized rubber lapped with a varnished cambric tape was not equal to the severe service demanded. Armouring was one of the means adopted to meet the requirements. American practice was to armour the cable with a spiral of galvanized mild steel. European practice favoured aluminium, though brass and nickel-silver helices were also used for armouring. Steel has a tendency to cut into the insulation, while after exposure aluminium tends to weaken and break away. A braided armouring of thin wire has also been used.

As an alternative to armouring, another development consists of a cellulose-varnished outer sheathing. The coating of cellulose varnish presents a bright, polished, smooth surface, usually left black, which will not crack when bent and serves as a protection against oil, petrol and water. This type of finish can be applied to any automobile flexible which has as its final protection a fine cotton braid. Startor cables are usually finished with a strong, stout braid heavily treated with a wax compound.

Another type of cable extensively used for the wiring of automobiles is the tough rubber sheathed (usually known as C.T.S.). The tough rubber filling and covering is not easily damaged; it is lasting and flexible, and greatly reduces the danger of earthing.

For further protection of cables, it is the practice of some makers to run the insulated conductors through flexible metal sleeves, which may be in different colours where desired.

Standard Lighting and Starting-Motor Cables.—Existing practice was largely standardized in B.S.S. No. 5002—1924. This standard specification for electric lighting and startor cables for automobiles recognizes the 6- and 12-volt systems with earth return and with insulated return. The types of covering specified are braided and compounded, armoured and C.T.S. The specification states that compounded braiding shall afford protection against water and oil, and the cable shall have a smooth flexible surface. Armouring is to be in the form of a close helix of metal of approximately half-round section not less than 0·015 in. thick. C.T.S. is to form a circular section. Lighting conductors shall be made up of tinned copper wires, 0·012 in. in diameter, and each conductor shall be insulated with vulcanized india-rubber not less than 0·025 in. thick. In a twin cable, the rubber shall be coloured red on one core and black on the other. In a triple cable, white shall be the colour of the smallest core. The S.M.M. and T. recommend that positive wires shall be red, negative wires black, and field wires green.

The B.E.S.A. sizes are given in Tables 2 to 4.

TABLE 2.

Lighting Cables with Insulated Return.

	Conductor	Maximum overall diameter	
		Braided and compounded, or armoured	C.T.S.
		in.	in.
Dynamo	2 × 35/·012 1 × 14/·012	0·38	0·4
Battery	2 × 35/·012	0·37	0·39
Lamp	2 × 14/·012	0·29	0·31

TABLE 3.

Lighting Cables with Earth Return.

	Conductor	Maximum overall diameter	
		Braided and compounded, or armoured	C.T.S.
		in.	in.
Dynamo	2 × 35/·012	0·37	0·39
Battery	1 × 35/·012	0·225	0·25
Lamp	1 × 14/·012	0·19	0·22

TABLE 4.

Starting-Motor Cables.

Conductor	Maximum overall diameter		
	Armoured	C.T.S.	Braided
	in.	in.	in.
37/·036	0·46	0·495	0·47
61/·036	0·545	0·58	0·555
61/·044	0·63	0·69	0·64

In some wiring systems all lighting and accessory cables are braided together, each conductor having a distinctive colour and being cut to the appropriate length.

The practice as regards fusing varies widely. One modern plan is to have a combined junction and fuse box of moulded material, each circuit being separately fused.

High-Voltage Cables.—All high-voltage systems have an earth return. Ignition cables are made of tinned copper wires, stranded and insulated with 1, 2, 3 or more thicknesses of rubber. The layer next the conductor is of pure rubber, the whole being vulcanized together to the required diameter. The strands are of Nos. 30 to 33 S.W.G. (about 0·01 in. diameter), the number varying up to 41. The overall diameter is made in sizes from 4 to 12 mm, the common size being 7-mm cable. For applying the rubber, two methods are in use: the longitudinal method in which the rubber is applied by means of grooved steel rolls, and the extrusion or forcing machine method.

As a further protection against deterioration from the effects of heat and oil, ignition cables can be braided and well treated with cellulose varnish. The varnish may be applied in distinctive colours to enable the cylinder connections to be readily traced.

Tough rubber sheathing also forms an admirable protection for high-voltage cables, and is now widely manufactured for this purpose.

For providing ready identification of the several wires, the S.M.M. and T. recommend the following colour code: No. 1, red; No. 2, yellow; No. 3, black; No. 4, green; No. 5, brown; No. 6, blue; No. 7, orange; No. 8, slate. This can be carried out by covering the cable with a cotton sleeve and impregnating with a baking varnish of the appropriate colour. The overall diameter of a 7-mm cable so treated should not exceed 8 mm.

BATTERIES.

Originally supplied for ignition purposes only, it may now be said that the battery is an essential part of practically every electrical device, except the magneto, at present used on automobiles. The earliest source of electricity on the car was a primary battery, soon to be followed by a lead-acid storage battery in a celluloid case. The number of cells was settled by the voltage, being 3 for the 6-volt system and 6 for the 12-volt system. An important influence on the size of the battery was the 3-brush charging dynamo, an ample battery being needed to anchor the voltage and to counteract to some extent the undesirable charging characteristics of the generator. The large capacity thus required proved invaluable for the starting motor, the severe demands of which led to the present mode of construction. In addition to the tax placed on the battery by the 3-brush dynamo and the starting motor, automobile batteries frequently suffer from neglect of topping-up and abuse from overcharging and over-discharging.

Construction.—In order to supply the very large current required at starting, the plate surface has to be made as large as possible. Thus the automobile cell is characterized by a large number of comparatively thin plates.

Rating.—The ampere-hour capacity of the battery is given either at the 10-hour or at the 20-hour discharge rate, the latter usually being somewhat higher, say 10 per cent, than the former. In addition, the discharge current is also given at the 5-minute rate, this current being about 30 times the current at the 10-hour rate, and is roughly the current taken by the starting motor on switching in.

Containers.—The celluloid container was replaced by separate 2-volt units in ebonite boxes placed in a wood case. Later the multi-compartment container moulded of ebonite or some synthetic composition was introduced, and the 1-piece moulded type with 3 or 6 compartments became standard practice. Each compartment is fitted with a moulded lid securely sealed at the edges, and is closed by a ventilated stopper or plug. The moulded container is made strong enough to render a crate unnecessary.

Mounting.—The battery is mounted on the running board or on the chassis, and secured by bolts or other arrangement.

TABLE 5.

Dimensions for Containers of Car Batteries.

Minimum capacity at 10-hour rate	Maximum overall dimensions				
	Length		Width	Height	
	6-volt unit	12-volt unit		Without lid	With lid
amp.-hours	in.	in.	in.	in.	in.
48	8½	13½	7½	9⅞	10¼
60	9½	16			
72	10½	18			
84	11½	21			
96	12½	24			

Plates.—In automobile cells the plates are ⅛ in. to 3/32 in. in thickness, the modern tendency being towards the substitution of 3/32 in. for ⅛ in. The separation between plates is reduced to a minimum. The height and width of the plates are frequently 4 15/16 in. by 5⅝ in. respectively; previously the height of 4 3/16 in. was more usual.

Separators.—These are necessary to prevent short-circuits due to buckling of the thin plates or dislodged paste. Different kinds of separators have been used, but wood separators are now almost universal. These are made in the usual grooved and ribbed design.

Dimensions.—For the guidance of makers and users, the maximum overall dimensions in Table 5 have been fixed to indicate the space to be left by the chassis maker. (For standard specification, see Table 1.)

Terminal Posts.—The terminal posts of startor and lighting batteries have been developed into the taper pattern with the following dimensions:—

Small diameter of negative post..	⅝ in.
Small diameter of positive post..	11/16 in.
Taper	1 in 9 on diameter
Minimum length of taper ..	11/16 in.

Cable Connectors.—The cable connectors for the battery are of brass, lead coated, the taper corresponding to the taper of the terminal posts. The clamp bolts for tightening the connectors are of mild steel, lead coated.

Density of Electrolyte.—In order to increase the capacity somewhat, it is usual to employ in automobile batteries stronger acid than in stationary batteries. The density of the electrolyte specified for filling varies from 1·25 to 1·3, the figure 1·28 being fairly common.

The chief differences between different makes are matters of detail, such as the means for securing the active material in the plates, prevention of internal short-circuit, anti-splash ventilation plugs, composition of the material of the container, etc.

Batteries for Commercial Vehicles.—For motor coaches and other large commercial vehicles larger batteries are often needed, though in some of these electric self-starting is not provided, or is only employed to move the engine sufficiently to draw an explosive mixture into the cylinders. For motor-omnibus lighting, the standard voltage is 12 volts and the capacity at the 10-hour rate of discharge may be 110 to 220 ampere-hours, the battery being made up in separate cells or in 6-volt units.

Alkaline Batteries.—Although, from a mechanical standpoint, the alkaline cell is well-suited to automobile work and is not damaged by heavy discharge current, the great obstacle to its use for starting automobiles has been its high internal resistance. Moreover, the relatively high cost of alkaline batteries has made competition with acid batteries difficult. Recently a nickel-cadmium cell has been developed in which efforts have been made to reduce the internal resistance. It is claimed that such a cell will discharge completely in 12 minutes at an average voltage of 1 volt, whereas under the same conditions an ordinary nickel-iron cell would give an average of only 0·5 volt. The 60-ampere-hour battery is able to maintain 200 amperes for 12 minutes; while it is stated that a 120-ampere-hour battery, designed for commercial vehicles, will give an initial kick of 500–600 amperes. With the reduced internal resistance it is therefore possible to employ alkaline batteries for starting. Alkaline batteries are making rapid headway for use with omnibuses, a common installation being 10 cells of 180 ampere-hour capacity at the 10-hour rate. A partial offset against their high initial cost is the long period for which they are guaranteed by the makers.

LIGHTING.

Experiments with electric lighting for automobiles date back to the early years of this century, when not only were the available carbon filaments too fragile and the batteries too undeveloped for road conditions, but a suitable mode of controlling the charging dynamo was lacking. The introduction of the metal-filament lamp was a marked advance, and later the gas-filled bulb provided an economical means of obtaining the requisite illumination for night driving at high speeds. Unfortunately, the progress made in solving one problem introduced another, namely, that of glare. The modern tendency is to use only gas-filled lamps for headlights, and vacuum lamps for the side, tail and dash lights. The lamp load may vary from about 40 watts on a small car to about 600 watts on an omnibus.

Headlights.—The present practice is to use parabolic silvered and varnished reflectors with the filament of the bulb at the focal point. British makers show a marked preference for the linear or straight-helical filament with the axis of the filament along the centre of the reflector [see Fig. 1 (*a*)], in contradistinction to the V-shaped filament with the apex at the focal point as favoured on the Continent [see Fig 1 (*b*)]. Accuracy of reflector shape is important to prevent focal variation in the beam intensity giving rise to streaks and patches. A frosted cover glass in front of the headlamp, giving a slight amount of diffusion, is commonly used to eliminate streakiness.

Glare.—Innumerable patents have been taken out with the object of obtaining adequate driving light with freedom from dazzle to oncoming traffic, but it is now generally recognized that any beam which will give a long range of illumination must produce dazzle to anyone meeting it. The present tendency is to use a normal driving beam which covers a fair vertical range in order to allow for variations in the trim of the car or contour of the road, and to provide means for depressing the beam when meeting oncoming vehicles. This depression can be obtained mechanically by tipping the reflector or the headlamp as a whole, or electrically by using two bulbs, or two filaments in one bulb, for producing a normal and a depressed beam respectively. In addition to depressing the beam, it is common practice to swing it slightly to the left to illuminate the near side of the road.

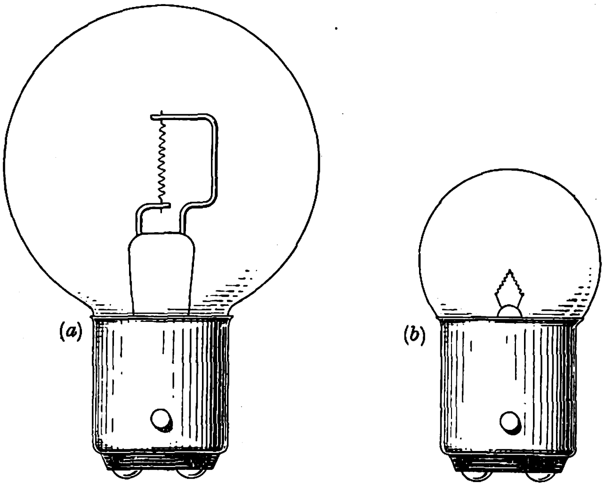

FIG. 1.—Automobile bulbs.

(*a*) Linear filament. (*b*) V-shaped filament.

Voltage Variation.—The voltage of a lead-acid cell may vary from 1·8 to 2·7 volts, and it is usual for the charging dynamo to be switched on when the lamps are in use. In order to prevent the lamp voltage becoming excessive, the dynamo voltage is usually adjusted so that with the headlights switched on the battery floats on the busbars. In this condition the lamp voltage is practically the open-circuit voltage of the battery. When the headlights are switched off, the battery will then take a charging current, so that the voltage may rise to 2·7 volts per cell. For the side and tail lamps, therefore, where a high efficiency is not demanded, it is common practice to supply bulbs of higher nominal voltage.

Standardization of Automobile Bulbs.—Electric lamps when used in the automobile industry are generally referred to as "bulbs." In 1923, the manufacturers of electric bulbs and of car-lighting equipments discussed the possibility of reducing the large variety of bulb types then in use. It was agreed that in future 10 definite types of bulbs would cover normal requirements, and a specification was drawn up by the Society of Motor Manufacturers and Traders and the Electric Lamp Manufacturers' Association of Great Britain. This specification was revised in 1929, and the I.A.E. Data Sheet No. 104R was issued, in which vacuum-type headlamp bulbs were deleted, leaving the 7 types shown in Table 6. The chief points are:—

TABLE 6.

Standard Automobile Bulbs.

Type	B.A.S. No.	Fig. No.	Rating		Initial rated efficiency *	Initial luminous flux †
			watts	volts	lumens/watt	lumens
Headlights (gas-filled)	1	1 (*a*)	12	6	14	168
	2		18	6	15	270
	3		24	12	16	384
	4		36	12	17	612
Side, tail and dash lights (vacuum) ..	8	1 (*b*)	3	6	7·5	22·5
	9		6	6	8·0	48
	10		6	12	8·5	51

* Tolerance ± 15 per cent. † Tolerance ± 20 per cent.

Types of lamp: Headlights (gas-filled); side, tail and dash lights (vacuum).

Standard voltages: 6 and 12 volts.

Rating: See Table 6.

Dimensions: The overall dimensions of bulbs, caps and holders are specified for the several bulbs.

Filament: Tungsten, disposed symmetrically in bulb, and supported to burn satisfactorily with lamp at any angle. To be uniform in appearance both at rated and at half rated voltage.

Cap: Straight-sided, of either of the following types:
(*a*) Small bayonet, double-contact cap.
(*b*) Small bayonet, centre-contact cap.

About 80 per cent of the orders for British bulbs are now for standard types. The automobile industry has also been experimenting with other types of bulbs, such as coloured bulbs, double-filament bulbs, etc., with a view to increasing their illuminating effect while diminishing glare.

CHARGING DYNAMOS.

The problem with the car-lighting dynamo was the same as with the train-lighting dynamo, and arose from the wide range of speed over which it was required to generate a constant voltage. In the earliest types a belt drive was common, no special provision being made for mounting or driving the generator. Many devices for obtaining constant dynamo speed were tried and discarded, along with other mechanically- and magnetically-operated contrivances for regulating the output. Ultimately the so-called "constant-current" type of dynamo ousted most of its rivals, until in its turn it has now to compete with the constant-voltage type.

Originally 2-pole machines were tried, often with only one pole wound, the eccentricity being used as a means of adjusting belt tension. The 4-pole type was soon found to be more economical in material and is now nearly universal. The shell is cylindrical, being made of mild-steel tubing or bent sheet with butt-welded ends.

In practically all modern equipments a reverse-current relay is employed as an automatic cut-out to isolate the generator from the busbars as soon as its voltage, owing to drop in speed, falls below a predetermined value, and to switch it into circuit when its voltage rises above a predetermined value. With many equipments a field switch mounted on the dash is supplied in order to enable the driver to switch the dynamo in and out of action.

The dynamo is usually positively driven by the engine, the speed ratio depending on circumstances. Common dynamo speeds are 1 to 1½ times engine speed. The output may vary from about 50 watts, requiring a machine with an outside diameter of some 3½ in., for a small car, to about 720 watts for an omnibus, the dynamo having an overall diameter of 8 in. and weighing about 120 lb.

Where coil ignition is used, it is a common practice to drive the ignition head from the end of the dynamo. In future, the dynamo may be relieved of this unwelcome burden. The two standard methods of mounting are by means of a cradle and straps and by means of a flange. In Table 1 reference is made to the specifications of standard dimensions adopted for both these arrangements.

Constant-Current Dynamo.—Regulation is here obtained by means of armature reaction, which distorts the flux and reduces its effective value as the current increases. To anchor the voltage a battery is needed, and with this combination it is possible to maintain a fairly constant current over a wide range of speed. In one arrangement a portion of the armature winding is short-circuited, but the rather large additional brushes tend to limit the application of the method to 2-pole machines and, consequently, its usefulness to motor-cycle work. The 3-brush dynamo, in which the field is excited from a main brush and a third or control brush, is the common solution, and this method of regulation is probably the one now most widely used in this country. Not only must a battery of ample capacity be employed to control the voltage, but the characteristic of the dynamo is the opposite to that required by the battery, namely a falling charging current with a rising voltage. To prevent excessive overcharging, a dynamo field-switch becomes essential. This sometimes takes the form of a 2-position switch for full- and half-charge; in the latter position a resistance is inserted in the field circuit to reduce the charging rate. The operation may be manual or automatic, the latter being favoured in many cases where coil ignition is employed. Correct charging rates, however, are difficult to obtain.

TABLE 7.

Cylindrical Brushes for Magnetos [see Fig. 2 (a)].

No.	Nominal diameter	Overall length	Head and neck				Groove (if required)	
	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*
	mm	mm	mm	mm	mm	mm	mm	mm
1C, 2C, 3C..	4	10, 13, 16	3·0	2·4	2·5	0·5	0·75	0·38
4C, 5C, 6C, 7C	5	10, 13, 16, 19	4·0	3·4	3·2	0·5	0·75	0·38
8C, 9C, 10C, 11C, 12C	6	10, 13, 16, 19, 27	4·5	3·9	3·5	0·5	0·75	0·38
13C	7	10	5·0	4·2	4·0	0·7	1·00	0·50

Constant-Voltage Dynamo.—This represents a further step towards making the operation of the charging set independent of the driver. Here a quick-acting field regulator, similar in principle to the Tirrill regulator, is used to control the voltage of a plain shunt-wound machine. With this device the dynamo can be used without the battery. Furthermore, the maximum charging rate occurs when the battery is in a discharged state, and falls off as the battery voltage rises. The sensitive part of this system is the contact points, but pitting and welding have now been practically overcome. This method is employed almost universally in Germany, but in Great Britain its use is mainly confined to commercial vehicles.

STARTING MOTORS.

The plain starting motor is usually a 4-pole series motor of relatively small diameter and considerable length. The problem here has been the transmission from the motor to the engine. Practically all forms of free-wheel and other drives have now given way to the so-called "Bendix drive," or its equivalent. This merely consists of a loose pinion running freely on a screwed quill and engaging with a toothed ring on the engine flywheel. The engagement and disengagement are automatic. The problem is to provide a combination which will exert sufficient breakaway torque under the worst conditions and will also bring up the speed to a sufficient value to cause the engine to fire. A gear-ratio of about 10 : 1 or 12 : 1 is usually adopted. The overall diameter of the motor varies from about 3½ in. with a breakaway torque of 5 lb.-ft. to about 6 in. with 40 lb.-ft., the latter being suitable for starting omnibus engines.

The motor is generally attached to the flywheel housing by means of a flange on the end-plate. (For standard specification, see Table 1.)

DYNAMOTORS.

Early attempts were made to combine the charging dynamo and the starting motor into a single unit. The compromise is a poor one both electrically and mechanically, but it enables two machines to be replaced by one. If the combined unit, commonly known as a dynamotor, is permanently geared to the engine, it is not feasible to have a gear-ratio greater than about 3 : 1 owing to speed limitations; on the other hand, in order to provide sufficient breakaway torque with a low gear-ratio a large machine is necessary. With higher gear-ratios, say 7 : 1, it is usual to employ gearing which engages automatically when the machine functions as a motor; when running normally as a generator the machine is driven at engine speed. Mountings for dynamotors have also been standardized (see reference, Table 1).

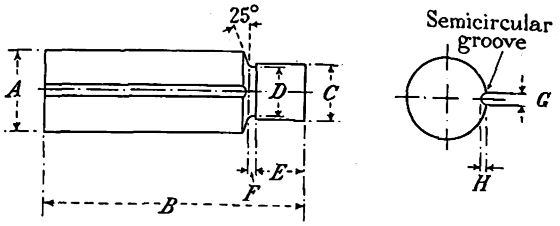

FIG. 2 (*a*).—Cylindrical magneto brush.

BRUSHES.

Carbon brushes have been developed to meet the needs of the various electrical machines used on automobiles. At present the variety of such brushes is very great, but attempts are now being made to conform to the standards which have been adopted by the S.M.M. and T. and the B.E.S.A.

Magneto Brushes.—The magneto with revolving armature needs two brushes to convey the high-voltage current from the slip-ring to the revolving distributor arm, also two low-voltage brushes—one for earthing the magneto windings and the other for short-circuiting the primary at the ignition switch. With stationary windings, the only essential brush is the one for conveying the current to the revolving distributor arm. Where a contact-type distributor is used a further brush is required, and this presents the chief problem, for a soft and graphic brush causes tracking, while too hard a brush produces scoring. Non-graphitic, smooth carbon brushes are used throughout on ignition apparatus, though on brass slip-rings electro-graphic brushes are occasionally employed. Standard dimensions of carbon brushes for magnetos are given in Tables 7 and 8 and Fig. 2 (for references, see Table 1). Fig. 2 (*c*) shows the dimensions of the earthing brush on the contact breaker.

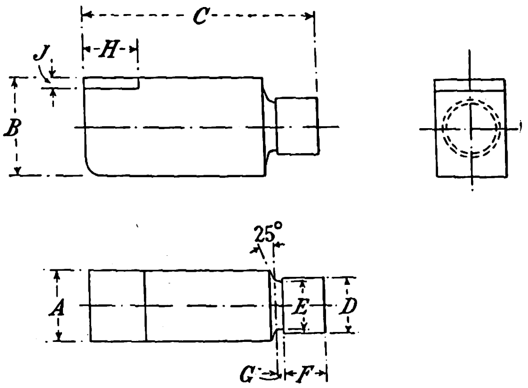

FIG. 2 (*b*).—Rectangular magneto brush.

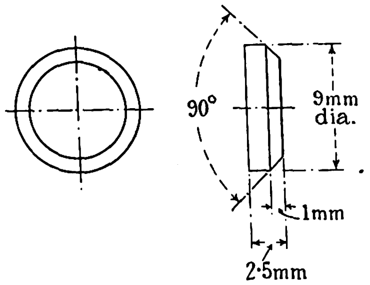

FIG. 2 (*c*).—Earthing brush on contact breaker.

TABLE 8.

Rectangular Brushes for Magnetos [*see Fig.* 2 (*b*)].

No.	Section		Overall length	Head and neck					
	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*J*
	mm	mm	mm	mm	mm	mm	mm	mm	mm
1R, 2R, 3R	5	7	14, 17, 20	4·0	3·4	3·2	0·5	4·0	1·0
4R, 5R, 6R	5	8	14, 17, 20	4·0	3·4	3·2	0·5	6·0	1·0
7R, 8R, 9R	5	10	14, 17, 20	4·0	3·4	3·2	0·5	6·0	1·0

Dynamo Brushes.—Owing to the high current densities now used—60 to 70 and even 90 amps. per sq. in.—carbon brushes have been replaced by electro-graphitic brushes. Natural graphite is occasionally used to reduce noise and costs. The control or third brush is often of hard carbon because of its cleaning properties, but brushes with higher graphitic content than the main

TABLE 9.

Brushes for 3-brush Dynamos (see Fig. 3).

Maximum length *A*	Width *B*	Thickness *C*	
Main and control	Main and control	Main	Control
in.	in.	in.	in.
$\frac{5}{8}$	$\frac{5}{8}$	$\frac{1}{4}$	$\frac{3}{16}$
$\frac{3}{4}$	$\frac{5}{8}$	$\frac{5}{16}$	$\frac{3}{16}$
$\frac{3}{4}$	$\frac{7}{8}$	$\frac{9}{32}$	$\frac{3}{16}$
1	$\frac{7}{8}$	$\frac{3}{8}$	$\frac{3}{16}$

Grade for all brushes to be electro-graphitic.

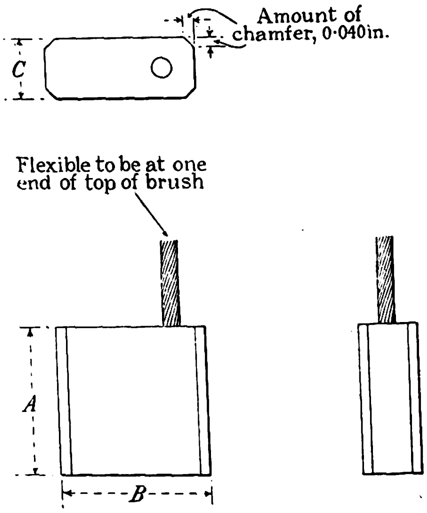
Amount of chamfer, 0·040in.
C
Flexible to be at one end of top of brush
A
B

FIG. 3.—Brushes for 3-brush dynamos.

brushes can also be used without sparking troubles. The output of the 3-brush dynamo is very sensitive to the bedding of the control brush, which should be perfect. Pressures of 4 to 5 lb. per sq. in. are employed, and higher pressures with very high current densities. The common type of holder used in this country is the box or slide type, and it is for this type that sizes have been standardized. In America the grip-type holder is fairly common.

In Table 9 and Fig. 3 the standard dimensions for brushes for 3-brush dynamos are given (for references, see Table 1).

Flexibles and terminal tags have also been standardized for dynamo and starting-motor brushes (see Table 1).

Starting-Motor Brushes.—Generally speaking, the starting motor is only in circuit when actually starting the engine. The density under the brushes at the instant of switching in may reach 2 000 amps. per sq. in., while 1 200 to 1 700 are figures frequently met with. Low contact drop, especially with 6-volt sets, here becomes all-important, and a copper brush with a very small percentage of graphite is used. For 12-volt systems, a grade with about 75 per cent copper is employed. In this connection, too, the pressure is all-important, the contact drop falling rapidly until about 8 to 10 lb. per sq. in. is reached. These high pressures are common for starting-motor brushes.

TABLE 10.

Brushes for Starting Motors (see Fig. 4).

Maximum length *A*	Width *B*	Thickness *C*
in.	in.	in.
$\frac{5}{8}$	$\frac{5}{8}$	$\frac{5}{16}$
$\frac{5}{8}$	1	$\frac{5}{16}$
$\frac{3}{4}$	$\frac{7}{8}$	$\frac{9}{32}$

Grade for all brushes to be copper-carbon with approximately 85 per cent copper.

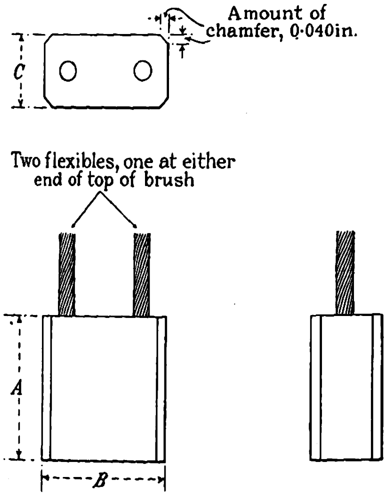
Amount of chamfer, 0·040in.
C
Two flexibles, one at either end of top of brush
A
B

FIG. 4.—Brushes for starting motors.

In Table 10 and Fig. 4 the standard dimensions for starting-motor brushes with slide-type holders are given (for references, see Table 1).

Dynamotor Brushes.—The brush most favoured on dynamotors is a copper-graphite grade containing about 65 per cent of copper. This brush has a low contact drop and runs well at generator loads. The pressure employed is 5 to 6 lb. per sq. in. and the current density at the instant of starting is usually about 1 200 amps. per sq. in. The third brush is generally of hard carbon.

In general, it would seem that the progress in brushes has kept pace with the development of automobile equipment.

MISCELLANEOUS.

Probably all the foregoing can be regarded as essential parts of the equipment of a modern automobile, with the exception, perhaps, of the startor, which is not always fitted to commercial vehicles. There are in addition a number of other current-consuming devices, many of which can certainly be regarded as desirable, even if not essential. Some of these appliances form part of the standard equipment of various makes of auto-vehicles.

Electric Horns may be of the solenoid type where the diaphragm is actuated by electromagnetic action, or of the motor-driven type where a star wheel strikes a metal pin fixed to a steel diaphragm.

Windscreen Wipers are electrically operated by a small motor through reduction gearing. The motors are either of the series-wound type or the attraction type in which the revolving element carries no winding.

Signalling Devices including a rear "stop" light consisting of a red lamp and an illuminated signal usually operated by the foot brake, and direction indicators often controlled from the steering wheel.

Fuel Pump to replace an automatic vacuum chamber and operated by a solenoid.

Solenoids are also employed for the automatic operation of other devices.

Petrol Gauges and Cigarette Lighters are further instances of electric devices. For appliances such as foot or rug warmers for use in cold weather a socket is provided.

Assembly of Equipment on Chassis.—Originally no provision was made for electric wiring or equipment, but in modern practice these are supplied with and mounted on the chassis. Likewise the instrument board is carried on the chassis independently of the body. It is also becoming general practice to mount all instruments such as clock, oil gauge, speedometer, ammeter, etc., on a facia board, usually of metal and arranged for interior illumination. The position of the controls and switches has not been standardized, but there is a tendency to arrange those used in normal driving, such as horn, headlights, dipping device and direction indicators, near to or on the steering column.

Present-Day Tendencies.—It is recognized that in many directions further simplification and standardization are desirable and possible. Many existing differences are unnecessary and hinder standard manufacture. Progress has already been made towards standard dimensions, as indicated in Table 1, and, with the further elimination of special sizes and ratings, manufacturing costs will fall. It is recognized that many of the special features favoured by various manufacturers are not improvements, while they certainly add to the burden of the electrical manufacturer, the garage engineer and the user.

IGNITION SYSTEMS.

The introduction of electric ignition dates back to the pioneer days of the automobile. Despite the troubles associated with the induction coil and trembler, actuated at first by a dry battery, and the complication of a coil for each cylinder, it was soon recognized that more accurate timing was possible with the electric than with any other system of ignition. With the development of the magneto in Germany, the various systems of coil ignition in this country almost went out of use, though in America the coil retained its stronghold. As a result, at the outbreak of the War the ignition industry of Great Britain had passed largely into German hands, only one or two British firms maintaining a small output of magnetos.

The advent of the War gave a great impetus to the manufacture of British magnetos for road, air and water transport, and since that time much of the development of magnetos has taken place in this country. Extensive research was necessary to keep pace with the growing demands of the petrol engine—higher speeds, larger compression ratios and greater numbers of cylinders—and to meet the active competition of coil ignition.

Detail Development.—With the introduction of the high-voltage distributor, permitting the use of a single ignition device with any number of cylinders, and the contact-breaker, ensuring precise timing of the spark, development became chiefly concerned with design details and materials of construction. Most of the early work was done on the revolving-armature magneto fitted with a horseshoe permanent magnet and a shuttle armature. The substitution of laminated for solid pole-shoes assisted starting by producing better low-speed performance with retarded spark. Mechanical rigidity was greatly improved by the construction of the base and the two end-plates as a single casting. In addition to the carbon-brush contact-type distributor, the gap type has also been developed. Nickel segments with a revolving nickel electrode are the chief features of the latter construction. Ventilation is necessary in order to remove the effects of ionization due to the spark. The rotary safety spark-gap is also used to reduce ionization. The original design of condenser, in which the mica and foil laminæ were assembled by punching or drilling holes and riveting into a block, has been superseded by designs in which the laminæ are securely clamped mechanically without any form of riveting. Several successful designs, with an increased factor of safety and reduced risk of cracking starting at the rivet holes, have been developed. Paper condensers have replaced mica condensers in certain magnetos with stationary windings and those used for motor cycles.

Moulded insulation materials for ignition appliances show remarkable progress. A moulded material was needed which would withstand the action of oxides of nitrogen produced by brush discharge and ionization. Many of the earlier hard-rubber compounds produced deliquescent nitrates and gave rise to surface leakage, especially in damp weather. The mouldings now employed can be divided into rubber-base and synthetic-resin-base materials. The former are composed of rubber and sulphur with a filling material to give body and rigidity to the vulcanized rubber, while the latter belong to the synthetic-resin class which is now finding so many uses in electrical and other work. Each class has its own sphere of application; for example, the brush track in the distributor requires a rubber-base material, and with the elimination of unsuitable ingredients the earlier troubles have been overcome. Synthetic-resin products have revolutionized the cheap and accurate manufacture of moulded materials for ignition apparatus.

The material employed for the contact points until recent years was an alloy consisting of 25 per cent iridium and 75 per cent platinum. The successful development of tungsten contacts has enabled the costly precious metals to be dispensed with for this purpose. With tungsten contact points the current must not exceed about 4 amps. nor the primary voltage at break about 280 volts, which limits the number of primary turns.

The insulating materials employed in ignition devices and their mode of application have been greatly improved. The load on an ignition device consists of a series of high-frequency surges with each spark, necessitating reinforcement of the end layers and careful insulation throughout the windings to prevent progressive breakdown. The satisfactory enamelling of very thin copper wire—about 0·004 in. in diameter with an enamel coating of 0·0005 in.—and the use of special varnished silk have enabled makers to produce satisfactory high-voltage windings occupying such small space and frequently subjected to centrifugal force.

TABLE 11.

Properties of Permanent-Magnet Steels.

Steel	Coercive force	Remanent flux-density	$(BH)_{max.}$
35 % cobalt ..	238	8 900	910 000
15 % cobalt ..	186	8 500	615 000
9 % cobalt ..	148	8 200	455 000
6 % tungsten .	62	10 000	287 000
2 % chromium	59	9 700	245 000

Permanent-magnet steel has shown remarkable development. Previously a 6 per cent tungsten steel was used for magnetos in this country, and a 2 per cent chromium steel in America, but the introduction in 1920 of cobalt steel, with its high coercive force, permitted a correspondingly small volume of steel to be used for a given output or energy storage. Representing the volume of steel in a magnet by AL (area × length) we have:—

$$AL = \frac{B}{B}A \times \frac{H}{H}L = \frac{(\text{flux} \times \text{magnetomotive force})}{BH}$$

The volume will thus be a minimum when BH is a maximum. This condition holds for maximum energy storage as well as for maximum output. Table 11 shows the improvement obtained in the value of $(BH)_{max.}$ by the introduction of cobalt alloys.

It is thus seen that with 35 per cent cobalt steel only one-third of the weight of material required with 6 per cent tungsten steel is needed. The cost of cobalt is its chief drawback. By its use, not only can the horseshoe shape be replaced by much shorter magnets, but such types of construction as the revolving-magnet magneto, otherwise impossible in the restricted space, become feasible. While cobalt steel was originally produced in rolled sections only, and earlier magnets were straight, or slightly bent, short lengths of steel, it is now possible to obtain 35 per cent cobalt-steel castings with coercive forces as high as 280 and $(BH)_{max.} = 1\,000\,000$. Experience shows that the ageing qualities of cobalt steel are at least as good as those of the earlier steels.

Later Types of Magneto.—Following the earlier type of magneto with revolving armature and stationary magnet, makers have developed types with windings and contact-breaker stationary. The polar-inductor magneto belongs to this class, the revolving part consisting of soft-iron inductors, while the magnets are also stationary. The revolving-magnet type, on the other hand, has a 2- or 4-pole cobalt-steel magnet. In both these types it is possible to obtain 4 sparks per revolution, compared with 2 sparks per revolution with the revolving-armature type. These newer magnetos, therefore, not only have the virtue of stationary windings and contact-breaker, but the speed of the 4-spark magneto is half that of the 2-spark magneto. This reduction in speed has enabled the magneto to keep pace with developments in the petrol engine, the 4-spark machines being widely used on engines with 6 or more cylinders. Cobalt steel is used on most of the later designs and also by some makers on the older type. (For references to standard parts of magnetos, see Table 1.)

Impulse Startors.—Where starting conditions are severe, as on large engines, trouble may arise with magneto ignition owing to the difficulty of rotating the engine at a speed sufficient to produce a spark with the lever fully retarded. Some improvement in low-speed performance is obtained by using a larger magneto, but auxiliary devices, such as the impulse startor, are now available. The impulse startor consists of two members linked together by a strong spring; one member is fixed to the driving shaft and the other to the magneto shaft, which is prevented from turning until the wound-up spring is released and gives a sudden forward impulse to the magneto, thereby producing the requisite spark. As the engine speed is increased, the impulse startor automatically falls out of action. I.A.E. Data Sheet No. 124 refers to impulse startor couplings.

Coil Development.—Many of the above progress details apply equally to the coil and the magneto. The cheapness of its construction, the simplicity of its drive and the ease of starting have enabled the coil to oust the magneto in many cases, and there are now probably as many makes of automobiles in Great Britain with coil as with magneto ignition. Most coils are provided with a straight core of iron laminations or wire, which leads to a very simple construction. The coil is usually mounted apart from the distributor and contact-breaker. The primary current is kept within the limit imposed by the contact points by the resistance of the primary circuit, and, in order to reduce heating in the coil itself, a large part of this resistance takes the form of a resistor external to the coil. By making this resistance of wire with a high temperature coefficient, an automatic means is provided of reducing the current from the battery when the switch happens to be left " on " and the contacts are closed with the engine at rest. In this way the safety of the coil is ensured and the rate of battery discharge diminished; also the fall in current at high speeds is reduced. Unlike the magneto, the coil functions best at low speeds, but difficulties may occur at high speeds with a large number of cylinders, for the contact period may then be too small to allow the current to attain a sufficient value to produce a spark. With 8 or more cylinders this difficulty may become pronounced, and some makers overcome it by using two distributors or by some equivalent device.

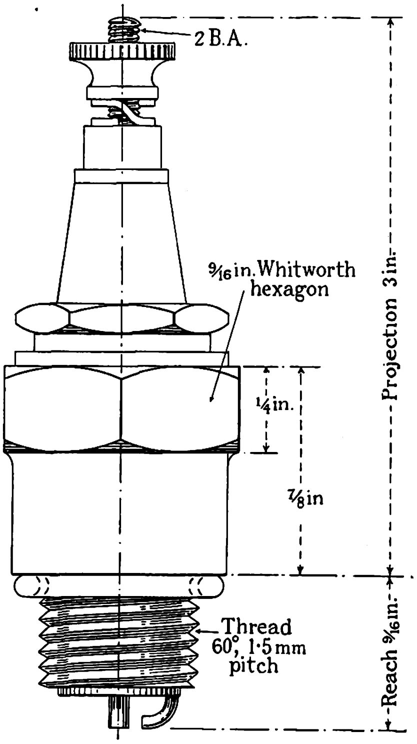

FIG. 5.—Standard dimensions of sparking plug.

Although there appears to be a tendency for both magneto and coil ignition to find their most suitable spheres of application, the outlook is not clear. It is possible that the revolving magnet will replace the revolving armature: this may influence future development. The coil as we now know it is largely an American development, but the problems peculiar to European practice, notably due to higher engine speeds, may also affect its future.

Dual Ignition Systems.—Only in a limited number of high-class vehicles are the two types of ignition combined, mainly with the object of securing greater reliability and easy starting. Various systems are in use, ranging from completely independent equipment with two sets of plugs to devices where a change-over switch controls a common distributor and contact-breaker, or the magneto winding is simply made to act as a transformer fed from the battery to facilitate starting. The fact that dual ignition is usually regarded as unnecessary may be taken as an indication of the high factor of safety attained by both the modern magneto and coil.

Automatic Ignition Timing Devices.—From time to time attempts have been made to simplify the driving of auto-vehicles by eliminating the need for manual control of ignition. The idea of fixed ignition was found to be unsatisfactory. The problem is to compensate both for throttle opening and for speed. Devices have been developed for dealing with both these variables, but they are usually too complicated for general application. It is possible, however, to design very simple devices based on centrifugal action to compensate for speed changes. With these devices fitted external to the ignition device proper, the ignition lever can be left in the fully advanced position, so that the optimum spark position of the magneto is not upset at starting or at low speeds. The hand lever can then be used for altering the timing as required by throttle opening. Ignition timing devices to compensate for speed changes are now a standard part of many equipments. Apart from convenience, their use leads to appreciable economy in heavy commercial vehicles.

Sparking Plugs.—The main dimensions of sparking plugs have been standardized for some years and the revised specification has been issued as B.S.S. No. 45—1928. The leading standard dimensions are reproduced in Fig. 5.

There is now a great variety of sparking plugs on the market, both of the porcelain and the mica type. The chief differences in detail have been made to keep pace with the increasing requirements of the engine. On the one hand the electrodes must be hot in order to burn off any oil or carbon deposit and to keep the plug voltage low; and on the other hand they must not be hot enough to cause pre-ignition. These requirements largely account for the difference in the design between a plug, say, for a racing engine and a plug for a touring engine. While, therefore, with the improved materials now used, the several types of mica and porcelain plugs have been made thoroughly reliable, their satisfactory use depends on correct application and gap adjustment. Owing to the wide range of service for which engines are designed, and to the diversity of cooling conditions to which a plug is exposed, a universal sparking plug seems at present to be an unattainable ideal.

CONCLUSION.

So many firms have generously supplied information for this review that it would be invidious to mention any by name; it must suffice to say that their aid was not only invaluable, but indispensable. To Mr. E. A. Watson and Mr. W. H. Glaser the author wishes to express his gratitude for the pains they have taken in criticizing the manuscript.

ELECTRIC TRACTION.*

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In the review published in the *Journal* in January 1927 (vol. 65, p. 143), Mr. F. Lydall gave a comprehensive account of the technical and statistical developments that had taken place up to that time. Consequently the present review will be confined principally to the events of the last three years.

Although there has been an awakened interest in railway electrification at home, attention must, nevertheless, be directed in addition to countries outside Britain, where many important suburban and main-line railways are electrically operated. Progress has been made in the engineering science of electric traction, brief details of which are given below.

(1) TECHNICAL.

The three years under review have been remarkable in the more highly developed countries for the intensification of road competition with tramways and railways by vehicles propelled by internal-combustion engines. In some cases, particularly with tramway systems having extensive interurban routes, the rail system has succumbed to the petrol omnibus; elsewhere, competition has resulted in a general speeding-up of traffic, with modernization of vehicles and increase of motive-power ratings. Certain railway systems have augmented their traffic by electrification, and on branch lines some success has been realized with petrol or oil electric rail-cars, incorporating a form of transmission that has been applied also to locomotives, especially in North America.

(*a*) INTERNAL-COMBUSTION ELECTRIC VEHICLES.

The internal-combustion electric vehicle comprises a prime mover, using either petrol or oil as fuel, driving a d.c. generator connected with normal series traction motors carried on the bogies in a manner similar to that employed in ordinary electric locomotives or motor-coaches. The high cost of petrol has been an obstacle in the development of petrol-electric vehicles in large units, and the design of Diesel engines has received corresponding encouragement. The advantages of the internal-combustion electric vehicle include without the necessity for contact-line gear and substations those of the electric drive, the elimination of smoke, noise and terminal delays, and economy of fuel. Although the Diesel engine possesses but small overload capacity, it has the ability, when combined with the electric drive, of supplying its full rating at any desired locomotive speed. Solid-injection engines are preferred, as their use renders air compressors and scavenging equipment unnecessary. A disadvantage of the Diesel-electric locomotive at present is its excessive weight, reaching 400 lb. per horse-power. The tendency of current design is to increase engine speeds. Piston velocities up to 1 250 ft. per min. at 600–1 000 revs. per min. are possible. The cooling difficulties are considerable with large units, since much heat must be conveyed away from the cylinder walls. Additional cooler-tenders have been found necessary in Russia.

The methods of control available include either constant or variable engine speed, combined with series-parallel connection and field weakening of the driving motors, and voltage control of the main generator, the field of which is usually supplied from a separate exciter. By providing the main generator with a differential compound field-winding, the output can be made approximately constant over a wide current-range.

A number of locomotives and rail-cars employing internal-combustion engines with electric drive are in operation in Canada, the United States and Russia. In Britain, the London, Midland and Scottish Railway have experimented with both a petrol-electric and a Diesel-electric motor-car.

(*b*) ELECTRIC LOCOMOTIVES.

The design of electric locomotives is proceeding in the direction of the elimination of side-rod drives. In the early days the application of electricity to train haulage presented problems in locomotive design which were solved by the direct use of the existing steam-locomotive mechanism. Subsequent experience showed that, if a rotating energy source were available, it was disadvantageous to convert it to reciprocation and back to rotation at the driving wheels. The electric side-rod drive was found to differ seriously from its steam prototype in that there was nothing corresponding to the cushioning action of the steam and sliding piston to take up play between the spring-borne motors and the driving axles. The consequent tendency to destructive vibration has resulted in maintenance costs rather higher than those necessary with individual-axle drives, which are therefore coming into still greater favour. It would, in fact, appear that the side-rod drive is obsolescent, at least for normal-gauge express locomotives. Several years of experience have amply demonstrated that individual-axle drives give a utilization of the available adhesive weight at least as good as that of coupled drives, so long as the motors are not connected in series. The side-rod drive persists, however, on the 3-phase zone in Italy. In the older locomotives, the transmission between the motor crank-shafts and the driving wheels comprised flat triangulated coupling frames, in the guide-bars of which the crank-pin of the central driving axle moved in a die block. The upkeep of this form of mechanism was found to be expensive, on account of the copious supply of oil demanded to keep the moving parts adequately lubricated. The more recent locomotives have therefore been provided with a 3-rod drive having a straight-line motion, eliminating the die block and guide-bars.

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* A review of progress. Reprints in pamphlet form, price 1s. each, can be obtained from the Secretary of the Institution.

The Buchli drive is used extensively in Switzerland and Central Europe, and the Westinghouse geared quill mechanism has been supplemented by the Oerlikon link-work drive; all these are for express service. A more recent design introduced in Europe utilizes motors with vertical shafts, arranged in pairs, driving a common axle by means of quill-mounted bevel gears. Advantages claimed include a comparative absence of space restriction, easier maintenance, and a high centre of gravity. The quill gear, with its linkwork connecting with the driving axle, runs in an oil bath, greatly reducing the wear.

Some development has been observable on single-phase railways by the introduction of motor-generator conversion. The single-phase to 3-phase system is well known, having been in successful service on the Norfolk and Western and the Virginian Railways in America, the special advantage being the possibility of automatic regenerative braking. More recently, however, a single-phase synchronous motor driving a d.c. generator has been used, so permitting the employment of standard d.c. series railway motors, economical control and fairly simple regeneration. Locomotives embodying this system are in use on the new Cascade Tunnel electrification of the Great Northern Railway (U.S.A.). The synchronous motor is started as an induction machine with the assistance of the main d.c. generator running as a motor from a secondary battery. By over-exciting the synchronous machine a high or leading power factor is obtainable, compensating to some extent for line drop.

The use of regenerative braking continues to be confined principally to those lines on which there is a definite operating need for it, and in these cases there may be some sacrifice of speed control in order to obtain a convenient and safe method of recuperation. Thus the use of motor-generator or split-phase locomotives, mentioned above, enables regeneration to be obtained in a simpler manner than is at present possible when no such auxiliary equipment is provided.

Single-phase motors, which are now solely of the series type, are constructed either with or without resistors in the connections between armature coils and commutator. This reflects on the design, since a greater flux per pole can be allowed when resistors are used, but a greater axial length is needed and a certain amount of difficulty is introduced in the armature construction. The tendency is to use as large a number of poles as can be economically accommodated, since this increases the ratio of normal to synchronous speed—a condition favouring good commutation. In a recent design for a large motor it was found possible to dispense even with the neutralizing winding, with consequent gain in the permeance of the magnetic circuit. Any increase in the number of poles, however, necessitates the provision of a like number of commutator brush-spindles.

Nose-suspension-drive motors on d.c. lines do not show marked advances. The single-turn coil and the lap winding are being employed for high-voltage motors, and 6 poles used instead of 4 for the larger outputs. Forced cooling is almost universal, and box frames with roller bearings are in general use. For spring-borne individual-axle drives the twin motor is popular, embodying in one housing a pair of armatures. The advantage of high peripheral speed is obtained, but the number of bearings, commutators and brushes is, of course, doubled.

Three-phase motors are largely confined to the Italian State Railways. The pre-war construction with hollow motor shaft and with slip-rings on the main crank extension is now abandoned. The slip-rings are placed within the rotor core to save space, an arrangement successfully made despite the multiplicity of rings required where pole-changing is used for speed control.

A subject of growing importance in Europe where extensive main-line electric traction is concerned, is that of train-heating, which represents an appreciable proportion of the cost of running. Especially is this true of international trains and of through trains from steam-operated zones. The majority of these are equipped for steam-heating, and in consequence separate coke, coal or electrically heated boilers have been tried when rolling stock so equipped is in the electrified zones. Steam-heating may be disadvantageous, however, and the problem has been attacked by a Committee of the Union Internationale de Chemins de Fer to find a suitable means of electric heating. The standard voltages chosen are 1 500 volts (d.c.) and 1 000 volts (a.c.) for international European rolling-stock, the electric heaters being duplicated by the normal steam-heated radiators. This solution is costly and complicated, and can scarcely be regarded as convenient. The amount of energy for heating—which may exceed 25 per cent of that for haulage—is great, and must be under the control of the train staff and passengers. Further, the inter-coach couplings must be robust so as to carry currents of the order of 400 amperes. In America the most common method is to install a boiler on the locomotive, fired with oil, coal or coke, since there are no through coaches electrically heated.

(*c*) Rapid Transit.

A number of large suburban electrification schemes have been initiated or extended during the last three years. The standards of suburban working are gradually becoming defined. Modern rolling-stock is of steel construction, weighing 70 000–90 000 lb. per vehicle, and is provided with pneumatic doors for city or underground working, although several extensive suburban lines employ converted steam rolling-stock and (in Britain) retain the separate compartments with which the travelling public is familiar. Motors for normal-gauge stock are rated up to about 300 h.p., with a specific weight of 28–30 lb. per h.p. Some progress has been made in lightening motors by the use of steel frames, square field-conductor sections, forced cooling and high speeds. The schedule speeds obtainable average 18–24 miles per hour, including stops, and rates of acceleration of 1·3 to 1·5 m.p.h. per sec. are common, with correspondingly high rates of braking up to 2 m.p.h. per sec. There has been but little headway in regenerative braking, although the Ernesto Breda concern of Milan has equipped a number of tramcars with a system involving a special " dynamotor " voltage-splitting device, allowing of recuperation almost to standstill, and it appears to be operating successfully.

The mild controversy between the open (vestibule) coach and the separate-compartment coach shows no sign of nearing a solution. The open car has the theoretical advantage of reducing the duration of station stops, on account of the alleged fact that, with fewer and wider doors, passengers do not delay traffic by looking for empty compartments. The claim is by no means proved, but the chief objection to the open car is that it reduces the seating capacity. There is, however, greater space for standing passengers, which may be advantageous on lines operating with very short headway, since automatic opening of doors is more easily applied. On underground lines, also, there is rarely room for the swing-door that has been accidentally left open. Nevertheless, in this country the majority of suburban lines converted from steam working retain the compartment stock.

(*d*) Tramways and Trolley Omnibuses.

The advances in street-railway working are again principally concerned with drives. The Cardan shaft mechanism, familiar in the automobile, has been successfully applied in various forms to tramway traction both in America and in Europe. The motors are entirely springborne, and considerable benefit in the reduction of track wear has been observed in consequence. The drive, which may be collective or individual with bevel, differential or worm gears, allows of the use of high-speed motors; this is naturally advantageous in the reduction of weight. There is also a tendency to use low-voltage motors, which have better commutation at high speeds. Roller bearings have been introduced for the main driving-axles, with some gain in energy consumption on account of smaller tractive resistance and improved coasting. Attempts have been made to provide greater comfort and an improved appearance in tramway rolling-stock, with a view to the attraction of passengers in the face of omnibus competition. Operating economies have been realized both in America and on the Continent by the introduction of " one-man " cars, in which the driver operates door mechanisms and takes fares and the " conductor " is superseded. On account of the stage fare-system common in Great Britain, the scheme is here rather more difficult to apply. Regarding systems of braking, the use of pneumatic and electromagnetic brakes appears to be more common for service stops.

Certain tramway systems have been replaced by trolley-omnibus services. The introduction of these vehicles is particularly advantageous when the electrical equipment (contact lines, substations and generating stations) is already available with but slight modification. In those cities where comparative figures are obtainable, the economic advantage of trolley over petrol omnibuses has been fully demonstrated.

(*e*) Substation Equipment.

The last few years have been noteworthy for the increasing use of automatic or semi-automatic substations, and for the development for traction of the mercury-arc rectifier. The new suburban electrification in Berlin, for example, will be supplied exclusively from rectifier substations, while an example of their use in main-line service is provided by the Midi Railway of France. Several tramway systems are employing rectifier substations, among them being the Leningrad Tramways.

(2) STATISTICAL.

It is intended here to give a general outline of the developments in railway electrification which have taken place since the last review was published. It is neither possible nor desirable to give exhaustive data; and the purpose of the notes below is to draw the attention of the general reader to the fact that railway electrification is making considerable headway in certain countries, even if the developments in Great Britain seem tardy by comparison.

Great Britain.

There has been a world-wide tendency within the last decade to grapple with the pressing problem of traffic in large cities by a unification of control of transport facilities under a single authority. In New York, Chicago, Paris and Berlin, for example, a private management is responsible for the co-ordination of transport (usually confined to " rapid transit " services) whether privately or publicly owned. The necessity for similar procedure is being recognized in London, where the proposal to merge the London County Council Tramways with the Underground group (which controls certain of the local passenger railway-lines and most of the omnibuses and tramway systems not owned by local authorities) has roused great interest and some controversy. The existence of all three methods of transport has been proved essential, but the great differences in capital cost act contrary to the best economic principles if resources are not pooled and facilities developed for co-ordination rather than for competition.

The Underground group in London has, within the period of this review, confined much of its important construction work to the architectural. In this connection it is sufficient to mention the new stations at Piccadilly Circus and Charing Cross. The former was completed at the end of 1928, and the latter at the beginning of 1929. These stations are capable of dealing with 25 million and 50 million passengers per annum respectively. Each has a large circulating area with escalators, automatic ticket-issuing and change-giving machines, and coloured route-signs where necessary to guide the interchanging passenger. The new head office of the group in Broadway, Westminster, is remarkable for its modern style, great size and height, and by virtue of its unusual planning.

The power house at Lots Road, Chelsea, one of the nine largest stations in the country, had an output of over 300 million kWh during 1928. The maximum load on the station was 76 000 kW, and the annual hourly load factor 46·5 per cent. The increasing traffic on the railways has necessitated a reduction of the headway of trains, a re-modelling of station platforms, and the use of more powerful rolling-stock. The effect of this on the energy consumption has required the adoption of a scheme of improvements upon which work is now progressing. Much of the original plant which has been in service for 24 years is to be replaced. The number of boilers will be halved, but the new installation will be capable of developing over 1 000 000 lb. of steam per hour at an increased pressure and superheat. When completed, the station will comprise nine 18 750-kW machines generating at 11 000 volts and 50 cycles. The present frequency is 33⅓ cycles.

At the time of the railway grouping in 1922, the South-Western section of the Southern Railway was operating electrically 49 miles of route on the 600-volt third-railway system, while the Brighton section had 24 route-miles operating at 6 600 volts and 25 cycles, with a single-phase overhead contact-line equipment. The conversion of the latter section to direct-current third rail was completed in September 1929, and the new lines on the South-Eastern section bring the total electrified zone up to 256 route-miles or 875 track-miles, the expenditure having been £11 500 000. Eventually a service aggregating 7¾ million train-miles per annum will be provided in the electrified zone. Energy is purchased for the South-Eastern and Central sections, but the company's own station at Wimbledon is used to supply the South-Western lines. At the annual meeting of the company in March 1928, it was stated that in the electrified area the number of passengers had increased by no less than 6 millions above the figure for 1927, and the receipts had increased by £213 000. Outside that area the revenue was less by £200 000.

The directors of the Southern Railway sanctioned an expenditure of about £60 000 on further extensions to their suburban system in June 1929. This will make the Southern electrified zone easily the largest in the world, and it may astonish the British reader that this great scheme has been brought into existence so quietly and unobtrusively, while foreign efforts rarely fail to obtain their measure of publicity and praise. The new electrified zones are those between Hounslow and Windsor, Dartford and Gravesend, and Wimbledon and West Croydon, totalling 50 track-miles. The new lines involve the reconstruction of a number of stations and the provision of three new substations. A 20-minute or 30-minute service will be provided, according to the traffic. In October 1929, the Southern Railway directorate announced the electrification of the main lines to Brighton and Worthing, and the work will be completed in a few years. This will form the first main-line conversion in Great Britain (although the traffic is almost of a suburban character), and the project will be watched with interest.

The greatly improved travelling facilities now afforded to the residents in South London have necessitated new signalling equipment, and to meet this demand an extensive colour-light system has been installed at the terminal stations. The new electrical signal-box at London Bridge has been described at some length in the technical Press. The box displaces 9 manual boxes, saving the services of 35 signalmen, 4 signal-lads and 5 signal-lampmen, and effects a total economy of working expenses of about £9 000 per annum, besides the saving in stores.

Automatic colour-light signalling has also been installed by the London, Midland and Scottish Railway Company between Bow and Barking on the Tilbury section of the Shoeburyness line. At present there are 26 trains per hour in each direction during "rush hours," and the signalling system will permit of this being increased to 40 trains per hour.

An unusual development has been the completion of the London Post Office Tube, which conveys postal material over a distance of 6½ miles east and west, linking up seven important offices. The gauge is 2 ft. and the tunnel diameter 9 ft. There are three substations, each equipped with two 400-kW synchronous convertors and transformers. The conductor rail is fed at 440 volts and 150 volts. The trains, which are composed of units of three cars, each with a pair of 22-h.p. motors, attain a maximum speed of about 38 m.p.h. Their operation is automatic between stations, but ingenious semi-automatic devices are installed at stations to reduce the speed and effect correct routing. A route lever signalling-system in conjunction with track-circuiting is employed.

Some activity is reported from Manchester, where for several years proposals have been made for a system of underground railways designed to facilitate interchange of passengers between important traffic centres and to relieve the roads. Profiting by the experience of London, the Manchester proposals envisage the physical connection of the underground lines with the suburban sections of the existing main-line railways at several points in the suburbs of the city. Such a scheme, which is thoroughly modern in conception, would give unrivalled local passenger transportation, with every prospect of financial success.

Work has begun on the conversion to electric traction of the railway between Manchester (London Road) and its large southern suburb, Altrincham. The railway is 9 miles long (27 miles of single track), is known as the Manchester South Junction and Altrincham Railway, and is worked by a joint committee of the London, Midland and Scottish and the London and North-Eastern Railways. The service is expected to be at intervals of 5 minutes during "rush hours." The installation is to have an overhead contact line at 1 500 volts (d.c.), the type of construction being compound catenary with suspension insulators, and the trains will be of the separate-compartment type, seating 536 passengers when full. The line will be supplied from two substations, one of which will be remote-controlled from the other. Two new stations will be built at the Altrincham end of the line. The early conversion of this line has been hastened by the impending development of the Wythenshawe estate between Northenden and Altrincham, which has been acquired by the Manchester Corporation for housing purposes.

The Ministry of Transport Railway Electrification Committee (1927) issued in 1928 a report in which the provisions made in the 1921 Report were revised. The adoption of the direct-current 1 500-volt overhead and 750-volt third-rail systems was recommended, with the option of the 3 000-volt overhead system subject to the consent of the Ministry. Loading gauges for locomotives intended for inter-running were also prescribed.

At the time of writing, a Government Commission is sitting on the question of the main-line electrification of British Railways.

FRANCE.

The Métropolitain and Nord-Sud subways in Paris, which form a close network covering the area within the old city walls, have for many years been inconvenient for residents living in the suburbs. The *octroi* system by which much of the income of townships in France is derived, requires the inspection of all public vehicles entering the city of Paris, and has hitherto proved an obstacle in the way of extensions outward on the part of the underground lines. Authority has now been given, however, for extensions to be carried out, and it is likely that connection will eventually be made with the main surface lines. This should prove of great benefit, for at present severe congestion takes place during rush hours at the main-line terminals, at which streams of suburban passengers congregate. The Chemin de Fer de l'Etat is particularly notorious in this respect, the congestion at its St. Lazare terminus being severe. The subway extensions will enable a general efflux of passengers to take place from many points, relieving the terminal stations to a marked extent.

The State Railway already operates an extensive network of electrified lines from its St. Lazare, Montparnasse and Invalides termini. The Ministry of Public Works announced, early in 1928, that the railway from St. Lazare to Versailles via St. Cloud was to be converted to electric traction, together with the Puteaux–Les Moulineaux line.

Electric street transport in Paris is being influenced by modern conditions in the same way as elsewhere. One by one the tramways are disappearing from the centre of Paris, and are being replaced by motor omnibus services. Several tramway routes were suspended in 1928, including two which came from beyond the Place de l'Etoile to the Madeleine and the Gare St. Lazare. In the Etoile a gyratory traffic system has been introduced on account of the great increase in numbers of vehicles. Unfortunately, the tramway route runs in a direction opposite to the rotation of other traffic, causing considerable confusion at rush hours.

The main-line electrification in France is directed towards the reduction of coal imports from foreign countries and the economy realized by the use of hydro-electric power. The schemes, confined principally to the Paris–Orleans (127 miles of route) and Midi Railways (980 miles), are being slowly proceeded with. Following the principle authorized in France, the railways are being electrified at 1 500 volts (d.c.) simultaneously with the development of a great industrial 3-phase network or "grid." The hydro-electric stations of the Massif Central and at Eguzon are already linked with the great coal-fired power stations in the neighbourhood of Paris, by lines along the Paris–Orleans Railway. Financial difficulties, from which all Europe is now suffering, have retarded the progress of conversion. A recent announcement, however, provides for the electrification of the Béziers–Neussargues line, 172 miles in length, which will connect with the Neussargues–Vierzon line of the Paris–Orleans Railway, all of which is to be electrified.

Three mountain lines are projected in the Pyrenees district, and it is reported that at least two of these will be equipped for electric traction.

GERMANY.

With characteristic thoroughness the German State Railway authorities are proceeding with a programme of electrification despite financial stringency. In 1918 the lines worked electrically totalled about 190 miles of route, with an energy requirement of 23 million kWh per annum. At present there is a length of nearly 1 000 route-miles electrified, with a consumption of 325 million kWh, including all main and suburban lines. The Bavarian group of lines (Munich to Regensburg, Salzburg, Kufstein and Reutte, with branches) accounts for 430 miles, the Silesian Mountain Railways (Görlitz–Breslau) for about 220 miles, and the Central German brown-coal district (Leipzig–Magdeburg) for 125 miles of route. The choice of lines for electrification was made with reference to the traffic density, line profile, the cost of energy and the importance of the route for main-line communication or suburban traffic. Energy is obtained from power stations owned by and operated for the railway, or from mixed stations in which the railway administration has part control. Although in the interests of the continuity of supply and of the load factor the mixed station (the basis on which the French railways are being converted) is preferable, yet it has hitherto been found that the railway power stations can operate more cheaply. An attempt to apply this principle to the Berlin suburban lines, however, met with such strenuous opposition that the decision to take a supply from the existing stations at Charlottenburg, Moabit and Rummelsburg followed inevitably.

The Berlin City, Ring and Suburban Railways are being electrified at 800 volts (d.c.) with despatch. The entire zone is being fed from 115 mercury-arc rectifier installations, forming the largest scheme in the world thus equipped. The route length electrified or under conversion is about 150 miles. Steel motor-coach trains are in use, to the number of nearly 600, equipped with completely automatic camshaft control-gear.

For main-line operation the single-phase system at 15 kV and $16\frac{2}{3}$ cycles has been standardized, and after many years of experimenting a short series of suitable locomotives, the majority of which embody some form of individual-axle drive, has been evolved. Control, however, has not yet arrived at a state suitable for standardization. While a considerable extension of the electrified system is as yet scarcely possible with the present financial position, it is kept in mind that the linking-up of the isolated zones is of prime importance. Probably the first important step would be the connection of the Bavarian network at Regensburg with Berlin, via the Leipzig–Magdeburg line, and the connection of the Silesian zone to this through route, via Saxony.

SWITZERLAND.

As regards world main-line railway electrification, first place is taken by Switzerland with 60 per cent of its Federal lines electrified. The opening of the Zurich–Oerlikon–Schaffhausen line (29 miles) in December 1928 completed the first stage in the Federal programme of 1 040 miles of route, including the entire main-line mileage. The electrified sections of the Swiss Federal Railways account for 77 per cent of the total traffic of the whole Swiss railways. The other important normal-gauge line is the Berne–Lötschberg–Simplon Railway from Berne to Brigue, at the northern portal of the Simplon Tunnel. In the west of Switzerland the Rhätian Railway operates an extensive network of narrow-gauge electrified lines. Practically the whole of the Swiss electrification is on the single-phase system at 15 kV and 16⅔ cycles. The completion of the first stage of the conversion was estimated to cost at least £30 400 000, but actually cost less by nearly £5 000 000, the necessary capital having been largely raised in Switzerland by means of loans on which the railways must pay £850 000 per annum. The saving effected by electrification has more than met the charges for interest and repayment of capital.

The analysis of the capital outlay is of interest. The power stations, of 195 000 kW installed capacity, accounted for 21·4 per cent; the 1 100 km of transmission lines, 7·9 per cent; 27 substations and locomotive repair-shops, 8·6 per cent; overhead contact lines, 17·8 per cent; non-recurring expenditure, 14·3 per cent; and locomotives and rolling-stock, 30 per cent. The energy is obtained from pairs of hydro-electric stations, a river and a storage station being worked together to ensure continuity of supply. The civil engineering and installation costs amount to 87 per cent of the cost per unit, which is progressively decreasing as the capital invested becomes more usefully employed. The mean cost in 1926 was 0·57d. per kWh for 213 million units. Ultimately a figure approaching 0·3d. is anticipated. It is noteworthy that advantages have resulted from electrification quite apart from fuel saving, for, at the present price of imported coal, the cost of motive power per locomotive-mile shows little difference.

The programme for the second stage of electrification is ready. It provides for the conversion of 260 miles of branch line on the Federal Railways. It is also reported that the line through the Simplon Tunnel from Brigue to Domodossola in Italy will be converted from 3-phase to single-phase working at 15 000 volts and 16⅔ cycles, by the Swiss authorities. At Brigue two systems—the single-phase and the 3-phase—meet, and international trains require the services of a steam locomotive for the change-over. Further, from the point of view of power-station economy, the railway administration desire to dispense with 3-phase equipment. The Domodossola–Milan route will remain steam-operated at present.

AUSTRIA.

The Austrian State Railways Administration announced in November 1927 the decision to proceed no further with their electrification programme, and to utilize in other directions the funds set aside for this purpose out of the international loan. Much criticism was levelled at the Government on the grounds that the development of water-power resources was to be suspended. It was also felt disadvantageous that the Vienna–Salzburg line, not being yet electrified, prevented a through run under electric traction of 480 miles across Austria from the Swiss frontier. The Chambers of Commerce accordingly asked the Government to permit their estimates to be examined by unbiased experts, to which the Chancellor, Dr. Seipel, agreed. An examining commission sat on the problem and a majority and minority vote resulted, the majority favouring a continuance of the electrification projects. No decision as regards extensions has yet been taken, and further information is awaited with interest. Meanwhile, some experience has been acquired with the use of Diesel-electric locomotives on branch lines with light traffic.

At present, a total of 390 miles of route, including privately-owned lines, has been electrified, this total including the Salzkammergut line (66 miles), the Arlberg, the Innsbruck–Salzburg and Innsbruck–Brenner Railways.

In Vienna, the city railway has been converted to electric haulage from steam working. The installation costs for a normal rapid-transit system were too high for such a conversion, and the problem has been solved by the adoption of a tramway service, interchangeable with and connected to the street tramways. The city lines extend from Hutteldorf-Hacking to Heiligenstadt, via either West Bahnhof or Haupt Zollamt. The contact-line equipment is of the simple catenary type at 750 volts (d.c.). The street-tramway voltage is 550 volts, so that higher speeds are obtainable on the railway routes. Trains of five to nine cars of the 2-axle tramway type are run, each train comprising two or three driving-cars, the rest being trailers.

SCANDINAVIA.

Developments in Norway and Sweden have been confined principally to a number of suburban lines round Oslo, such as the Hoved Railway to Lillestrom. The main lines comprise the Lulea–Narvik or Riksgränsen mineral route (which crosses the country from the North Sea to the Gulf of Bothnia), and the important Stockholm–Gothenburg Railway. Both of these are worked on the single-phase system at 15 kV. A total of some 800 miles of route has been electrified in the two countries.

ITALY.

Further electrification of the Italian Railways has been carried out during the past two years, and the total now amounts to rather more than 1 000 miles. During the last financial year, nearly 100 million lire were spent on electrification.

The electrified lines in Italy can be roughly divided into three zones. In the north there is an extensive network of 3-phase lines at 3 700 volts and 15 cycles. The main routes are from Modane (Mt. Cenis) to Pisa and Leghorn (340 miles), and from Bolzano to the Austrian frontier at Brenner, a heavily-graded line about 56 miles in length. In the central zone the Rome–Tivoli–Sulmona Railway has been electrified at 10 000 volts, 3-phase, 45 cycles, this being the mean industrial frequency in the neighbourhood. In the south a trial has been made on the 62-mile Benevento–Foggia route with direct current at 3 000 volts, and there is a short suburban line out of Naples using the third rail. The Bologna–Florence line operates at 650 volts (d.c.). In addition there are a number of privately owned electric railways, a noteworthy example being the Turin–Ceres Railway which is operated at 4 000 volts (d.c.). The State Railway has nearly 700 electric locomotives, the majority being 2-speed or 3-speed 3-phase machines with induction motors. These have remarkably good maintenance records, in spite of the preponderance of side-rod drives. The 3-phase traction system demands the use of two overhead contact lines per track; no difficulty has, however, been experienced, although the arrangement at crossings and junctions is particularly complex.

SPAIN.

The Spanish Northern Railway has in operation, or nearly completed, the sections Barcelona–Manresa (40 miles), Moncada–San Juan de la Abadesas (67 miles), and Irun–Alasasua (64 miles), all double track at 1 500 volts (d.c.).

The Diesel-electric rail-car has made its appearance in Spain on the Pamplona–San Sebastian Railway where a number of such vehicles have been installed. The line is 57 miles in length, and runs tortuously through a part of the Pyrenees. It has a 1-metre gauge with sharp curves.

As in many other European capitals, the suburban passenger traffic in Madrid has increased greatly since 1918. The population is about 800 000. Of the projected underground railway, a number of routes are now operating. The lines are of the sub-surface cut-and-cover type, the deepest parts being 20 yards below ground-level. Some of the grades are extremely steep. Overhead contact-wires are used to supply the trains at 600 volts (d.c.), a simple wire suspension like that used on tramways being employed.

The Government, after two years of deliberation, announced a new programme of railway electrification early in 1928. All the main lines out of Madrid encounter mountainous country, making electrical operation particularly favourable, especially as much available water-power can be developed. The lines intended for electrification comprise a route length of 500 miles on the Northern Railway, centring on Barcelona, Bilbao and Madrid, 380 miles on the Southern Railway, between Barcelona, Tarragona, etc., and 385 miles on the Andalusian Railway Co.'s lines, embracing Bobadilla and Granada. This great scheme will require the strengthening of tracks and bridges for heavier and faster trains. The estimated cost of the conversion, which is to be carried out at 1 500 volts (d.c.), is 300 million pesetas.

OTHER EUROPEAN COUNTRIES.

No reports from Russia are yet thoroughly reliable, but the Union of Socialist Soviet Republics is said to be seriously contemplating railway electrification. Diesel-electric locomotives have been purchased from Germany, with a view to trials on the long Asiatic lines where water may be very scarce.

The only electric railway of importance in Holland is that between Rotterdam and Amsterdam, which is operated at 1 500 volts (d.c.).

The railways administration of Czecho-Slovakia in 1924 legalized the use of the 50-cycle industrial network for main-line railway electrification; direct current at 1 500/3 000 volts was therefore chosen as a standard system and a start made with the suburban lines round Prague. Some of these were inaugurated in February 1928. The lines centre on the Wilson terminal station. Locomotives for both passenger- and goods-train haulage are employed. Further developments will, as usual in Central Europe, depend on the economic situation, but probably the route Prague–Ceska Trebova (102 miles) will be undertaken next, since this line carries heavy traffic aggregating 95 million gross ton-miles per annum.

Hungary has little water power, and energy production rests almost exclusively on the limited fuel deposits, which, at the present rate of consumption, can scarcely last more than 50 years. While railway electrification is expected to help this situation, it is felt that a system applicable most directly to the industrial network is essential in order to obtain the highest load factor and economy. Consequently the high-voltage, normal-frequency, single-phase system devised by K. von Kandó, of the Ganz Co., Budapest, has received attention. This involves distributing the phases of the industrial 3-phase supply along the route in order to obtain balance of the traction load as far as possible, and using synchronous phase-convertors on the locomotives with 3-phase traction motors of the induction type. A locomotive of this type was built in 1924 and underwent trials near Budapest. The economic situation in Hungary, however, is so bad that the expenditure necessary for electrification cannot yet be contemplated.

UNITED STATES OF AMERICA.

After a short period of comparative quiescence, railway electrification in the United States has recently shown a revival. Road competition is probably more severe in America than elsewhere, even the trans-continental trunk routes having been duplicated by luxuriously-appointed fast motor-coach services.

Several suburban rapid-transit schemes have recently been put into operation or their future electrification announced. The Illinois Central terminal electrification was inaugurated in 1926 in connection with the Lake Front Improvement plans, and is in successful operation. The Baltimore and Ohio Railway electrified its Staten Island (New York) suburban lines in 1924–1926 under legislation providing for smoke abatement, and to conform to possible future operation as a part of the New York City Rapid Transit system. It is noteworthy that the co-ordination of all forms of public transport in large cities is receiving great attention in America. The Long Island Railway, a subsidiary of the Pennsylvania Railway, is the largest suburban electrified system in America, and transports over 100 million passengers per annum. In New York City proper, several extensions have been made to the subway and elevated railways. There are about 210 track-miles traversing the city. Some criticism has been levelled at the distribution of these lines; it is pointed out that 86 per cent of the city's population is concentrated in 97 square miles of area in which a good rapid-transit service is available, the remaining 14 per cent being spread over 202 square miles where the facilities are poor. This, it is alleged, indicates the manner in which a population will follow rapid-transit facilities.

Transit Companies into a homogeneous system, and power will be purchased from the Edison Co. The plans show a scheme of co-ordination on a scale hitherto unequalled.

A route length of 9 miles of subway now accommodates

SUMMARY OF ELECTRIFIED LINES, 1929.

Country	Voltage	System*	Conductor	Miles		Date
				Route	Track	
Argentine	800	D.C.	Overhead and third rail	60·5	132	1916/23
Australia..	1 500	D.C.	Overhead	227·5	603·5	1919/28
Austria	800	D.C.	Overhead	17	—	1925
	5 000	3-ph. (25)	Overhead	57	—	1907
	15 000	1-ph. (16⅔)	Overhead	370	—	1912/28
Bolivia	575	D.C.	Overhead	6·5	8·7	1905
Brazil	1 500	D.C.	Overhead	45	—	1927
	3 000	D.C.	Overhead	179	—	1921/28
Canada	2 400	D.C.	Overhead	36	95	1915/27
	3 300	1-ph. (25)	Overhead	3·5	12	1908
Chile	660	D.C.	Third rail and overhead	16	22	1926
	1 500	D.C.	Overhead	25	31·5	1927
	2 400	D.C.	Overhead	15	24	1916
	3 000	D.C.	Overhead	166	—	1927
China	1 200	D.C.	Overhead	25	43	1914
Cuba	650	D.C.	Overhead	101	168	—
	1 200	D.C.	Overhead	54·5	111	1920
Czecho-Slovakia ..	700	D.C.	Overhead	14·5	—	1903
	1 500	D.C.	Overhead	16	40	1928
Dutch East Indies ..	1 500	D.C.	Overhead	31	75	1925/26
France	650	D.C.	Third rail	39	—	1900
	1 500	D.C.	Overhead	704·5	—	1900/28
Germany..	600	D.C.	Overhead and third rail	9	—	1903/16
	800	D.C.	Third rail	140	—	1924/28
	1 000.	D.C.	Overhead	11	—	1909
	3 000	1-ph. (25)	Overhead	1·5	—	1911
	6 000	1-ph. (25)	Overhead	20·5	—	1908/24
	15 000	1-ph. (15)	Overhead	30	—	1913
	15 000	1-ph. (16⅔)	Overhead	752	—	1912/28
Great Britain	600	D.C.	Third rail	337	852	1910/29
	600	D.C.	Third and fourth rail	214	479	1890/1929
	1 200	D.C.	Third rail	13·9	29	1913/16
	1 500	D.C.	Overhead	18·5	48·5	1915
	6 600	1-ph. (25)	Overhead	9·5	19·5	1908/11
Holland	1 500	D.C.	Overhead	84·5	217	1908/27
India	1 500	D.C.	Overhead	68	164·5	1925/28
Italy	650	D.C.	Third rail	67	—	1902
	800	D.C.	Overhead	46·5	—	—
	3 000	D.C.	Overhead	94	—	1928/29
	3 700	3-ph. (16⅔)	Overhead	696	—	1911/29

* The figures in brackets indicate the frequency.

A recently announced scheme, involving the ultimate expenditure of 1 000 million dollars, provides for the construction of new and interconnecting subway lines in New York City. Eventually all the city-owned subways will be consolidated with the lines of the Interborough Rapid Transit and Brooklyn Municipal

a rapid-transit system at Rochester, the lines having been laid in what was formerly the Erie Canal.

A new subway/elevated system has been built at Philadelphia. The line runs out from Broad Street, and embodies all modern features of this type of service, including automatic couplers and doors, colour-light signalling, track-circuit control, train-stops, etc. Six-car trains, accommodating a maximum of about 1 200 passengers, are run during busy periods with a 2-minute headway.

Announcements are made of the electrification in the immediate future of the New York City suburban lines of the Delaware, Lackawanna and Western Railway to the extent of about 65 miles of route. The system chosen is 3 000 volts (d.c.), with multiple-unit rolling-stock. The cost of conversion is estimated at 14 to 18 million dollars. The Cleveland Union terminal and its approach lines, totalling 16 miles of track, is also to be electrified. Trains will be handled by 204-ton passenger locomotives, each rated at 3 000 h.p.

Philadelphia has already a suburban electrification in the local lines of the Pennsylvania Railway which have recently been extended. The Reading Railway Co. has announced the conversion of 50 miles of route in this neighbourhood at a cost of 20 million dollars. The same system will be used, viz. single-phase at 11 000 volts and 25 cycles. It is expected that the Bethlehem–Pottsville line will next be converted, and there is a possibility that the Philadelphia–New York main route will eventually be electrified.

As regards street transport, much activity is manifested in speeding up services and modernizing rolling-stock. Mention may be made of the street-car subway under construction at Los Angeles between Hill Street and

SUMMARY OF ELECTRIFIED LINES, 1929—*continued.*

Country	Voltage	System*	Conductor	Miles		Date
				Route	Track	
Italy	4 000	D.C.	Overhead	26	—	1921
	10 000	3-ph. (45)	Overhead	67	—	1927
	3 000	3-ph. (15)	Overhead	65	—	1902/13
Japan	650	D.C.	Overhead and third rail	7	13	1910
	1 200–1 500	D.C.	Overhead	208·5	—	1904/29
Mexico	600	D.C.	Overhead	15	18·5	1924
	3 000	D.C.	Overhead	64	70	1924/27
Morocco	3 000	D.C.	Overhead	158	—	1924
New Zealand	1 500	D.C.	Overhead	15	—	1924/28
Norway	6 000	1-ph. (25)	Overhead	15	—	1908
	10 000	1-ph. (16⅔)	Overhead	28·5	—	1912
	15 000	1-ph. (15)	Overhead	71	—	1922/25
Spain	1 500	D.C.	Overhead	113	—	1926/29
	3 000	D.C.	Overhead	38·5	50	1924
	5 500	3-ph.	Overhead	18·5	—	—
Sweden	10 000	1-ph. (25)	Overhead	44·5	—	1908/15
	16 000	1-ph. (15)	Overhead	287	—	1915/23
	16 000	1-ph. (16⅔)	Overhead	286	—	1925/26
	16 000	1-ph. (25)	Overhead	101·5	—	1921
Switzerland	750	3-ph. (40)	Overhead	39	—	1899/1919
	840	D.C.	—	20·5	—	1903
	1 000	D.C.	Overhead	53·5	60	1901
	3 300†	3-ph. (16⅔)	Overhead	12·5	—	1906
	5 500	1-ph. (25)	Overhead	34	—	1910
	8 000	1-ph. (15)	Overhead	12·5	—	1910
	11 000	1-ph. (16⅔)	Overhead	172	198·5	1913/22
	15 000	1-ph. (16⅔)	Overhead	1148·5	—	1910/27
Union of South Africa ..	1 500	D.C.	Overhead	26·5	67	1927/28
	3 000	D.C.	Overhead	171	287	1926
United States of America	650	D.C.	Overhead and third rail	367	1187	1895/1926
	1 200	D.C.	Overhead	196	313	1911
	1 500	D.C.	Overhead	38	133·5	1915/26
	2 400	D.C.	Overhead	37·5	123	1913
	3 000	D.C.	Overhead	659	883	1915/27
	11 000	1-ph. (25)	Overhead	540	1504	1909/29
	22 000	1-ph. (25)	Overhead	16·5	50	1926
Venezuela	1 500	D.C.	Overhead	22·7	25	1928

* The figures in brackets indicate the frequency.
† Being converted to 15 000 volts, single phase, 16⅔ cycles.

Glendale on the Hollywood and San Fernando Valley route. The territory served by this route has had a remarkable growth during the past three years, and at the same time traffic congestion in Los Angeles has become acute. The new line will serve the former and relieve the latter.

Articulated trams, resulting in a flexible but compact train, have made their appearance in several American cities, and in a few instances trolley omnibuses have successfully replaced street tramways.

The conditions of main-line railway electrification in America differ from those in Europe, and the reasons for electrification are correspondingly different. The motive of coal conservation is unimportant, and the use of water-power is scarcely more than incidental. More usually the difficulties of tunnel operation, mountain grades, the smoke nuisance, or increase of terminal capacity, are responsible for electrification. The Chicago, Milwaukee and St. Paul Railway, for example, has a main route over which the traffic is scanty. Electrification was undertaken to overcome the difficulties of steam traction on heavy gradients and in severe weather.

The largest main-line railway electrification, as regards traffic hauled, is the New York, New Haven and Hartford Railway, which operates its main line from New York City into New England at 11 000 volts and 25 cycles, single-phase. The details of this line are probably familiar to engineers in Britain, especially as much experimental work in locomotive design and the elimination of telegraph and telephone interference has been carried out. The Norfolk and Western and the Virginian Railway electrifications—both for heavy coal traffic in hilly districts—are also familiar, although of more recent origin.

An announcement of great importance was made in 1928 by the authorities of the Pennsylvania Railway when the decision to convert the main line from New York City to Wilmington, Delaware, and eventually to Washington, was announced. This great scheme involves 330 miles of route electrified on the single-phase system at 11 000 volts and 25 cycles, and the provision of 365 electric locomotives. The total cost is estimated at 100 million dollars, of which 40 million are for rolling-stock. The first section, from Philadelphia to Wilmington, is now complete, and the next, from Philadelphia to Trenton, N.J., is under construction. This scheme is the most extensive and costly yet undertaken in route length, traffic volume and density, and equipment. In connection with the project a new passenger station is being built in West Philadelphia, and the existing suburban services will be diverted into a new underground terminal station adjoining the present Broad Street Station. The reasons for electrification are, briefly, for economy and the relief of congestion, for increasing revenue, and for handling through-passenger service into the underground terminal stations at New York and Philadelphia. Connection will be made with the New York, New Haven and Hartford Railway at Hell Gate Bridge, so that through electric trains will be made possible from New England via New York into the Southern Atlantic Coast States. This will be especially advantageous for freight traffic.

The developments on the Cascade Tunnel division of the Great Northern Railway were mentioned in the last review. The new zone extends from Everet on Puget Sound to Wenatchee through a new tunnel which is being constructed through the Cascade Range. The line is of interest more particularly on account of the change of system made; it was formerly the sole example of 3-phase electrification in America, but has now been changed to single-phase at 11 000 volts and 25 cycles.

The 22 000-volt, 25-cycle electrification on the Detroit, Toledo and Ironton Railway is being extended. The locomotives used are of the motor-generator type, and are of unique design in that the entire weight is carried on the motor-axle bearings, there being no side frames or axle-boxes as usually understood. There is a possibility that this 25-mile zone will be extended by 400 miles to the Ohio River.

Further tentative announcements relate to the proposed extension of the New York Central Railway (which already operates a direct-current system near New York City) to Buffalo, at a cost of 150 million dollars. If this project materializes, it is probable that the single-phase system will be used.

CENTRAL AND SOUTH AMERICA.

Two new lines are due to start electric services in Central America by the end of 1930. The normal-gauge railway just built between San Felipe and Quezaltenango, in Guatemala, is being equipped for direct-current working at 1 500 volts. Motor-coach trains will be run on this 28-mile route, which has grades as steep as 1 in 11. The narrow-gauge line in Costa Rica between the capital, San José, and the port of Puntarenas, is being electrified at 15 000 volts and 20 cycles, and its whole length of 80 miles will be supplied from a single feeding-point. Both these railways will obtain energy from hydro-electric sources.

The section of railway from Los Andes, Chile, to Mendoza, Argentina, constitutes the Transandine Railway which forms the central link between the Pacific and Atlantic coasts. It has a 1-metre gauge and is laid for combined rack and adhesion service. Although the actual volume of traffic did not itself justify electrification, the exceptionally severe winter weather and the difficult grading made the conversion advisable. At present the Rio Blanco–Los Cuevas section has been electrified at 3 000 volts (d.c.). The Chilean State Railways are already electrified on the same system between Valparaiso, Santiago and Los Andes.

Extensions have been made to the Paulista Railway, Brazil, on account of the excellent results of the initial stage. Further work has also been done in the Buenos Ayres suburban zone.

During the last two years the Campos dao Jordac Railway has been electrified at 1 500 volts (d.c.) with overhead contact-line. The motor coaches have direct control, i.e. the switching operations are made in a drum controller. In Venezuela the La Guaira–Caracas Railway has been electrically equipped on the same system. A number of Diesel-electric rail coaches have been supplied to Uruguay from this country.

CANADA.

It is reported that developments may be expected in Montreal, where the problem of new terminal facilities has been investigated. As with a number of cities in America and Europe, the elimination of the locomotive smoke nuisance and the increase in value of land and buildings due to electrification indicate the use of an underground terminal station with its immediate zone electrified.

The electrification of the line belonging to the Montreal Harbour Board has been completed, and the service along 11 miles of waterfront is now maintained by electric locomotives. The system is 2 400 volts (d.c.) and the 100-ton locomotives are each equipped with four 400-h.p. motors. The service is of a heavy shunting type, with train weights up to 5 000 tons or more.

The Canadian National Railways have a number of oil-electric railway vehicles in use, including the 290-ton, 2 660-h.p. double-unit locomotive now operating between Brockville and Belleville, Ontario.

INDIA.

The first stage in the electrification of the suburban services of the Bombay, Baroda and Central India Railway was opened at Bombay by the Governor on the 5th January, 1928. The lines extend out northward from Bombay through Salsette Island into which the suburbs are rapidly spreading.

The important scheme of the Great Indian Peninsula Railway in the neighbourhood of Bombay, including the main lines to Igatpuri and Poona, mentioned in the last review, has now been completed. The 1 500-volt d.c. overhead system is used. Several 2 600-h.p. freight and 2 160-h.p. passenger locomotives for this railway have recently been supplied from this country. The form of drive shows a departure from the nose-suspension type more commonly supplied. The goods engines are of double 6-wheeled coupled-bogie pattern with 2 motors per bogie geared to a jack shaft. The passenger locomotives have a flexible individual-axle drive with double-reduction gear and a form of the Oldham universal flexible floating coupling between the centrally-placed gear wheel and the driving axle.

Proposals, on a large scale, for the construction of a tube railway in Calcutta have been worked out. The scheme would cost £4 000 000 and would be put forward in conjunction with a project for the electrification of the suburban lines of the East Indian and Eastern Bengal Railway. A suburban and city electrification scheme has also been devised for Madras.

AUSTRALIA AND NEW ZEALAND.

In Australia the Sydney suburban and city railways are being proceeded with. The plans involve the interconnection of a new subway network with the existing suburban tracks of the surface railways—a scheme which is completely modern in its conception, since it provides a definite forward step in the co-ordination of the city's transportation facilities. Several sections of the scheme are in operation.

In New Zealand, the first electric train on the 7-mile Christchurch–Lyttelton line of the Government Railways ran on the 14th February, 1929. The 1 500-volt d.c. system is used. In recent years the limitations of the 1⅝-mile single-line tunnel between Lyttelton and Heathcote have proved increasingly severe, and the decision to electrify followed inevitably. The single substation is fed from the New Zealand "grid" network, and is equipped with single-commutator rotary convertors.

The first electric railway in New Zealand was the Otira Tunnel section (Arthur's Pass), completed in 1924.

SOUTH AFRICA.

The rapid expansion of the suburban traffic in the vicinity of Cape Town during the second decade of this century led, in 1917, to the appointment of consultants to report on the matter, and also on several other sections of the South African Railways. The period of depression retarded any realization of the consultants' findings, but provision was made during 1924–5 for some 26 miles of the 3 ft. 6 in. gauge suburban lines near Cape Town to be converted for electric traction at 1 500 volts (d.c.). A power house at Paarden Island, Salt River, supplies six substations serving the Cape Town–Simonstown and Cape Town–Sea Point routes. The effects of road traffic have been severely felt.

The Glencoe–Pietermaritzburg line, in Natal, is now completed and has been functioning efficiently for two years. The financial results are disappointing, on account of the increase in traffic not coming up to expectation, and of the greatly increased costs for energy, consequent upon the transfer of the Colenso power station to the Electricity Supply Commission. An increased expenditure of approximately £90 000 per annum has been involved, and this has rendered the immediate extension of the electrified zone to Durban financially uneconomical.

MOROCCO.

Electric operation has been in use since 1927 on the Casablanca–Kourigha and Casablanca–Rabat Salé routes, a total of 160 miles. The lines are heavily graded, making the equipment of some of the locomotives with regenerative apparatus an economic necessity. The system used is 3 000 volts (d.c.) and several motor-coach trains are working with this voltage on suburban services. Energy is obtained from both hydraulic and thermal stations.

JAVA.

The island of Java, in the Dutch East Indies, is extremely fertile and supports a large population. With a view to more efficient transport and the utilization of existing water-power, the railway authorities embarked on a scheme of electrification in 1921. Up to date a route length of 56 miles is worked at 1 500 volts (d.c.), with overhead contact line, from a hydraulic station at Oebroeg. The initial part from Meester Cornelis, Batavia (the capital) to Pasar Senen and Tandjong Priok was opened in 1924–5. An extension from Manggarai to Buitenzorg was put in service in 1928, together with some local lines at Batavia. Locomotives are used, and both synchronous convertors and mercury-arc rectifiers are being tried in the substations.

JAPAN.

The first electrified railway in Japan was a short suburban section at Tokyo, which has since been extended to a route length of over 60 miles. Trains of

4 to 8 coaches are run with a headway of 2 to 12 minutes. The electrically-operated routes comprise a circular line, a line running west to Yokohama and Sakuragicho, and a route running diametrically across the circle from north to south, then turning west to Kokobunji.

After the War, attention was drawn to main-line conversion, in connection with the use of available water-power and the elimination of smoke from trains in Tokyo. A scheme for the electrification of about 400 route-miles was prepared and work began in 1922. By 1924 the Tokyo–Odwara main 4-track line had been electrified, together with a short branch. A total of about 70 electric locomotives are in service on this line. An overhead contact arrangement at 1 500 volts (d.c.) is used for the main lines and 1 200 volts for the suburban routes, on which motor-coach trains work. Some of the recent locomotives have been constructed entirely in Japan. During the last two years a total of 18·6 miles of Government route have been added on the 1 200/1 500 volt (d.c.) system, while 185·5 miles of privately-owned lines have been equipped, all on the d.c. system at 600 or 1 500 volts. A route length of 326 miles will be added to the Government lines by 1934, and a further 60 miles of private route is due for completion in the immediate future.

A short underground railway has been in operation in Tokyo for some years, and it will eventually be extended. At present, however, the heavy cost of underground construction prevents any further work.

The rack railway over the Usui Pass has been electrified at 650 volts. The line has grades up to 1 in 15 and long tunnels, and great difficulties were encountered when the line was steam-operated before the conversion.

TEES-SIDE SUB-CENTRE: CHAIRMAN'S ADDRESS

By J. M. Gibson, Associate Member.

"THE PROGRESS OF ENGINEERING AS APPLIED TO AGRICULTURE."

(*Address delivered at* Middlesbrough, *16th October*, 1929.)

Under the powers given to the Electricity Commissioners by the recent Electricity (Supply) Acts it is proposed to create in this country a great distribution system fed by highly efficient generating stations. The main object of this proposal is to produce electricity as economically as possible and make it available for distribution throughout the country, and thus to extend its use beyond the limited areas in which it is now available.

The needs of our cities and urban areas have already been provided for to a very great extent, but it may reasonably be said that the rural portion of the country is virgin soil to the great majority of supply undertakings.

The provision of the main trunk routes by the Commissioners has relieved the distributors of the necessity of spending vast amounts of capital in this direction, thus making it possible for them to spread out their distribution lines into the less thickly populated areas.

Before embarking on a scheme of rural distribution it is necessary to consider what channels are open for the utilization of electricity in rural areas. There are four main channels: (1) Lighting and heating, (2) local industries, (3) irrigation (in some parts of the country only), and (4) agriculture.

There is no doubt that an efficient and reliable source of artificial lighting will be of great value in rural areas, and it is reasonable to assume that there will be a certain demand for heating, particularly in areas remote from the coalfields.

Local industries have, in a great many instances, long felt the need of a cheap motive power which would help them to return to a state of prosperity.

Irrigation schemes such as are in operation in some areas could undoubtedly be improved by the use of electricity.

The application of electricity to agriculture, however, is a subject of many possibilities and a great many difficulties, and in the hope that a better understanding of these difficulties will assist in the development of rural electrification schemes it is my intention to make a brief survey of "The progress of engineering as applied to agriculture."

We are told by archæologists that engineering in its simplest forms was first applied for purposes of war and agriculture—for war, for the purposes of making arms and armour, and in agriculture for the manufacture of cultivating tools such as sickles and ploughshares. It has been proved that such implements were in use as far back as the days of the ancient Egyptians, and it is an interesting fact that those implements in almost their original form are still in use in this country.

Little can be said about the need for the application of engineering to agriculture in any form during the period prior to the sixteenth century. In the early days man tilled the soil only to provide for his own needs, and in the latter part of that early period the land was in the hands of warlike barons and similar men, who made the local inhabitants into serfs and soldiers. Under such conditions progress, as we understand it, could not very well be expected.

Such machinery as windmills, water wheels and treadmills are known to have been utilized at an early date, but it was not until about the middle of the eighteenth century that the inventive mind began to produce machinery for general use in agriculture.

During the sixteenth and seventeenth centuries comparatively rapid strides were made with the invention and improvement of implements for the main agricultural operations.

Following James Watt's discovery of a method of utilizing steam as a motive power, it is recorded that he took out a patent for steam ploughing in the year 1770, but little progress was made in this direction until nearly a hundred years afterwards, and even after that date progress was very slow.

Machines for sowing seed appear to have been introduced in the seventeenth century. Joseph Locatelli of Corinthia invented such a machine in 1662. Some of his machines were imported into this country, but in 1783 Cooke, a Lancashire clergyman, patented a drill, the principle of which was to be the foundation of all drills now in use. Similarly, threshing machines were devised by Menzies in 1732, being improved in 1758 by Leckie and in 1786 by Meikle, whose ideas are embodied in most modern machines.

Harvesting machines were not developed until 1808, improvements being brought forward in 1826, 1849, 1851, 1878 and 1879, and during the last-mentioned two years the forerunner of the string binder now in use was produced. It is interesting to note that a clergyman was again amongst the inventors of this machine. Mowing machines were introduced in 1852 and another type was produced in 1854. This latter, with the addition of certain improvements, became, in 1860, a machine representative of a present-day production.

Numerous other machines of less importance were introduced during the first half of the seventeenth century, but all these required the use of horses to provide the motive power, with perhaps the exception of the large American machines which were later hauled by steam engines, and the larger portable threshing machines in use in this country, which were, and still are, hauled and worked by steam engines.

The year 1903 brought a new form of prime mover into the agricultural world, in the form of the Ivel motor tractor. This type of machine, although used to a small extent in 1910 for ploughing, did not come seriously into the agricultural field until the Food Production Campaign of 1917–18, when horses and men were difficult to obtain for farm work. These machines proved to be such an asset in agriculture at that time that, although only a few existed in 1908 and 1913, yet in 1925 there were 14 565 in use for field operations and 2 116 in use for stationary work.

The greater proportion of mechanically provided power utilized in agriculture during the last 20 years or so has been obtained from steam, oil or petrol engines, as revealed by the following returns.

	1908	1913	1925
Steam engines	8 690	7 719	3 731
Oil or petrol	6 911	16 284	56 744
Gas, wind, water, electric and other machines . .	1 730	5 240	5 254

It will be noticed that the use of oil and petrol engines increased very rapidly. Apart from the machinery which has been directly applied to farm work it should here be mentioned that that great branch of our engineering industry, the railways, has played a very important part in the advancement of agriculture.

Having briefly considered the history of engineering as applied to agriculture, let us now consider the possible causes of its slow growth as compared with engineering in other industries. This I propose to do under three headings, viz. (1) Psychological, (2) social, and (3) commercial.

(1) *Psychological.*—Agriculture is known to be one of the oldest industries, and the earliest date at which attempts were made to obtain a subsistence by the tilling of the soil may perhaps be as far back as Biblical days. In any case it has been proved, so far as this country is concerned, that the ancient Britons did a certain amount of farming. It is doubtful, however, whether any serious attempt was made to extract from the soil a reasonable yield of the riches it contains, until the many foreign invasions with which this country was afflicted came to an end.

It is probable that at this time those who laboured on the soil were driven to it by task-masters or were forced to cultivate the soil in out-of-the-way places, where they would not be molested, in order to obtain food. From this state of things our agricultural industry appears to have slowly but surely grown, and if such were the circumstances under which the farmer began to exist it is not surprising to find that in the main he is of a reserved and retiring disposition and not too prepared to accept anything new without definite proof of its worth.

In the process of time the ever-present fear that his next-door neighbour might raid him for the sin of holding opposite political opinions, or that the nearest baron might find some means of taking his land and impressing the services of himself and his family, has undoubtedly died down, but it seems to have left the seed of mistrust in the hearts of the farmer and the rural dweller.

The conditions under which the early farmer lived in isolated areas, before roads were made, tended to make him a confirmed individualist, and although the introduction of transport facilities, in the form of roads, and education did bring about social changes he remains an individualist.

(2) *Social.*—From this point we may consider the social changes which have taken place in rural areas during the last decade.

It has previously been noted that clergymen were responsible in some cases for the development of new ideas in machinery. Here education begins to enter forcefully into the agricultural field. Later the Church schools put forth a helping hand and then in 1870 the "school board" national education system was instituted, this being again revised by the Act of 1902. Although this probably resulted in a large number of the more healthy-minded young men leaving the land to seek their fortunes in other spheres and industries, yet education has been an enormous influence for the good of the farm and rural dweller.

The introduction of transport facilities by means of roads and railways has further expanded their social outlook, to the extent of producing almost a different type of people. Whilst the evolution of mind has slowly progressed, so has the adoption of improved methods of cultivation advanced, so that whereas 50 years ago a new machine was looked upon by the small farmer and farm labourer as a nine days' wonder, he now recognizes the ordinary agricultural machine as a necessity and a friend.

The more recent improvements in educational methods, together with the intensive developments of transport services, which enable country children and youths to attend better schools, are exerting a greater influence upon the minds and lives of the rural dweller.

As the result of these changes it will be found that the electrical engineer is entering the field with the way infinitely better paved than it was for the mechanical engineer, although many of the old prejudices and doubts still exist.

(3) *Commercial.*—Although the personal element has had, and will continue to have, a great influence on the development of engineering in the agricultural world, yet it is the financial outlook which really governs the industry.

Farming has almost solely been a one-man business and since the days when he traded by barter the farmer has been noted as a bargainer who desires worth for worth. He has a deeply-seated dislike for trading on borrowed money, and would rather work his hands bare to the bone on a piece of land he has sufficient capital to stock, than work a larger farm on capital on which he has to pay interest and which has to be redeemed.

The basis of the farmer's financial law is, as in all other industries, that he shall so balance the cost of producing his final saleable article with the capital he has invested, mainly represented by stock, that at the end of each year he can have a reasonable return on his capital. The means by which he obtains this balance must of necessity depend on the class of farm he works, i.e. whether it is a dairy farm, a sheep farm or a mixed farm. Each class of farm presents its own peculiar problems.

Closely coupled with the question of stocking a farm is the question of manning it efficiently and providing the necessary amount of power, either in the form of horses or mechanical contrivances, so that he will not have to pay out more revenue than is necessary on hired labour, nor have more capital invested in machines which cannot be profitably employed, than he can afford. The words "profitably employed" are very significant when applied to agricultural machinery. Although there are a great number of operations which can be carried out on a farm by mechanical means, yet there are practically none which can be designated as continuous processes. The greater proportion of these operations occupy only a few minutes per day, or possibly a few days per annum. On the other hand, man-power is required constantly in all operations on the farm, and the problem of how much such revenue-absorbing help can be supplanted by capital-absorbing machines is one which needs very careful thought. The same consideration has also to be given to the use of mechanical power in place of horses. It is perfectly true that machines can be made use of, but the farmer has to decide whether they can be used more profitably than men and horses in each particular circumstance.

Some idea of the acuteness of this problem may be gathered from the following figures relating to the value of stock and machinery:—

Sheep	Stock to buy: £2 Fat for sale: £3 10s.
Cattle	Stock to buy: £14 Fat for sale: £20–£22
Oil or gas engines	£50
Harvesting machines	£56
Mowing machines	£25
Drills (seed and manure)	£24–£30

Thus the farmer can buy 25 stock sheep or 3 stock cattle for the price he would have to pay for an engine. The sheep and cattle will live and fatten on the products of the soil, and eventually sell at such a price as to return him his capital plus a profit, whereas the value of the engine decreases with time and use. The purchase o the engine must therefore depend on whether or not its use will save for him, in other expenditure, more than that stock would return to him.

Having considered all the circumstances the farmer becomes faced with the fact that he can only afford to expend a very small proportion of his capital on machinery; hence it is that only on the larger farms are the more expensive machines to be seen at work.

Mr. Borlase Matthews in his paper * read before the Institution in 1922 mentioned that, in England and Wales, out of a total of 418 000 farms and small-holdings only 36 000 (or 9 per cent) of these were over 150 acres in area, and only 13 500 (or 3¼ per cent) over 300 acres. Mr. Matthews also mentions that for farms under 150 acres careful thought must be given to ensure that an adequate return is obtained on the capital expended. This remark should not be interpreted to mean that farms below 150 acres in area would not be worth supplying, but rather that a great deal of thought would have to be given to the question of how best to apply the capital the farmer could afford to lay out in machinery and other labour-saving devices.

The electrical engineer has at his disposal infinitely more useful and adaptable appliances than the mechanical engineer has had. Not only can he offer to his client the heavier type of power unit, and an efficient and safe method of lighting, but he can introduce an infinite number of smaller labour-saving devices of which the farmer and his wife do not appreciate the need, because they have been so accustomed to doing things by hand.

In approaching the farmer it will not be sufficient to tell him that such and such things can be done. He may believe it, but he will not appreciate to the full what it would mean to him.

As I have already mentioned, the farmer is a reserved man and a bargainer, desiring to know the worth of all things before he will commit himself to purchase them. He knows little or nothing of what electricity is capable of performing, therefore if success is to be attained in rural development the electrical engineer must be prepared to demonstrate to him those capabilities, and above all to give him all the assistance in his power to enable him to lay out his capital in the most economical manner.

To press on to him an ill-considered scheme will end in creating mistrust and tend to bring about the failure of rural electrification.

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* "Electro-farming," *Journal I.E.E.*, 1922, vol. 60, p. 725.

SOME MEASUREMENTS IN CORNWALL OF THE SIGNAL STRENGTH FROM 5XX.

By J. H. Reyner, B.Sc., Associate Member.

(*Paper first received* 10*th October, and in final form* 19*th November*, 1929.)

Summary.

In connection with the testing of wireless receivers, information was desired concerning the field strength obtained from 5XX in Cornwall, this district being known to be poor from the point of view of wireless reception.

An investigation of the field strength was therefore carried out with the aid of portable equipment. This particular apparatus was simpler than that usually employed but appears from the consistency of the results to be reliable.

When the experiments were conducted, a curious effect was brought to light which appeared to be a radio shadow caused by the masts of the beam station at Bodmin. This gives rise to an interesting distribution of the contours in the Truro district.

The general order of field strength appears to coincide with theory up to this point, if due allowance is made for attenuation, but there is a rapid falling-off towards the extreme west of Cornwall.

(1) Apparatus Employed.

For certain reasons in connection with receiver testing it became desirable to obtain information regarding the signal strength of Daventry 5XX in Cornwall, as the evidence obtained from reception tests appeared to indicate a more rapid attenuation than normal. A simple portable equipment was therefore constructed, and a series of measurements was made covering a wide area. A small aerial and counterpoise system was used, the masts being in three sections so that they could readily be dismantled. The signals received on this aerial system were applied to a screened receiver comprising one stage of high-frequency amplification followed by an anode-bend rectifier.

A screened local oscillator was employed in conjunction with the equipment, the method of taking the measurements being as follows. The receiver was tuned in to 5XX and the rectified current in the anode circuit of the detector valve was measured by means of a sensitive microammeter. The receiver was then switched over to a dummy aerial having the same characteristics as the actual aerial system. In this circuit was included a coupling coil from the screened local oscillator, the output from which was adjusted to produce the same rectified current as before.

Provided that suitable obvious precautions are taken, such as ensuring that the oscillator is correctly tuned to the receiver, this method gives consistent and reliable results. The amplification of the receiver employed may vary from day to day, but since it is only used for the purpose of providing a visible indication of the rectified current the actual amplification is immaterial, the point which is important being the output from the oscillator.

The oscillator was straightforward in character, consisting of a simple valve-maintained oscillating circuit to which a small pick-up coil was coupled. The inductance of this pick-up coil was kept small, only a few turns being employed, and the distance from the main tuning coil carrying the oscillating current was sufficiently great to render the capacity coupling negligible. Under such circumstances, the voltage induced in the pick-up coil is proportional to the current in the oscillating circuit and to the number of turns on the coil itself. The oscillator was so calibrated that the voltage induced in the pick-up coil was known in terms of the oscillating current, for each of the pick-up coils used.

A thermo-couple was included in the oscillating circuit, and the leads from this were taken to terminals on the case of the oscillator to which a meter could be connected externally. The H.T. voltage on the anode of the oscillating valve was made variable by means of a suitable high resistance, and by this system it was found practicable to control the oscillating current within wide limits and thereby to vary the induced voltage from 0·1 to 3 mV. This was found to be more than sufficient to cover the range of field strength encountered during the tests.

By means of this equipment, therefore, it is possible to measure, in any desired locality, the actual voltage in millivolts set up in the aerial by the radiations from 5XX. If the effective height of the aerial system is known it is possible to convert these figures into field-strength values. The best way of doing this is to measure the field strength from 5XX with the same apparatus at some point relatively close to Daventry such that the field strength is sufficiently large to be measured directly. For this purpose an absolute measurement of the signal strength from 5XX was taken at the author's laboratories at Elstree, and at the same time a reading was taken on the portable equipment. This enabled any readings obtained with the portable apparatus to be converted to millivolts per metre by direct comparison, and at the same time enabled the effective height of the aerial system to be ascertained. The dimensions of the aerial system are shown in Fig. 1.

For the absolute measurement of signal strength a large frame aerial of 4 ft. side was constructed and this was arranged to tune with a relatively small value of capacity to Daventry's wavelength. A sensitive valve voltmeter was connected across the tuned frame, and the reading on this meter was observed when the frame circuit was tuned to resonance.

The frame was then placed at right angles to the maximum position, in which case no signal was induced from 5XX, and a voltage was set up in the frame from a calibrated source. This voltage was adjusted until the deflection on the valve voltmeter was the same as before.

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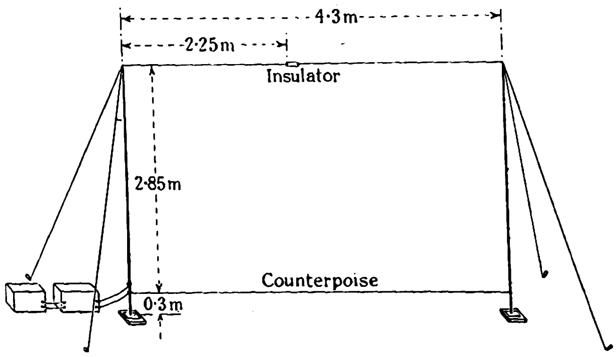

FIG. 1.—Arrangement of aerial system.

In order to check any serious error two methods were employed for inducing the necessary voltage in the frame aerial.

The first method consisted in the use of the same screened calibrated oscillator as was used with the portable aerial. Knowing the voltage induced in the various coupling coils per milliampere of oscillating current, it was a simple matter to determine the actual voltage induced in the frame. The second method consisted in introducing a 2-ohm resistance into the frame circuit. An oscillating current was passed through this resistance and the current was adjusted until the meter deflection was the same as before. The product of this current and the resistance gave the induced voltage.

Both methods gave consistent results in good agreement one with another. From the values of induced voltage so determined the field strength in millivolts per metre is easily evaluated from the well-known formulæ for frame aerial reception. As a result of these calculations, the field strength from 5XX at Elstree was found to be 12·5 millivolts per metre, a value which, as indicated in Section (3), is in good agreement with theory.

(2) RESULTS OBTAINED.

The first tests consisted of a series of readings taken at selected points in the county in order to obtain some idea of the general contour to be expected. At first, there appeared to be little unusual, beyond the fact that the signal strength was lower than had been anticipated. Moreover, it was at once apparent that the contours were not circular or even approximately so in formation, being rather in the nature of a wedge in which the high signal-strength areas extended further west inland than on the coast. It was as if the coast-line were exercising some marked absorbing effect. Apart from this, however, the contours were not unusual, being of the general character indicated in Fig. 2.

Acting on this first rough contour, a number of further readings were taken and the results obtained were compared with the theoretical expectations. The figures were not in agreement and the discrepancies were for some time very puzzling. In some cases the signal strength would be distinctly lower than was anticipated, while in other cases it would be higher. Another curious effect was that in the Perranporth district the signal

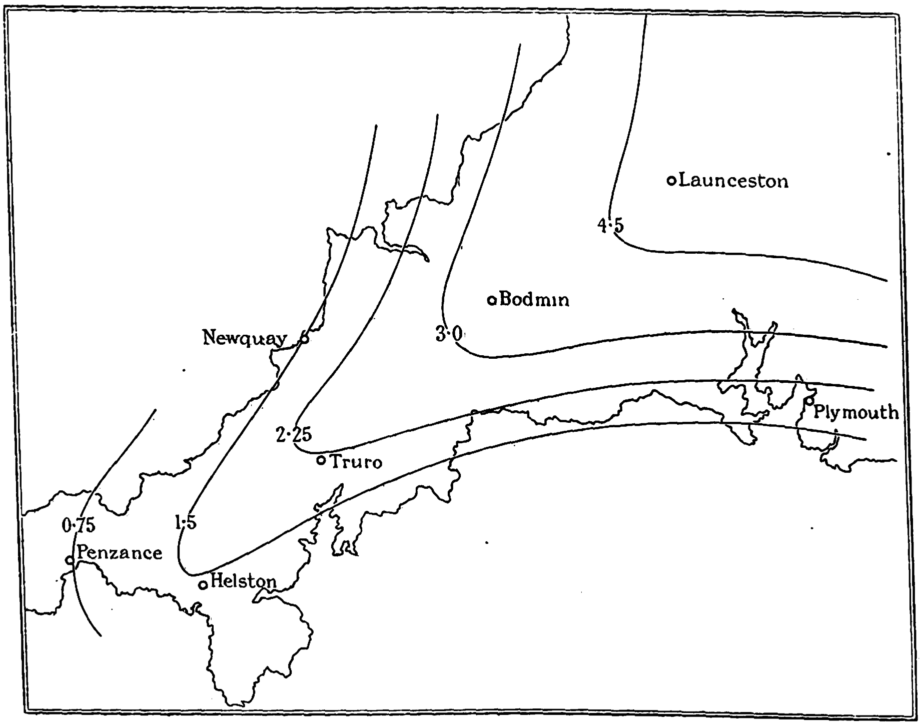

FIG. 2.—Apparent contours after first tests.

strength on the coast-line is approximately half that on the hilltop, only two miles inland. This effect was confirmed by the local residents who had noticed a marked difference in actual reception in the two localities.

In the course of the investigations, however, the breasting of a hilltop one day suddenly brought into view the masts of the Bodmin beam station and this immediately suggested the possibility of a radio shadow. The results so far obtained were re-examined in the light of this possibility and appeared to give some confirmation of the view. Further investigations were therefore put in train in order to confirm or disprove the theory.

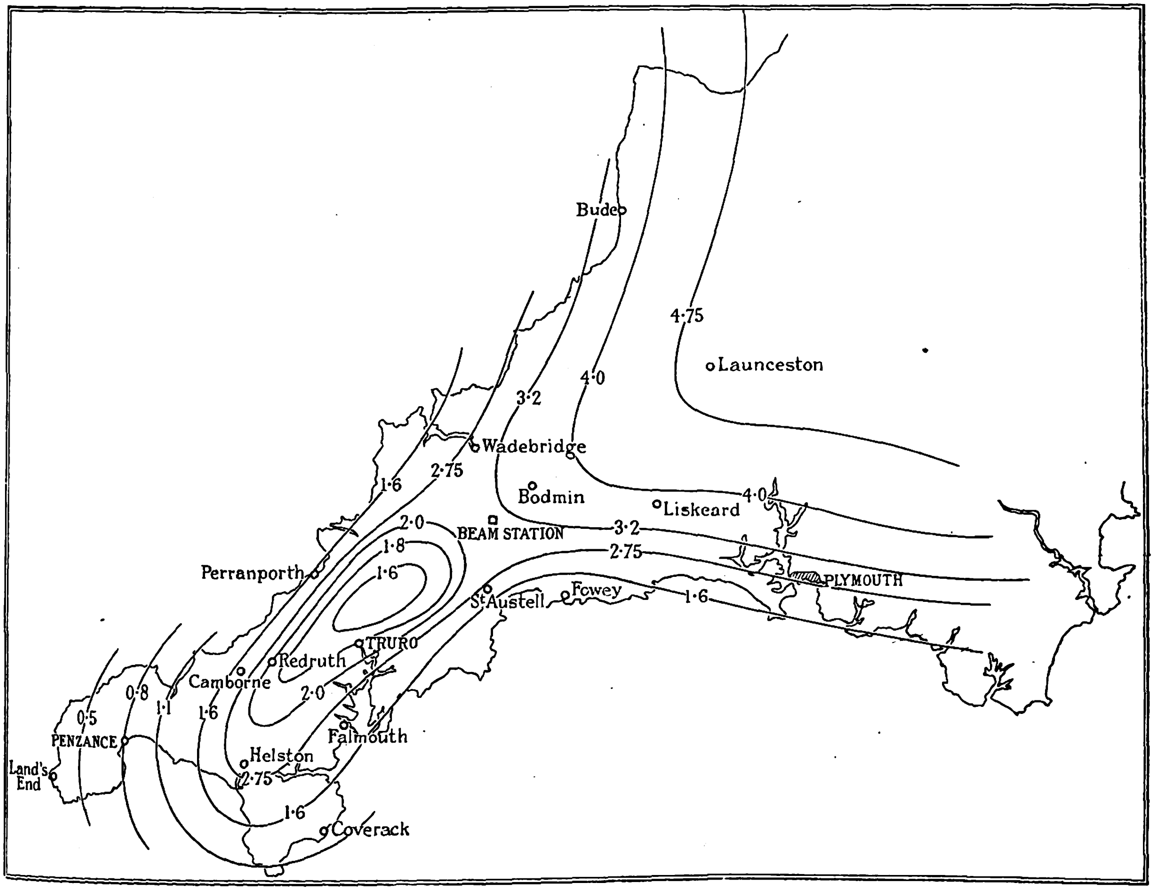

Fig. 3.—Final contours, showing shadow effect.

In every case the results obtained appeared to bear out the suggestion remarkably well, the final contours being shown in Fig. 3. On the north-east side of the Bodmin beam station the strength is of a normal order and in conformity with the contours shown in Fig. 2. At a point less than 10 miles to the south-west, however (on the other side of the Bodmin masts), the strength falls to approximately half its former value. Moreover, this region of bad reception extends in an almost direct line from Daventry through Bodmin as far as Redruth, a distance of nearly 25 miles.

A further interesting point is that surrounding this area of low signal strength is a ridge of good reception. Thus as one goes out towards the coast from a central point such as Truro, the signal strength rises on either side and then falls away rapidly towards the coast-line. What is perhaps more peculiar is that as one proceeds farther west the signal strength rises at first instead of falling and then subsequently attenuates very rapidly.

Particular care was taken to confirm this point in order to determine whether the ridge of high field-strength was maintained completely round the shadow area or whether it would be observed at the two sides only. Definite evidence of good signal strength, however, was found at such places as Helston and Camborne, both of which points lie on the theoretical contour line which one might expect. It appears, therefore, that this belt of good reception does actually exist immediately beyond the dead area around the Truro district.

The falling-off, once this high-field-strength ridge has been passed, is very rapid. In the short distance between Camborne and Penzance, for example, the signal strength falls to nearly one-third of its initial value, while the effects, already cited, of the very rapid drop in signal strength along the coast-line in such localities as Perranporth are also attributable to the same cause.

Whether the shadow effect is actually produced by the Bodmin masts is a point which can only be definitely confirmed by further experiments. There is, of course, the possibility that the curious configuration of the contours is due to mineral deposits. In order to obtain further information inquiries were made in various localities regarding any observed difference in the reception from 5XX after the erection of the Bodmin beam station. The station commenced operation some years ago and the information therefore is not reliable, but there is a distinct impression that the interference experienced during the reception of 5XX has been greater since the beam station was erected. Indeed, it is understood that representations were made to the Post Office to this effect when the station was first brought into commission, and investigations were made to see what interference was being produced by the beam station. No evidence of such interference was forthcoming and the matter was dismissed.

The suggested theory of a radio shadow, however, provides a satisfactory explanation. In certain districts the signal strength would fall considerably, in consequence of which the reception in those areas would be rendered more liable to interference from shipping and atmospherics, both of which are particularly troublesome in this part of England. The complaint of more interference, therefore, was apparently justified, but the nature of the interference was of a different character from what was anticipated.

(3) ANALYSIS OF RESULTS.

No detailed analysis of the results has been made, having regard to present-day theories of wave propagation. Certain check calculations have been made, however, which appear to indicate that the results are of the order to be expected. All readings, of course, were taken during the daytime, the period being the month of June 1929, and no readings were taken after 7 p.m. as it was felt that there might be danger of interference by the indirect ray at later times than this.

The first check calculation was the effective height of the 5XX aerial as deduced from the observed field strength at Elstree. As the distance from Daventry is 90 km there is little likelihood of serious attenuation. An estimate of the attenuation was made from Sommerfeld's formula and a figure of 4 per cent taken.*

On this assumption, the un-attenuated field strength at Elstree would be 13·0 millivolts per metre, approximately. Thus the effective height of the 5XX aerial, based on an assumption of 60 amperes aerial current, would be 80·5 m.† The 5XX masts are 164 m high, the aerial being of T shape and the down-lead being approximately 130 m high. In the light of these figures, the value of effective height appears to be eminently reasonable.

The second check was on the signal strength actually received in Cornwall as compared with the theoretical value calculated from the usual formula. In view of the distorted contours it is somewhat difficult to decide what shall be taken as the mean field strength at any given distance from Daventry. The wedge-shaped formation is also troublesome, for there are two ways of regarding this. One is to consider the strength at the peak as correct and to assume that the falling-away at the sides is due to some absorption effect produced at the coast-line. It is not quite clear how such an effect could arise. The second way of regarding the contours is to assume that the true contours are at the coast-line and that the extension of the contour towards the west inland is due to the Bodmin masts in a similar but opposite manner to the shadow effect on the other side of Bodmin. There appears to be some justification for this point of view because the attenuation deduced on the first assumption is very small, rather less, indeed, than that over sea water.

Probably the most satisfactory procedure is to take a mean value and this has been done in Table 1.

TABLE 1.

Comparison of Actual and Theoretical Field Strength.

Distance from 5XX	Theoretical field strength (un-attenuated)	Mean observed field strength	Ratio
km	mV/m	mV/m	per cent
280	4·18	3·8	90·5
305	3·81	3·2	84·0
335	3·5	2·5	71·5
360	3·27	1·6	49·0
385	3·04	0·8	26·3

It will be observed that up to 300 km the attenuation is fairly small but not unreasonably so, and the figures coincide approximately with the values obtained from Sommerfeld's theory. Beyond this point, however, the attenuation is increasingly rapid, and at Land's End, which is only 400 km away, the field strength is less than one-quarter of its theoretical value.

As was previously stated, this analysis is very rough and was intended merely as a check on the reasonableness of the figures obtained. The author has not had time nor is he sufficiently well acquainted with the formulæ to make a comprehensive analysis, but it is hoped that the results quoted will be of assistance to more qualified investigators in their endeavours to define the laws governing the propagation of wireless waves.

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* "The Attenuation of Wireless Waves due to the Resistance of the Earth," *Journal I.E.E.*, 1926, vol. 64, p. 766.

† The wavelength of 5XX at the time of the tests was 1 562·5 m.

THE CAPACITY EFFECT AND NATURAL FREE PERIOD OF A DIRECT-CURRENT ARMATURE.[*]

By J. C. Prescott, Associate Member.

(*Paper first received 2nd April, and in final form 26th July,* 1929.)

Summary.

The analogy between the absorption of energy by a coil free to rotate in a constant magnetic field and the charging of an electrostatic condenser was pointed out by Swinburne[†] in 1902, and was again stated by Kapp in developing the theory of his vibrator.[‡]

The phenomenon of instability of direct-current shunt motors with interpoles was treated by Siebert,[§] Wagner,[||] Rosenberg[¶] and others, while the instability of differentially compounded motors was dealt with by Greeve[**] and Andrade.[††]

In the present paper the correspondence between electrostatic and "dynamical" capacities is re-stated in a somewhat different form, and the theory of the instability of compounded motors is developed as an extension.

A series of experiments is described, the results of which are cited as confirmation of the results obtained by the mathematical analysis, and, in the Appendix, details of the solution of certain of the equations are given.

List of Symbols.

$a, A, A', A'', b, B, B', \gamma$ = numerical constants.

$\alpha, \alpha', \alpha'', \beta, \beta'$ = constant angles (radians).

C = electrostatic capacity (farads).

E = e.m.f. (volts).

$\mathbf{I}$ = moment of inertia of armature (lb.-ft.^{2}).

i = instantaneous value of current (amperes).

i_f = armature current due to friction loss (amperes).

K = percentage change in induction factor.

k = stiffness of galvanometer suspension.

L = self-induction of armature (henrys).

M = induction factor.

n = number of parallel paths through armature.

p = number of pole-pairs.

Φ = flux per pole.

$\phi = \text{arc tan}\,\dfrac{abM^2}{R\mathbf{I}\omega}$.

R = resistance (ohms).

T = natural free period of armature (secs.).

$\mathbf{T}$ = torque (lb.-ft.).

t = time displacement from zero (secs.).

θ = mechanical displacement of armature (radians).

ω = angular velocity of e.m.f. vector (radians per sec.).

z = number of active conductors on armature.

Introduction.

As pointed out by Swinburne[*] and Kapp,[†] a coil free to vibrate in a magnetic field of constant strength reproduces, when subjected to an alternating e.m.f., the effects of a large capacity. It can be shown, however, that this capacity effect is also present when a direct e.m.f. is applied to the coil.[‡]

If we consider a direct-current armature whose induction factor[§] and resistance are M and R respectively, then

$$E = aM\frac{d\theta}{dt} + Ri \quad . \quad . \quad . \quad . \quad (1)$$

$$bMi = \mathbf{I}\frac{d^2\theta}{dt^2} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where E = applied e.m.f.,
i = current at any instant,
θ = mechanical displacement of the armature,
$\mathbf{I}$ = moment of inertia of the armature,
and a and b are constants.

This gives as a solution the exponential equation

$$i = \frac{E}{R}e^{-abM^2/(R\mathbf{I})} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and may be compared with the conditions in a circuit containing electrostatic capacity C and resistance R. The current in this case is given by

$$i = \frac{E}{R}e^{-t/(CR)}$$

Inspection of equation (3) shows that the rate of decrease of current is reduced as R or $\mathbf{I}$ is increased, and suggests a method of facilitating the performance of the Kapp retardation test on machines of small moment of inertia[||] by adjusting the resistance in series with the armature to such a value that the rates of change of current and voltage are so low as to be easily observable. The equations become identical if the following substitution be made:—

$$CR = \frac{R\mathbf{I}}{abM^2}$$

or

$$C = \frac{\mathbf{I}}{abM^2}$$

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (excepting those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] See Bibliography, (2).

[‡] *Ibid.*, (6).

[§] *Ibid.*, (3).

[||] *Ibid.*, (4).

[¶] *Ibid.*, (5).

[**] *Ibid.*, (11).

[††] *Ibid.*, (12).

[*] See Bibliography, (2).

[†] *Ibid.*, (6).

[‡] *Ibid.*, (1).

[§] Induction factor = $2\Phi zp/(10^8 n)$, where Φ is the flux per pole, z the number of active conductors on the armature, p the number of pole-pairs, and n the number of parallel paths through the armature. The value of the induction factor is assumed to be constant except where otherwise stated.

[||] See G. Kapp: "The Principles of Electrical Engineering," vol. 2, p. 156 *et seq.*

Thus, in the dynamical case, $\mathbf{I}/(abM^2)$ may be termed the "equivalent capacity" of the circuit.*

The behaviour of the armature under the influence of an alternating e.m.f. may now be considered.

If we let ω represent the angular velocity of the e.m.f. vector, in radians per second, and t the time displacement from zero, in seconds, then the following equations must be satisfied:—

$$aM\frac{d\theta}{dt} + Ri = E \sin \omega t \quad . \quad . \quad . \quad (4)$$

$$\mathbf{I}\frac{d^2\theta}{dt^2} = bMi \quad . \quad . \quad . \quad . \quad . \quad (5)$$

which give as a solution, when the transient term has disappeared,

$$i = \frac{E \sin (\omega t + \phi)}{\left\{\left(\frac{abM^2}{\mathbf{I}\omega}\right)^2 + R^2\right\}^{\frac{1}{2}}}$$

where $\tan \phi = \frac{abM^2}{R\mathbf{I}\omega}$

Thus with increasing frequency the current through the armature will rise.

This may be compared with the equation for the current flowing under the influence of an alternating e.m.f. $e = E \sin \omega t$ in a circuit containing electrostatic capacity C and resistance R, namely,

$$i = \frac{E \sin (\omega t + \phi)}{\left\{\left(\frac{1}{C\omega}\right)^2 + R^2\right\}^{\frac{1}{2}}}$$

where $\tan \phi = \frac{1}{CR\omega}$

Thus it is seen that the equivalent capacity may still be represented by

$$C = \frac{\mathbf{I}}{abM^2}$$

It is perhaps of interest to compare the nature of this capacity with that of the electrostatic capacity. In the latter, energy is stored by the establishment of an electrostatic stress in the dielectric. In the former, the energy is stored kinetically in the rotating armature, which, if there were no losses in the coils or friction in the bearings, would continue to rotate after the removal of the e.m.f. from its terminals, thus maintaining itself in a state of charge, due to the presence of the kinetic energy of rotation, which energy could be abstracted by the establishment of electrical connection between the terminals.

An electrostatic capacity involves a strain in the dielectric; the dynamical capacity depends upon the velocity of the moving parts and upon their mass, and has, in electrostatic units, the dimensions of a length, for the induction factor varies directly as the flux. Therefore

$$C \propto \frac{\text{Moment of inertia}}{(\text{Flux})^2}$$

$$\propto \frac{(\text{Mass})\,(\text{Length})^2}{\left\{(\text{Length})^{\frac{1}{2}}\,(\text{Mass})^{\frac{1}{2}}\,\epsilon^{-\frac{1}{2}}\right\}^2}$$

$$\propto (\text{Length})\epsilon,$$

where ϵ is the specific inductive capacity.

The magnitude of C may be determined by inserting the values of a and b.

Thus, if $\mathbf{I}$ is in lb.-ft.², and θ (the mechanical displacement of the armature) in radians, equations (1) and (2) require that

$$a = 0 \cdot 159$$

and $b = 3 \cdot 76$

therefore $C = \frac{\mathbf{I}}{0 \cdot 596 M^2}$

Thus, for an armature with a moment of inertia of 100 lb.-ft.² and an induction factor of 37 (giving about 750 r.p.m. at 460 volts),

$$C = \frac{100}{0 \cdot 596 \times (37)^2} = 0 \cdot 124 \text{ farad}$$

THE EFFECT OF SELF-INDUCTION.

Since self-induction is, in general, present in a direct-current armature, the previous equations can only be taken as representing a special case.*

Let L be the self-induction of the armature; then if the latter be accelerated above its normal running speed, its motion may be represented by the equations

$$-aM\frac{d\theta}{dt} = Ri + L\frac{di}{dt} \quad . \quad . \quad . \quad . \quad (6)$$

$$bMi = \mathbf{I}\frac{d^2\theta}{dt^2} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

which give for θ three values depending upon whether $abM^2/(L\mathbf{I})$ is greater than, equal to, or less than $R^2/(4L^2)$.

In the two latter cases the solutions are of the exponential form, but the first solution is trigonometrical:

$$\theta = Ae^{-Rt/(2L)} \sin \left\{\left(\frac{abM^2}{L\mathbf{I}} - \frac{R^2}{4L^2}\right)^{\frac{1}{2}} t + a'\right\} \quad . \quad (8)$$

where A and a are constants.

This represents the damped harmonic vibration of a system the undamped free period of which is $\sqrt{[abM^2/(L\mathbf{I})]}$; and thus it is seen that, for certain values of M, L, R and $\mathbf{I}$, the direct-current armature has a natural free period of vibration the damping of which is directly proportional to the resistance of the circuit.

In this respect the mechanical oscillation is similar to an electrical one for, in a circuit containing a condenser of capacity C in series with a self-induction L having a resistance R,

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* Cf. expression obtained by Kapp in the theory of the vibrator. [See Bibliography (6).]

* See Bibliography, (11).

$$i = A''e^{-Rt/(2L)} \sin\left\{\left(\frac{1}{CL} - \frac{R^2}{4L^2}\right)^{\frac{1}{2}} t + a''\right\}$$

This may be compared with the vibration of a moving-coil galvanometer, having a coil of induction factor M connected across a non-inductive resistance R, the stiffness of the suspension being k.

The equation of motion is

$$\mathbf{I}\frac{d^2\theta}{dt^2} + \frac{abM^2}{R} \cdot \frac{d\theta}{dt} + k\theta = 0$$

and the solution when $\frac{k}{\mathbf{I}} > \frac{a^2b^2M^4}{4R^2\mathbf{I}^2}$ is

$$\theta = A'e^{-abM^2/(2R\mathbf{I})t} \sin\left[\left\{\frac{k}{\mathbf{I}} - \left(\frac{abM^2}{2R\mathbf{I}}\right)^2\right\}^{\frac{1}{2}} t + a'\right]$$

where A' and a' are constants. In this case the damping is inversely proportional to R.

CONDITIONS FOR OSCILLATION.

In order that oscillation may be possible, it is necessary that $R^2/(4L^2)$ shall be less than $abM^2/(L\mathbf{I})$; that is, R and $\mathbf{I}$ must be small and M and L large. $\mathbf{I}$ will in general depend upon the diameter of the armature, and for large machines, at voltages up to 500, $abM^2/\mathbf{I}$ will be comparatively small. Thus, in order to achieve the oscillating condition, L must be made large and the natural free period

$$T = 2\pi\sqrt{\left(\frac{L\mathbf{I}}{abM^2}\right)}$$

must of necessity be high.*

It is therefore unlikely that free periods of oscillation lower than 2 or 3 seconds will be encountered in practice, but that this free period may exist is shown by the equations above and by oscillograms which are reproduced later in the paper (see " Experimental Work ").

FORCED VIBRATIONS.

Since the armature, when self-induction is present, exhibits an inherent free period, it is reasonable to expect that the displacement should vary with the frequency of an applied disturbance, reaching a maximum as this frequency approaches the resonant frequency of the armature.

The equations of forced vibration under a varying voltage may be written

$$aM\frac{d\theta}{dt} + L\frac{di}{dt} + Ri = E \sin \omega t \quad . \quad . \quad (9)$$

$$\mathbf{I}\frac{d^2\theta}{dt^2} = bMi \quad . \quad . \quad . \quad . \quad . \quad (10)$$

which give as a solution, when the transient term has disappeared,

$$\theta = \frac{bME \sin(\omega t + a)}{\omega\left\{(L\mathbf{I}\omega^2 - abM^2)^2 + (R\mathbf{I}\omega)^2\right\}^{\frac{1}{2}}} \quad . \quad (11)$$

and

$$i = -\frac{E\mathbf{I}\omega \sin(\omega t + a)}{\left\{(L\mathbf{I}\omega^2 - abM^2)^2 + (R\mathbf{I}\omega)^2\right\}^{\frac{1}{2}}} \quad . \quad (12)$$

where

$$\tan a = \left(\frac{abM^2 - L\mathbf{I}\omega^2}{R\mathbf{I}\omega}\right)$$

θ will reach a maximum for $\omega = 0$, and, if R is small, will have a second maximum at $\omega \approx abM^2/(L\mathbf{I})$; while if R is near to its second critical value,* the second maximum will occur at $\omega = abM^2/\left\{(\sqrt{3})L\mathbf{I}\right\}$. The current will, however, have only one maximum, which will occur at $\omega = abM^2/(L\mathbf{I})$, irrespective of the magnitude of the resistance.

For this value of ω,

$$i = \frac{E}{R} \sin \omega t$$

imitating the condition of resonance for a circuit containing inductive resistance and electrostatic capacity.

The condition examined above would correspond to the case of a motor supplied with a periodically fluctuating voltage, but forced vibrations may also be set up by fluctuations in the torque demanded of the motor. If the torque be represented by

$$\mathbf{T}' = \mathbf{T} \sin \omega t$$

this condition can be defined by the equations

$$aM\frac{d\theta}{dt} = L\frac{di}{dt} + Ri \quad . \quad . \quad . \quad . \quad (13)$$

$$\mathbf{I}\frac{d^2\theta}{dt^2} + bMi = \mathbf{T} \sin \omega t \quad . \quad . \quad . \quad . \quad (14)$$

which give, as a solution for θ,

$$\theta = \frac{\mathbf{T}\sqrt{(R^2 + L^2\omega^2)} \sin(\omega t + \phi)}{\omega\left\{(L\mathbf{I}\omega^2 - abM^2)^2 + (R\mathbf{I}\omega)^2\right\}^{\frac{1}{2}}}$$

and for i,

$$i = \frac{\mathbf{T}}{M}\left\{1 + \frac{\omega\sqrt{(R^2 + L^2\omega^2)}}{\left\{(L\mathbf{I}\omega^2 - abM^2)^2 + (R\mathbf{I}\omega)^2\right\}^{\frac{1}{2}}}\right\} \sin(\omega t + \phi)$$

which, if R is small, has a maximum at

$$\omega \approx \frac{abM^2}{L\mathbf{I}}$$

INSTABILITY.

If the direct-current armature rotate in a compounded field, the motion may be unstable if the compounding is such as to weaken the field for an increase in motoring current.† If K is the percentage change in the induction factor for unit current in the series field, the equations of motion may be written

$$E = a(M - Ki)\frac{d\theta}{dt} + Ri + L\frac{di}{dt} \quad . \quad . \quad (15)$$

$$\mathbf{I}\frac{d^2\theta}{dt^2} = bi(M - Ki) \quad . \quad . \quad . \quad . \quad (16)$$

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* See Appendix.

See Appendix.

† See Bibliography, (11).

the exact solution of which is a matter of considerable mathematical difficulty. If, however,

$$(KE - RM) < \frac{4abM^4L}{I}$$

approximations may be employed to give

$$i = Be^{-\gamma t}\cos(\delta t + \beta) \quad . \quad . \quad . \quad (17)$$

where

$$\gamma = \frac{RM - KE}{2ML}$$

$$\delta = \sqrt{\left\{\frac{abM^2}{LI} - \left(\frac{RM - KE}{2ML}\right)^2\right\}}$$

and B and β are constants.

$$\frac{d\theta}{dt} = \frac{1}{aM}\left\{E - B'e^{-\gamma t}\cos(\delta t + \beta')\right\} \quad . \quad (18)$$

where B' and β' are constants.*

Thus it is seen that if KE/M is greater than R the index of e is positive, and the amplitude of the vibrations of current and velocity increases with time after the initial disturbance, an increasing harmonic vibration being set up. Inspection of equation (15) confirms this result, for it is seen that, for certain values of K, $d\theta/dt$ and R, the term $K \cdot d\theta/dt$ may be greater than R and $i(R - Kd\theta/dt)$ may have a negative value for a positive (i.e. motoring) current; thus, in effect, a negative resistance is introduced into the circuit and may be expected to induce instability. The value of this negative resistance for given values of R and K will depend on $d\theta/dt$, and thus a certain critical speed will exist above which the machine will become unstable, and below which instability will not appear.

EXPERIMENTAL WORK.

In order to confirm the results of the mathematical investigation, a series of measurements was made on direct-current machines in the Laboratories of Applied Electricity at the University of Liverpool.

One phase of the armature of a Schrage commutator motor was used to give an alternating e.m.f. of low frequency. This type of motor has many advantages when used as a frequency changer; the frequency of the voltage appearing at the brushes is continuously variable from zero, with the armature rotating at synchronous speed, to supply frequency, with the armature at rest; the voltage at the brushes depends only on their "spread" (which is adjustable) and is independent of the armature speed; and the wave of voltage is practically free from harmonics.

In the first series of experiments the armature of the Schrage motor was connected to the armature of the direct-current machine under test. The Schrage motor was excited with current at a frequency of 50 cycles per sec. from the mains and was driven by a direct-current motor at a speed approximating to the synchronous speed. In order to compute the periodicity at the brushes, an integrating device was used which consisted of a clock mechanism from which the balance wheel had been removed, and the escapement of which was operated by means of an electromagnet connected in series with a non-inductive resistance across the brushes of the Schrage motor (Fig. 1). A pointer attached to the escapement wheel made one complete revolution for 50 cycles at the brushes, and thus, by timing a whole or partial revolution by means of a stop-watch, the frequency could be directly measured.

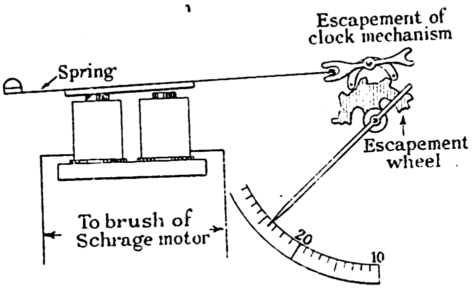
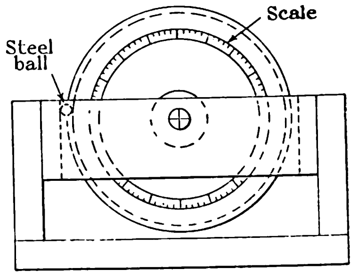
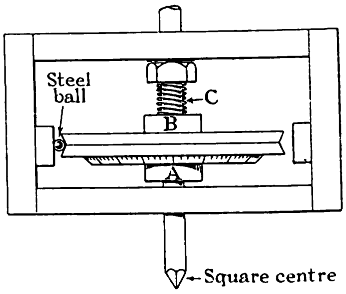


FIG. 1.

For observing the angular deflection of the direct-current armature, the device shown in Fig. 2 was used. It consists of an ebonite wheel in the edge of which is cut a V-shaped groove. This wheel is driven from the shaft by the friction of the collars A and B, one of which is rigidly fixed to the shaft while the other acts as a washer to transmit the pressure of the spring C. The frame of the instrument is provided with two vertical plates at a distance of $\frac{1}{16}$ in. from the wheel. When observing the angular displacement, a small steel ball was placed between the grooved rim of the wheel and the plate; thus the wheel was free to rotate with the shaft in one direction, but, due to the binding of the ball between the wheel and the plate when the shaft rotated in the opposite direction, the wheel



Elevation



Plan

FIG. 2.

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* See Appendix.

slipped between the collars and progressed in one direction only.

A graduated scale attached to the wheel enabled the total progression for a given number of oscillations of the armature to be observed. Thus the amplitude of the swing could be determined. Since the displacement of the armature on either side of the mean position was not always the same, observations of the displacement in both directions were taken by moving the ball from one side of the wheel to the other.

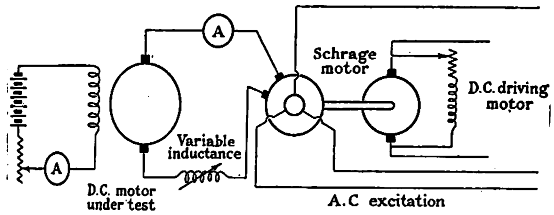

FIG. 3.

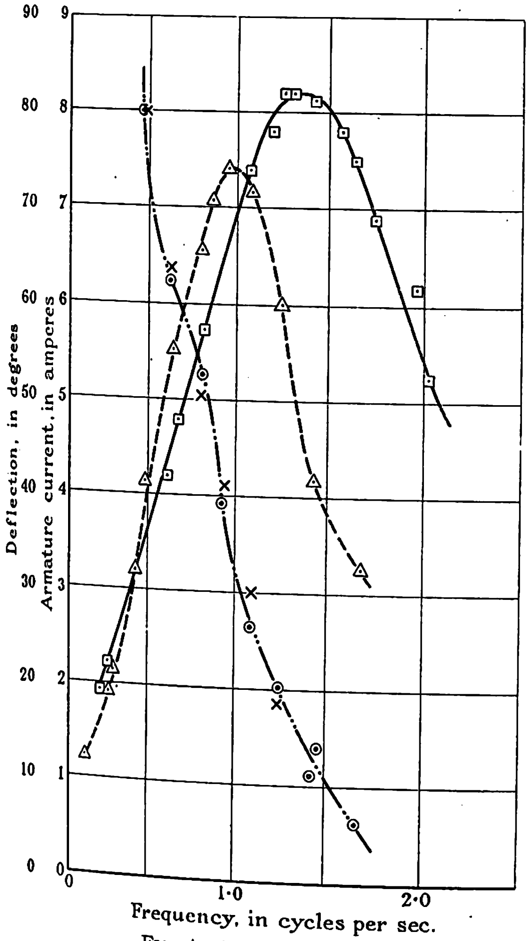

FIG. 4.—Machine 1.

——— Armature current; self-induction in circuit = 0·0675 H.
- - - - Armature current; self-induction = 0·115 H.
— ·· — Deflection (degs.). Self-induction = 0·115 H.
(Calculated points shown ×).
Constant applied p.d. = 5 volts.

In making the measurements, a hot-wire ammeter was placed between the direct-current motor under test (the field of which was maintained at a constant value) and the Schrage motor (see Fig. 3). Readings of armature current and frequency were taken with various amounts of self-induction in series with the direct-current armature.

Examples of the curves obtained at constant voltage are shown in Fig. 4, in which, also, the displacement of the armature, both calculated and observed, is plotted against frequency. It is seen that, although the current through the armature reaches a definite maximum in each case, the deflection decreases as the frequency rises, since the resistance in the circuit (viz. 2 ohms) was greater than the second critical resistance for the machine. A definite point of inflection, however, appears on the deflection curve at a point somewhat below the point of resonant frequency on the current curve.

In calculating the displacement, the formula

$$bM(i - i_f) = \mathrm{I}\frac{d^2\theta}{dt^2}$$

was used, which gives, assuming a sinusoidal current wave-form,

$$\theta_{max.} = \sqrt{2}\left\{\frac{bM}{\mathrm{I}\omega^2}(i - i_f)\right\}$$

where i_f is the friction current of the machine, which is assumed constant and which in the machines under test was 1 ampere. The results of these tests are given in Table 1.

TABLE 1.

	Machine 1	Machine 2
Moment of inertia	12·6 lb.-ft.²	9·7 lb.-ft.²
Induction factor	9·6	16·6
Number of poles	4	4
$\frac{1}{\text{Equivalent of capacity}}$ ..	4·34	16·75
Observed free period		
Self-induction = 0·115 H	1 sec.	—
$L\omega_r^2$	4·54	—
Self-induction = 0·0675 H	0·77 sec.	—
$L\omega_r^2$	4·5	—
Self-induction = 0·096 H	—	0·475 sec.
$L\omega_r^2$	—	16·7
Self-induction = 0·062 H	—	0·386 sec.
$L\omega_r^2$	—	16·4

NOTE: ω_r is 2π times the frequency at which current resonance occurs.

To show the swing of the direct-current machine graphically, a shunted Einthoven galvanometer was used. The machine was run up to speed as a motor, and when steady conditions had been obtained the supply was interrupted for a short period. The oscillations of current on the re-establishment of the supply were recorded photographically by the galvanometer.

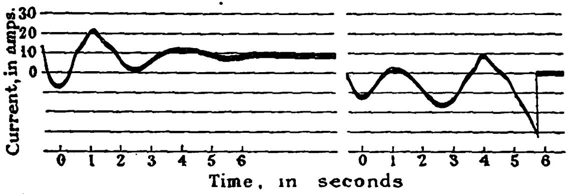

FIG. 5. FIG. 6.

Current/time curves.

$M = 7{\cdot}6$; $\mathbf{I} = 38{\cdot}4$ lb.-ft.^{2}; calculated periodic time $= 2{\cdot}1$ secs.
In Fig. 5, brushes on neutral; compounded field $KE < RM$.
In Fig. 6, brushes rocked 1 segment back to give, with the compounding, $KE > RM$.

Examples of the records obtained with various degrees of compounding on the motor are shown in Figs. 5 and 6.

CONCLUSION.

The author wishes to express his thanks to Dr. E. W. Marchant, Member, for much encouraging criticism and advice; and to Mr. U. S. Haslam-Jones, M.A., for the mathematical treatment of the "second critical resistance" and for the solution (much more elegant than that obtained by the author) of the equation for the compounded motor.

APPENDIX.

The Starting Current of a Direct-Current Armature on Constant Voltage.—The equations that must be satisfied are

$$E = aM\frac{d\theta}{dt} + R(i + i_f)$$

$$bMi = \mathbf{I}\frac{d^2\theta}{dt^2}$$

where i is the current required for acceleration and i_f the current required to supply the losses. This latter is, as an approximation, assumed to be constant. These equations can be combined to give

$$E = aM\frac{d\theta}{dt} + \frac{R\mathbf{I}}{bM}\frac{d^2\theta}{dt^2} + Ri_f \quad . \quad . \quad (18a)$$

where $d\theta/dt$ is the angular velocity of the armature. Integrating, we obtain

$$\frac{d\theta}{dt} = \frac{1}{aM}(E - Ri_f)\left\{1 - e^{-abM^2t/(R\mathbf{I})}\right\}$$

Substitution for $d^2\theta/dt^2$ in equation (18a) gives

$$i = \left(\frac{E}{R} - i_f\right)e^{-abM^2t/(R\mathbf{I})}$$

If $\quad E = e_0$ when $t = 0$

then $\quad i = \dfrac{E - e_0}{R}e^{-abM^2t/(R\mathbf{I})}$

Second Critical Resistance of a Direct-Current Armature.—In order that the armature may exhibit a free period, the auxiliary equation of

$$L\mathbf{I}\frac{d^2\theta}{dt^2} + R\mathbf{I}\frac{d\theta}{dt} + abM^2\theta = 0$$

must have unreal roots. That is to say, the radical $\sqrt{\left(\dfrac{R^2}{4L^2} - \dfrac{abM^2}{L\mathbf{I}}\right)}$ must be imaginary.

The first critical resistance will therefore be

$$R = \sqrt{\left(\frac{4LabM}{\mathbf{I}}\right)}$$

When the armature is subjected to a periodic potential difference, the following equation must be satisfied:

$$L\mathbf{I}\frac{d^2\theta}{dt^2} + R\mathbf{I}\frac{d\theta}{dt} + abM^2\theta = bME\sin\omega t$$

which gives as a solution

$$\theta = \frac{bME\sin(\omega t + a)}{\omega\left[(L\mathbf{I}\omega^2 - abM^2)^2 + (R\mathbf{I}\omega)^2\right]^{\frac{1}{2}}}$$

This will reach a maximum for $\omega = 0$, and for certain values of R there will be a second maximum. Thus, θ will reach a maximum when

$$\omega^2\left\{(L\mathbf{I}\omega^2 - abM^2)^2 + (R\mathbf{I}\omega)^2\right\}$$

is a minimum.

Differentiating this expression with respect to ω and equating to zero, we obtain

$$3\mathbf{I}^2L^2\omega^4 + 2\mathbf{I}\omega^2(R^2\mathbf{I} - 2abM^2L) + a^2b^2M^4 = 0 \quad (19)$$

When ω^2 is small this is positive, so θ decreases; also when ω^2 is large this is positive, so θ decreases. Thus θ either decreases steadily or has a minimum and a maximum value in the range.

In order that there may be a real critical value of θ it is necessary and sufficient that the roots of equation (19) should be real and positive; that is

$$(R^2\mathbf{I} - 2abM^2L)^2 > 3L^2a^2b^2M^4$$

$$R^2\mathbf{I} - 2abM^2L < 0$$

These may be combined to give

$$2abM^2L - R^2\mathbf{I} > \sqrt{3}LabM^2$$

$$R < \sqrt{\left\{\frac{(2 - \sqrt{3})abM^2L}{\mathbf{I}}\right\}}$$

This may be termed "the second critical resistance," since it is that resistance above which no second maximum appears in the curve of armature displacement plotted against frequency of disturbance.

The Current Equations for a Compounded Motor.—For a motor in which an increase in current causes a reduction in the strength of the main field,

$$E = a(M - Ki)\frac{d\theta}{dt} + Ri + L\frac{di}{dt} \quad . \quad . \quad (15)$$

$$\mathbf{I}\frac{d^2\theta}{dt^2} = bi(M - Ki) \quad . \quad . \quad . \quad . \quad (16)$$

where K is a factor depending upon the degree of the compounding.

Differentiating equation (15) and combining with equation (16) gives

$$\frac{KE - RM}{(M - Ki)^2}\frac{di}{dt} = \frac{ab}{\mathbf{I}}i(M - Ki) + \frac{L\,.\,d^2i/dt^2}{(M - Ki)} + \frac{LK(di/dt)^2}{(M - Ki)^2}$$

If K and L are small, this equation may be solved for small values of the current by neglecting KL and Ki; thus

$$ML\frac{d^2i}{dt^2} - (KE - RM)\frac{di}{dt} + \frac{abM^3}{\mathbf{I}}i = 0$$

which, if $(KE - RM)^2 < \frac{4abM^4L}{\mathbf{I}}$, gives

$$i = Be^{-\gamma t}\cos(\delta t + \beta)$$

where $$\gamma = \frac{RM - KE}{2ML}$$

$$\delta = \sqrt{\left(\frac{abM^2}{L\mathbf{I}} - \frac{RM - KE}{4M^2L^2}\right)}$$

and B and β are constants.

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A READY METHOD OF MEASURING THE VOLTAGE RATIO AND PHASE ANGLE OF HIGH-VOLTAGE TRANSFORMERS.[*]

By G. YOGANANDAM, B.E., Graduate.

(*Paper first received* 21*st February, and in final form* 27*th May,* 1929.)

SUMMARY.

A quick and ready method of measuring the ratio and phase angle of high-voltage transformers is described in which the well-known high-voltage Schering bridge is employed. Formulæ for the voltage ratio and phase angle are given, together with expressions for the sensitivity of the bridge. The accuracy obtained by the method meets the requirements of all industrial tests as well as of research work.

INTRODUCTION.

In 1927 a method of measuring the ratio and phase difference of high alternating voltages was described by B. G. Churcher.[†] Though it is the only simple and accurate method so far known, yet, in the present author's opinion, it is not quite suitable for routine testing in its existing form. The present method makes use of the entire apparatus that is available in all manufacturing firms and high-voltage laboratories and is commonly known as the high-voltage Schering bridge.

METHOD OF MEASUREMENT.

In the case of a high-voltage transformer taking its supply on the high-tension side, the high- and low-tension windings are connected in opposition as indicated by the arrows in Fig. 1, and the junction of the windings is earthed. The other terminal of the low-tension winding is connected to one end of a good quality, variable mica condenser, which can withstand the voltage of the low-tension coil. The other end of the condenser is connected to the terminal marked "Test" in the bridge box PQRS (Fig. 1). The remainder of the connections are the same as those for testing cables or insulators. The condenser C is set to a value such that its ratio to the capacity of the standard condenser S (100 $\mu\mu$F) is approximately equal to the nominal ratio of the transformer. Then R_3 and C_4 are adjusted until balance is obtained. The connections of the terminals marked "Test" and "Standard" have to be interchanged if balance is not obtained with the circuit shown in Fig. 1. At balance, the resistances R_3 and R_4 are nearly equal, the latter being generally a fixed resistance of 1 000/π ohms.

FORMULÆ FOR RATIO AND PHASE ANGLE.

Fig. 2 gives the vector diagram of the circuit shown in Fig. 1.

Let

V and v = high-tension and low-tension voltages respectively,

ϕ = phase angle between them,

C = setting of the condenser C,

δ = loss of angle of the condenser for the particular setting C,

θ = phase angle between the currents i_1 and i_2 in the condensers S and C respectively [θ (at balance) = arc tan $\omega C_4 R_4$],

γ = phase angle between v and v_c, the voltage across the condenser C,

$\omega = 2\pi f$, f being the frequency,[*]

v_3 and v_4 = voltages across R_3 and R_4 respectively.

Referring to Fig. 2, OB is the low-tension p.d. lagging behind the high-tension p.d. OA by an angle ϕ which will be taken as positive. The current i_1 leads the high-tension p.d. V by an angle $90-\delta'$

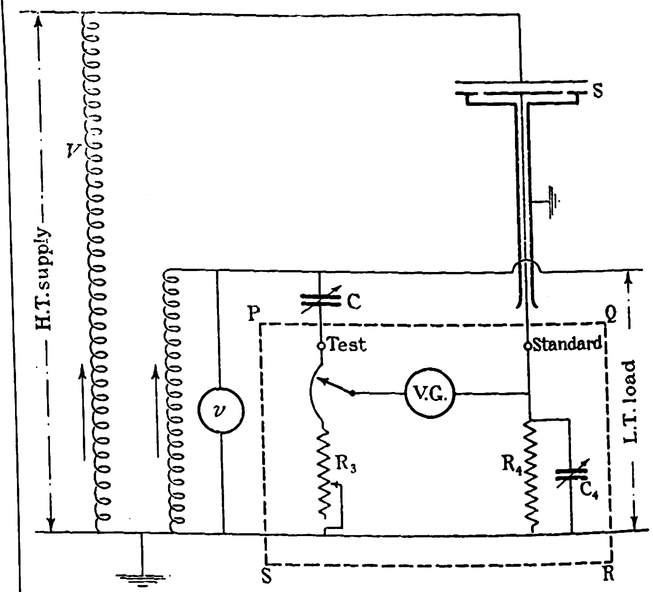

FIG. 1.

where
$$\tan \delta' = \frac{\omega S R_4 \cos^2 \theta}{1 + \omega S R_4 \sin \theta \cos \theta}$$

The voltages v_3 and v_4, which at balance are equal and in phase with the current i_2, are represented by OC.

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (excepting those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] *Journal I.E.E.*, 1927, vol. 65, p. 430.

[*] In this paper it is assumed that $f = 50$.

From Figs. 1 and 2 we have

$$v_4 = V\frac{\sin\delta'}{\cos\theta}$$

and

$$v_3 = \frac{v}{\left\{1 + \frac{\cos^2\delta}{\omega^2C^2R_3^2} + \frac{\sin 2\delta}{\omega CR_3}\right\}^{\frac{1}{2}}}$$

Putting $v_3 = v_4$ and simplifying, we get

$$R = \frac{V}{v} = \frac{\omega CR_3 \cos\theta \operatorname{cosec}\delta'}{\left[\cos^2\delta + \omega^2C^2R_3^2 + \omega CR_3 \sin 2\delta\right]^{\frac{1}{2}}} \quad . \quad (1)$$

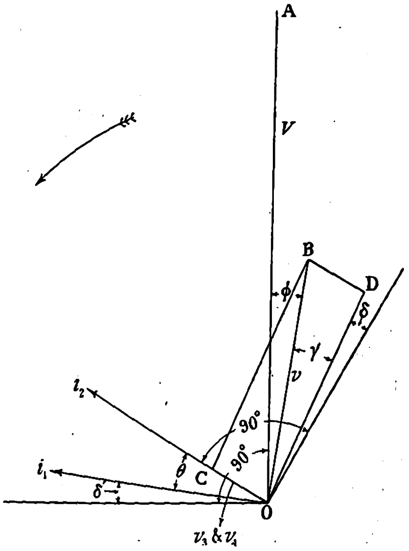

FIG. 2.

If δ' is sufficiently small to justify writing $\sin\delta' = \omega SR_4 \cos^2\theta$, and if in addition $C \not> 0{\cdot}5\,\mu$F and $\sin\delta \not> 0{\cdot}0005$, equation (1) can be rewritten

$$R = \frac{CR_3 \cos\gamma}{SR_4 \cos\theta} \text{ (approx.)} \quad . \quad . \quad . \quad . \quad (2)$$

where $\tan\gamma = \omega CR_3$ (approx.).

Also $$\phi = \theta + \delta' - \gamma - \delta \quad . \quad . \quad . \quad . \quad . \quad (3)$$

From (3) it is seen that the maximum negative phase angle that can be measured by the circuit shown in Fig. 1 is $\gamma + \delta - \delta'$. For larger negative angles, with the change of connections mentioned above, R and ϕ are given by

$$R = \frac{CR_4 \cos\theta}{SR_3} \times \frac{1}{\left[1 + \omega^2C^2R_4^2 \cos^2\theta + \omega CR_4 \sin 2\theta\right]^{\frac{1}{2}}} \text{ (approx.)} \quad (4)$$

and $$\phi = \theta - \delta' + \gamma + \delta \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where

$$\sin\gamma = \frac{\omega CR_4 \cos^2\theta}{\left[1 + \omega^2C^2R_4^2 \cos^2\theta + \omega CR_4 \sin 2\theta\right]^{\frac{1}{2}}} \text{ (approx.)}$$

and $\tan\delta' = \omega SR_3$.

In deriving the above expressions the following additional assumptions have been made:

(1) That the effect of stray electric fields is negligible. This is true if all the apparatus except the transformer under test and the standard condenser are kept in an earthed metal enclosure.

(2) That the total capacity in parallel with R_3 or R_4, due to safety gaps and earthed screens, produces a negligible error in the ratio and phase angle. The total capacity does not generally exceed 400 $\mu\mu$F and can be neglected.

(3) That the effect of that portion of the slide wire (Fig. 1) which is in series with the condenser C is negligible.

EXPRESSIONS FOR SENSITIVITY.

For a change of 1 in 10 000 parts in the ratio or of 0·0001 radian of phase angle, the galvanometer deflection is given by

$$d = \frac{v\omega CR_4S \times 10^6}{10^4\left\{(2R_4 + R_g)^2 + \omega^2L_g^2\right\}^{\frac{1}{2}}} \text{ mm (approx.)} \quad (6)$$

where S is the sensitivity of the galvanometer in mm per microampere and R_g and L_g are the constants of the galvanometer coil. Taking the example of a 220/110 000-volt testing transformer, the value of C is 0·05 μF. Now putting $\omega = 314$, $R_4 = 320$ ohms, $R_g = \omega L_g = 250$ ohms (approximately), and $S = 30$ mm, the value of d at half the rated voltage of the transformer is found to be 1·8 mm. In industrial testing a sensitivity of one-tenth of the above amount would be sufficient and there would be no difficulty in obtaining consistent balance in practice. The present sensitivity is, however, also possible in practice if care is taken to keep the supply voltage and frequency constant.

ADDRESS TO THE LONDON STUDENTS' SECTION

By A. H. RAILING, D.Eng., Member.

"THE PHILOSOPHY OF ENGINEERING."

(*Address delivered* 19*th April*, 1929.)

Two ways were open to me in choosing the subject for this Address. The first way was to select some technical subject arising out of my everyday work, such as heavy engineering, factory management or administration, a lecture giving my audience some facts which might prove helpful to them in their own careers. Naturally, such a subject would be specialized, appealing, like most purely technical subjects, only to a fraction of the audience. The second possibility was to choose some personal message, something which could not be read in textbooks, something which would convey to you the angle from which the speaker views his profession, which is also yours. I have chosen the second, because I consider that the ordinary Institution lectures provide you with sufficient technical data, and because I feel that it will interest you more to learn how I regard the broad aspect of the electrical engineering profession in its relation to the affairs of humanity, and how my outlook has from time to time helped me to maintain correct perspective and preserve enthusiasm in my everyday work.

The mainsprings of a happy life—and that means a successful life—are character, knowledge, and imagination. The first is largely a gift of the gods, in part inherited from ancestors. The second and third presuppose the ability to assimilate other people's experience and points of view. But these points of view require elucidation and comparison. It is to your imagination that I wish to appeal specially in this address.

My subject, if it has no very practical issue, is yet most intimately connected with one's whole outlook on life and the ideals underlying it. You have selected for various reasons the engineering profession for your life's work; perhaps because, as somebody once confessed to me, "I cannot think of anything else to study"; or because your parents thought—wrongly, I am quite sure, as you will find out for yourselves—that it is easy to make a lot of money in the profession; or—and this is the best reason of all—because you felt instinctively drawn to it. You are now engaged in getting together the tools for your life's work, and when you start in earnest to apply them the mainsprings of your activity will be the anxiety to earn a living, to get on, to prove successful, to become a real power, to rule others. Now, either you will succeed in these endeavours, or you will fail; either, through hard work and constant application, through innate ability or good luck, you will rise from the ranks to the top, or you will be destined to remain in the ranks. But, whichever is the case, the day will come when routine work will become monotonous (and there is routine work even in the highest positions); when the initial glory of achievement will pale, when you will reach the point of asking yourself what sense is there in all this work, what satisfaction beyond a livelihood or a piece of cheap self-satisfaction; when you will ask yourself whether you would not have done better in theology or law or as a doctor. When this day comes, unless you visualize and appreciate the part which you and the engineering profession are playing in the world, unless you realize that, whatever your individual part, you are a unit in one of the greatest forces in the general scheme of progress of humanity, your work cannot be really satisfying, for no life can be really happy unless the worker feels that whatever latent energy is in him has been translated into dynamic energy as a contribution, be it ever so small, to a community, to a general scheme.

The object of this Address is to provide you with a few thoughts, more or less at random, which illustrate the position that our profession holds in this general scheme of mankind, what the pioneers in our profession have done in the past, and the road which we have to travel in the future. If you grasp the sense and meaning of our profession in this light, you will possess something that will enable you to see the situation in true perspective, even when you are engaged in pure routine work.

Consider the various professions. Theology has taught man the laws of ethics and morals, and his relation to that higher Power which is both within and without. The legal profession has taught him the rights and duties of one individual against another, one class against another, one race against another; it has taught him to supplant brute force by order. The medical man has studied the functions of man's organisms and the laws which govern their actions, in an endeavour to apply these laws for man's physical betterment. The field of the engineer is a realm apart from living organisms; it ranges from planets to atoms, with their infinite variety of combinations, energies, and applications in the service of mankind. It is materialistic, the older professions often say. Yes; but the basis of everything, including men and, *ipso facto*, their professions, is idealistic, because it is only the knowledge that we possess to-day which can give us a proper understanding of the world and mankind, and their purpose, thereby leading to the possibility of further progress.

Let us look first at the historical facts of the past. What has been achieved by engineering, regarding the profession in the light of the definition I have just given? You will not expect this subject to be exhausted in this Address; I can dwell on a few aspects only, and since we are all electrical engineers you will forgive me if my picture is coloured in that direction. That which applies to electrical engineering in particular applies to all branches of engineering in general.

As man emerged from the age when he was merely a hunter there followed the development of the nomad tribe who kept cattle instead of hunting animals. Later came the tiller of the soil; then, on account of the sedentary method of living, successively, the builder of homesteads, the priest caste, the medicine man, the lawgiver, and so forth. All these vocations have already been in existence for thousands of years. Why has engineering, and especially electrical engineering, come so late, and what is its mission? As humanity progressed, it dealt with men and matter as it found them, and it used the kinetic energy of men and animals, and perhaps of wind and water, as well as certain known substances and some of their physical properties. Attempts were made from time to time to probe deeper, but practically nothing was known of the structure of matter, or of energy in its manifold variations, until a comparatively short time ago. The problems of dynamics, if we leave out Aristotle, were dead until the time of Galileo and Newton; the problems of matter, until Priestley and Berzelius. Engineering science meant, as in Galileo's law, going away from this earth to other worlds, or, as in the atomic theory, going deeper and deeper into the infinitesimal.

Electrical engineering started when humanity was prepared for an advance in this direction. In its narrower sense it means the application of the knowledge of what we call "electricity." In its broader sense, it embraces to-day all knowledge of matter and its attribute "energy," or vice versa, energy which manifests itself in the form of matter and its applications.

If we consider the history of the progress of the knowledge of matter, the sequence is a logical one. First, laws were discovered dealing with the physical properties of matter, of measurable bodies which we could see; later, with the properties of the invisible molecule, which was already a theoretical conception; later still, with those of the atom; and now, with those of the electrons, proceeding step by step to smaller and smaller units.

If, on the other hand, we consider the history of the progress of the knowledge of motion, we find exactly the same development from Galileo's and Keppler's law of the planets to the knowledge of the potential and kinetic energies of moving visible bodies, of heat and cohesion; the energy of the molecule to chemical energy, the energy of atoms, and thence to the knowledge of electricity and light and the energy of corpuscles as the basis of all. The knowledge of all these problems and the application of such knowledge went hand in hand, sometimes practice leading and theory following, sometimes theory first and practice afterwards; and it is self-evident that the sequence depended partly on the demand for practical applications to aid human need, the desire to achieve something, or, on the other hand, the mental craving to understand the fundamentals underlying certain established facts and, by understanding them, gradually to govern them.

I have tried here to show how and why engineering, and especially electrical engineering, came as the latest revelation of visible matter, and of the energy of visible matter, leading further and further into the region of the invisible and infinitesimal.

Having shown the path leading to our profession, I now come to the second point. How far has engineering, and especially electrical engineering, already contributed to human development by improving human progress and efficiency? The following are some of its contributions:

(1) Our profession enables us to make better use of matters by increasing the number of varieties in existence, by producing these more cheaply, and by making better use of their properties.

(2) It enables us to make better use of all the available forms of energy.

(3) It increases the space that can be inhabited and made use of by man.

(4) It increases the physical and mental power and efficiency of each individual of the whole human race.

(5) In addition to increasing the efficiency of the individual, it increases the efficiency of the whole human race, increasing either the average efficiency or the total efficiency.

The proof of what has been achieved could be given in innumerable ways. One could relate the romance of materials; how man passed from the Stone Age, when he knew of no metals, to the Iron and Bronze Ages, until to-day he has knowledge of over 80 elements and of thousands of combinations, each one of which combinations he can produce at will out of the elements, each one of which elements he can reduce out of certain composite bodies. One could relate the story of transport, from the building of roads on terra firma and the discovery of the wheel, to the hundreds of thousands of miles of railway laid and motor-cars built; or the story of transport on water, from the boat burnt out of a hollow tree, to the galley, to the sailing boat and steamer, and thence to the oil engine, turbine, and electrically driven monsters of to-day. One could tell of the submarine, and the conquest of the air, or a hundred and one other achievements.

From a philosophical point of view—which means a natural science point of view—engineering, and especially electrical engineering, is the most potent factor in the increase of mankind's efficiency for the five reasons which I have just stated, and to which I will now refer in rather more detail.

(1) *Electrical engineering enables us to make better use of matter by increasing the number of varieties in existence, by producing these more cheaply, and by making better use of their properties.* You know of the electro-deposition of metals, of the electrolytic processes and of the reduction processes. To mention a few examples, a new metal, aluminium, has been given to us by electric reduction of kaolin; electrolytic copper, of which 42 000 tons were produced in 1870, has by electrical processes risen to a production of 1 400 000 tons in 1920. The production of gold by the cyanide process, of lead and zinc from low ores, of oxygen and hydrogen for the bleaching of cotton and paper, of caustic soda, of nitrogen from the air for fertilizers; these and many other examples which could be cited show what has been done during the last 30 years. Think of the values created, of

the avenues of progress opened and of the results achieved.

(2) *Electrical engineering enables us to make better use of all the available forms of energy.* We have in successive steps arrived at the knowledge that energies are restricted to and based on one, and only one, electric energy. All other energies are merely variations—radiation, the energy of accelerated corpuscles; chemical energy, the energy of groups of corpuscles called atoms; heat, the energy of groups of atoms called molecules; mechanical energy, the energy of molecules grouped in measurable volumes.

We have thus acquired the knowledge that energy does not exist apart from matter, but is its attribute; one form of energy can be converted into another. What is the result? Most, if not all, of the energy of this planet is derived from the heat and radiation energy of the sun. Most energy available from this source is available either in the form of kinetic energy in rivers and the tides of the sea, or in the chemical energy of coal, oil and other organic substances. We take this energy wherever we find it, use it in our prime movers, transform it into mechanical energy, re-transform it in our dynamos into electrical energy and, since this electrical energy is more easily and efficiently transported than any other form of energy, we transmit it for hundreds of miles to places where we require it. Now energy is required in the form of light, heat, mechanical and chemical energy, and since electrical energy is not only the easiest to transmit but is also the easiest to convert, we re-convert the current into light, into heat, into mechanical energy, thereby enabling the efficient working of mines, factories, steelworks, mills, trains, lifting machinery, and a thousand industrial applications. Thus electrical energy has annihilated space. But it has annihilated time as well. Whereas in tropical countries during monsoon time the kinetic energy of water ran to waste, we now collect it in the mountains by damming it up. How these achievements should appeal to the imagination! For instance, hundreds of miles from Bombay sufficient water is collected during the monsoon period to drive for the whole year the cotton mills of that city, requiring 100 000 kW.

Two years ago I travelled over the plains of Palestine, once a fertile country, now waste on account of lack of the power necessary to pump water for irrigation purposes; and I stood at Lake Tiberias with another man, developing the scheme which is now under construction for collecting the water that comes into that basin during 4 weeks, and which is sufficient to provide power for a country for irrigation and industry for 12 months.

(3) *Electrical engineering increases the space that can be inhabited and made use of by man.* It is already clear from the previous section that certain materials which can now be produced by electricity could not have been produced without it, since it would have been too costly to transport the raw materials to the available sources of energy, or to bring the energy to the raw materials. But, further, given a definite number of human beings the increased rapidity of locomotion which engineering, and especially electrical engineering, has produced has the effect of decreasing distances, thus increasing the radius of action of every human being and allowing a greater number of people to live in a given area.

Engineering allows us to produce lower temperatures in hot climates and higher temperatures in cold areas. Wireless telegraphy enables us to spread instruction and news around the globe. Thus we have increased the area which is inhabitable by man, improved and equalized the conditions under which the earth can be inhabited, and increased the possible number of people which can inhabit a given area. Think of the triumph of cotton planting in Egypt, of the Panama Canal, of the irrigation schemes in India and Iraq, of the reclaiming of the Zuider Zee in Holland.

(4) *Electrical engineering increases the physical and mental power and efficiency of each individual.* Let us first deal with the material side. The mastery of available materials and energies leads to a huge increase in production and a consequent cheapening of raw materials and finished products like food, clothing, dwellings, tools and also luxuries. The immediate consequence of the cheapening of these commodities is a vast increase in the individual comfort of those living in centres of production. It is not realized to what a tremendous extent engineering, and engineering alone, is responsible for this higher standard of living.

The next result made possible by transport was the spreading of these advantages and the equalizing of living conditions and comfort from town to country, from one climate to another, and from countries with old civilization to uncivilized territories.

(5) What of the mental side? Each new item of knowledge gained in the world is a step in the path of progress of mankind. Only by understanding can we create; only by creation can we progress. Consider the knowledge of matter and energy as it was only 200 years ago, and compare it with conditions to-day. I believe it was H. G. Wells who said recently: " If the time of human existence on this globe were represented by the span of a man's life, then it is only a day ago that we knew of steam and an hour ago that we knew of electricity." What has been achieved in these 60 minutes for mankind, as against the thousands of years that went before? How different is our conception of the world, of the elements and their composition, and of energy and its working. Think how only the fundamental laws, the law of conservation of mass, the law of conservation of energy and the law of dissipation of free energy, help us to understand our surroundings and all the problems connected with life. Without a knowledge of natural science and its applications, in which is bound up practically all the activity and the organization of modern society, an efficient grasp of the problems of the world, of life and of society seems impossible.

Our profession has just reached a stage at which it is impossible to keep our knowledge as that of a caste. It is essential that its fundamentals should and must become matters of general knowledge. In previous ages the knowledge of carrying arms, of handicraft, ethics, reading and writing, all originally known only to a few, had to be spread broadcast when it became evident that it mattered more than anything else in life and progress.

And now, finally, with the progress of the individual is bound up the progress of mankind. We have just seen that engineering has acted as perhaps the greatest democratizing agent. It has taught us to make full use of the materials and energies available, and thus, on the one hand by cheap production, and on the other by cheap transportation, has changed commodities and tools which were the properties of a few into the properties and tools of the masses of mankind.

Its next effect was to an ever-increasing extent to replace manual labour by other available energies, thus conferring a further boon on mankind by allowing us to spend our energy more and more in a form which we are allowed to call a higher one, that is, as mental energy.

The very great progress made in science during the last century is largely due to this fact. Through this emancipation of mental energy, science and knowledge, instead of being the labour of the few, have become the labour of many.

In conclusion, let us refer to a third factor which contributes to the efficiency of the human race. This efficiency, as has already been pointed out, greatly depends on the universal spreading of the knowledge or experience that has been gained by individuals either in theory or in practice. Such knowledge was originally part and parcel of the individual until language enabled him to communicate with his fellow men, and the written, and later the printed, sign allowed him to pass it on to a greater and greater number. To-day, the knowledge of one individual can, within an hour, become the knowledge of mankind in all distant parts of the globe. The transmission of messages by electric conduction or radiation has removed the time factor and the factor of distance from the spread of knowledge throughout civilization.

The picture is not complete, but I think I have shown that electrical engineering has led to a better understanding, to a more extended and efficient use of nearly all existing forms of matter and energy. It has led to a better understanding of animal and human organisms and problems. It has bridged space and time and minimized their influence where they had become resistance factors against energies mental and physical; it has increased the efficiency of individuals and of society and it has therefore proved to be perhaps the most important factor in the progress of mankind.

At present, either you are engaged in learning how to use the tools of your profession, or you have begun to apply them. You will go out into the world to build roads and bridges, to make or use internal-combustion engines or steam turbines, to spread electric power networks or erect wireless stations, to try to manufacture better or cheaper classes of products; and you will very often find that, whatever your particular work may be, it is sometimes tedious and uninteresting routine work, unsatisfactory and soul-depressing. There is only one thing which will help you to carry on and get through your work, and that is the knowledge that your life does not merely mean slaving for food, but that its inner meaning is team-work by which humanity shall be led out of its bondage to a better existence.

I have tried to show you the ideals underlying our profession. No man is happy if his work has only a relation to his own well-being. Happiness in life can only be found if we see a larger meaning in our work, a creation of values for a larger community. I have tried to show that our profession, in the creation of knowledge and in the application of such knowledge, has created modern society. It is your duty to use the tools which the pioneers have produced, and on your application of them in your life's work depends largely the future rate of progress of our country and mankind.

PROCEEDINGS OF THE INSTITUTION.

791st ORDINARY MEETING, 7th NOVEMBER, 1929.

Colonel Sir T. F. Purves, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 24th October, 1929, were taken as read and were confirmed and signed.

Messrs. R. L. Bell and L. Champney were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the result of the ballot was declared as follows:—

ELECTIONS.

Associate Members.

Abbott, William St. George, Lieut.-Commdr. R.N.
Bennett, Abraham Francis.
Edgar, Edward James.
George, Henry Hale, B.E.
Hampson, William Wills.
Handy, William, M.B.E.
Jonas, Edward, D.Eng.
Lewis, Charles George H.
Mitchell, Gordon William B., B.A.
Moody, Harold Sydney, B.Sc.(Eng.).
Sowman, Alan Victor.
Swift, Leslie Albert.
Turner, Leonard George H.
Whipp, Fred.

Companions.

Barlow, The Rt. Hon. Sir C. A. Montague, Bart., P.C., K.B.E., M.A., LL.D.
Rubin, Albert Reginald.

Graduates.

Marwick, Robert William.
Nanda, Vasheshar Nath.
Owen, Albert Sydney H.A.
Phillips, William Eric, B.Sc.
Pitcher, Christopher Walter.
Pulling, Martin John L., B.A.
Smith, Charles Janson, Lieut. R.N.
Young, Tyrrell Francis, B.A.

Students.

Angold, George Henry C.
Ashthana, Rajendra Prasada, M.Sc.
Barnes, David Errington, B.Sc.
Barrett, Alfred Archibald.
Barton, Richard James.
Beresford, George.
Bhattacherjee, Barada Nath, B.Sc.
Bloor, Reginald Morris.
Bogra, Amir Chand.
Bradshaw, Harry Edward.
Brown, Edgar Louis.
Brown, Ian Harvey.
Chatterjee, Kamal Chandra.
Clarke, George Hessell K.
Din, Umar.
Edwards, John Griffiths.
Edwards, Noel Houghton.
Fenwick, William.
Fisher, Frank James.
Fox, John Ffoulkes.
Galley, Gordon William.
Gash, John Edward.
Gibson, Maurice.
Girdlestone, Richard Owen.
Greaves, John Milne.
Green, Robert.
Grote, Edwin Whitcomb.
Hargreaves, George.
Heyes, Vincent Gerrard.
Hobson, Frank.
Holmes, Victor Irving.
Horner, Frederick William L.
Hurdley, Thomas Charles.

Students—continued.

Hyde, Gilbert Anthony M., B.A.
Jones, Eric Owen.
Kashyap, Ram Nath.
Khandhar, Jagmohandas Popatlal.
Lyon, William Joseph R.
May, Henry John.
Nicoll, Robert Scott.
Owen, Edward Lionel.
Pett, John Percival C.
Radhakrishnan, Venkataramayer.
Ralphs, Leonard Charles.
Rishi, B. R.
Russell, Eric Ellis.
Sackville-Scott, Philip.
Saxen, Jerome Jaxon.
Setterfield, Edgar John.
Shivram, Tiruvottiyur Munuswami.
Singh, Gur Baksh.
Smith, Ernest Gilbert.
Smith, Ralph Balmforth.
Stanton, Thomas Leonard.
Stoyle, William Arthur R., B.Sc.
Stretton, Jack Arthur.
Swift, George.
Teal, Arthur Edward.
Thistleton, Richard.
Thomas, Howell Hugh.
Tudhope, Graham Wainwright.
Unne, Frank Ernest.
Wadhwa, Hans Raj.
Walker, Harold William.
Wilding, John Robert Harry.
Wilson-Dickson, William Gordon.
Wood, Thomas Lunn.
Yardley, Robert Oliver.

TRANSFERS.

Associate Member to Member.

Darling, Henry John.
Inglis, William.
Lawson, Robert Johnston.
Martinez, Giuseppe.
Radbone, Victor James.

Associate to Associate Member.

Bellhouse, Charles.

Graduate to Associate Member.

Agate, Purushottam Narayan, B.Sc.
Bullock, Percy Charles.
Clinton, James Stanley.
Davis, Basil Montefiore J.
Elliott, Harold John.
Emery, Arthur Joseph, B.Sc.(Eng.).
Frost, Albert Harry.
Garbutt, Sidney.
Geis, John Edward.
Ginno, Sidney Charles.
Gripper, Laurence Albert.
Harber, Frank Ollerenshaw.
Hodge, Gilbert Woffinton.
Hollin, Archibald Stewart.
King, Wallis Lovell.
McCollum, George.
Philpott, Stuart Fred.
Powell, Robert Desmond F.
Staygle, Edmund George.
Taylor, Edward Abraham.
Taylor, John Lishman.
Valentine, Arnot Stirling.

Student to Associate Member.

Macnee, Douglas Hamilton, B.Sc.

The President announced that, during the month of October, 42 donations and subscriptions to the Benevolent

Fund had been received, amounting in the aggregate to £103. A vote of thanks was accorded to the donors.

The President: To-night we have to thank two members for the notable additions which they propose to make to the Institution's collection of portraits in this Lecture Theatre. I shall first call upon Sir Thomas Callender to say a few words in regard to the portrait of Hopkinson.

Sir Thomas Callender: When I heard a short time ago that there were spaces on the Lecture Theatre walls which ought to be filled and that one of the portraits desired was that of my old friend John Hopkinson, I felt it incumbent on me to offer to provide it. I knew John Hopkinson for many years, both privately and in business, and I regard him as one of the great instances of a man of science being at the same time an exceedingly genial, happy and pleasant man with whom to deal. Among other pursuits he was particularly interested in mountaineering, and I have a vivid recollection of his recounting to me an adventure which he had had when mountaineering in the West of Scotland, where he missed disaster by only a few inches. I shall not endeavour to give a history of Hopkinson's achievements. The records of the Royal Society, of which he was for many years a Fellow, contain numerous descriptions of patents, lectures, and papers bearing his name and in all cases adding to his reputation. The same remark applies to the records of this Institution. As we all know, Hopkinson was a Lancashire man; he came from Manchester. Like all Manchester men, and especially those born about the same year as himself, in 1849, he was interested in engineering and music. In his early youth it was suggested that he should join his father in business, but, fortunately, those who were responsible for his education decided that he should go to Cambridge. He possessed a wonderful mind and great powers of application; he became a Double Wrangler (the first, I believe, to achieve that distinction) and won other honours, and by the time he left Cambridge he was an outstanding figure in electrical science and in engineering. Hopkinson began his practical life work in connection with lighthouse engineering, and he was responsible for important improvements therein. Later, when he devoted his life work to electrical engineering, he did more than anyone to give us the means of distributing electrical energy as light or power. He was, indeed, responsible for many vital improvements in the production of this form of energy. The subject of light provided his occupation throughout his life. We say that a man who makes two blades of grass grow where one grew before is worthy of honour; and so, also, the man who makes it possible to distribute electricity over three or four times the distance that was possible before his advent is worthy of honour: and that is only one of the things for which honour is due to Hopkinson. It has always been a source of the greatest happiness to me that I was with him at the very beginning of his work. I had some difficulty in getting an artist to undertake the task of painting this portrait; but I think that we have succeeded, as both the artist and myself have been helped by many members of this audience; and Mrs. Hopkinson herself has done immense service in that way. To her, to all those who helped me to collect the necessary data, and also to the artist, Mr. R. H. Campbell, I desire to express my thanks. I now ask the President to accept the picture for the Institution as a humble tribute to my knowledge of John Hopkinson as a very lovable man, an exceedingly great scientist, and one who did much for electrical engineering in all its branches.

Mr. W. M. Mordey: I am one of those who knew John Hopkinson fairly well, and all that has been said about his work and character I entirely endorse. He was undoubtedly a great man. With regard to the portrait, the artist, Mr. R. H. Campbell, did not know Hopkinson, but his talent and industry enabled him to make the admirable and lifelike portrait for which we now have to thank Sir Thomas Callender. Twenty years ago my last task on stepping down from the presidential chair was to receive from Mrs. Hopkinson the marble bust of John Hopkinson by Sir Hamo Thornycroft which now adorns this building. It was presented to us by Bertram Hopkinson on behalf of his mother, who was present and whom we are very glad to welcome here to-night. Bertram Hopkinson in many respects shared the gifts of his father; and on that occasion he gave a short but excellent sketch of his father's life and work. I should like to call the attention of the members, and particularly the younger members, to that sketch of his father which they will find in the *Journal.** I suggest that they should also read the memoir which Bertram Hopkinson wrote as a preface to the two volumes of his father's collected works, which were published in 1901. These two volumes contain 58 papers or addresses, all of a very high standard, and include the addresses given by Hopkinson when he was twice our President. As illustrating the value of his work I may perhaps be allowed to refer in particular to two of those papers. In 1884, Silvanus Thompson published the first edition of his book on "The Dynamo." At the end of the preface he wrote: "We want some new philosopher to do for the magnetic circuit what Dr. Ohm did for the voltaic circuit 50 years ago. Until we know the true law of the electromagnet there can be no true or complete theory of the dynamo." The "new philosopher" was John Hopkinson. I do not know to what extent, if at all, Hopkinson was led to undertake his investigations by those words of Silvanus Thompson, but the following year he read his great paper † on "The Magnetization of Iron" before the Royal Society, giving us the true law of the electromagnet; and in 1886, in another paper before the Royal Society, he and his brother Edward gave us the true law of the dynamo.‡ By those two papers the knowledge of the dynamo was raised from chaos to an orderly science. I have now formally to ask you to thank Sir Thomas Callender for the beautiful portrait which he has given us, to assure him that we accept it with gratitude and that it shall occupy a place of honour in the company of our portraits of Faraday, Kelvin, Volta and Wheatstone.

The President then called upon Mr. Ll. B. Atkinson to say a few words with regard to the portrait of Maxwell.

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* *Journal I.E.E.*, 1910, vol. 44, p. 2.

† *Proceedings of the Royal Society*, 1885, vol. 38, p. 265.

‡ "Dynamo-Electric Machinery": *Philosophical Transactions of the Royal Society*, 1886, vol. 177, p. 359.

Mr. Ll. B. Atkinson: When, three years ago, the Council decided to endeavour to decorate the Lecture Theatre with portraits of the pioneers of electrical science, the benefits of whose work are reaped by us all, I asked that I might be allowed to contribute a portrait of James Clerk Maxwell. The selection of material for a posthumous portrait is always a difficult task. There were in existence certain photographs of Clerk Maxwell, taken at various ages. Most of them were in the library at Trinity College, Cambridge, where I and the artist, Mr. R. H. Campbell, visited them and looked them over. There are two others that are of importance. Of one of them we have a copy hanging in the Common Room in this building. The other, which was selected as the more pleasing, was a side-view photograph, and the copy of it from which we worked was very kindly given to me by Sir Ambrose Fleming, who, by the great interest he has taken and the visits he has made to the studio during the progress of the work, has done much to help to produce this very successful portrait. I should like, in addition, to thank Sir Arthur Schuster, who visited the studio and helped the artist in matters of colouring and the like. Both these gentlemen knew Maxwell personally. As it is 50 years since his death, there are not many now living who really knew him during his lifetime. The object shown on the table at the side of the picture is the revolving-coil apparatus which was designed by Lord Kelvin, and with which, in 1863, at King's College, London, the first determination of the value of the ohm in electromagnetic units was made, by Maxwell himself, working with Balfour Stewart and Fleeming Jenkin. Next let me express my grateful acknowledgments to the artist, Mr. R. H. Campbell, who has, I think, made a very beautiful representation from a scanty foundation. In 1881 I was a student at evening classes under the late Professor Ayrton, and I remember that one night he referred us to Maxwell's treatise on electricity. Shortly afterwards this book came into my possession. Much of the mathematics in it is beyond my scope, but I have read it again and again, and I dare say I shall read it many more times. It was published in 1873, and had been 10 years or more in the making, for much that was fundamental in it was contained in the paper which Maxwell presented in 1864 to the Royal Society on the dynamical theory of the electromagnetic field. This is not the place to detail the profound change in thought regarding electricity and magnetism and their actions that was brought about by that paper and by his subsequent treatise. Maxwell laid down, in equations and verbally, the conditions governing the properties of the electromagnetic field in a relatively stationary medium or ether, and the principle that changes of state produced at one point in such a field were propagated like a wave to other points. Notwithstanding the immense changes in our knowledge of physics and electricity since that date, his equations, modified to cover moving media, are by common agreement accepted to-day. Of his work in colour vision, thermodynamics, the theory of gases and the viscosity of gases, only mention can be made, but in all of them his work was fundamental. As to Maxwell—the man—I quote from the " Life of Maxwell " by Lewis Campbell and William Garnett: " The leading note of Maxwell's character is a grand simplicity, and in attempting to analyse it we find a complex of qualities that exist separately in other and smaller men. Extraordinary gentleness is combined with keen penetration, wonderful activity with no less wonderful repose, personal humility and modesty with intellectual scorn. His deep reserve in common intercourse was commensurate with the fulness of his kindly outpourings for those he loved. Not less instinctive was the sense of equality in all human beings which underlay the plainness of his address, but, on the other hand, his respect for the actual order of the world and for the wisdom of the past was at least as steadfast as his faith in progress. While fearless in speculation, he was strongly conservative in practice. In his intellectual faculties there was also a balance of powers which are often opposed. His imagination was in the highest sense concrete, grasping the actual reality and not only the relation of things. No one was ever more impatient of mere abstractions. Once more, while he was continually striving to reduce to greater definiteness man's conceptions of physical laws, he seemed habitually to live in a sort of mystical communion with the infinite." I have much pleasure in asking the Institution to accept this portrait.

Sir Ambrose Fleming: By the kindness of the President I am permitted to accept, on behalf of all the members of the Institution, this portrait of James Clerk Maxwell donated to us by Mr. Atkinson. It is noteworthy that this presentation is made just two days over 50 years from the death of Maxwell at Cambridge, on the 5th November, 1879. When we remember all the immense achievements which have taken place since that date in the utilization of those electromagnetic waves which Maxwell was the first to recognize and discuss, I am sure we all feel that it was an absolute necessity for the Institution to possess some worthy representation of this great pioneer. I am probably one of very few present who knew Maxwell personally. I attended his lectures and worked under him in the Cavendish Laboratory in the last few years of his life, and I can testify to the excellence of this portrait as a likeness of Maxwell at his best. Maxwell's work was far too extensive to be referred to, even in the faintest outline, in a single speech, but I trust that it may be possible to have Maxwell Lectures established, analogous to the Kelvin Lectures which are given annually, to commemorate that great work. Maxwell was an extraordinary man, and an inspiration to all who came in contact with him. During one of the last lectures he gave at Cambridge, an American sitting next to me turned to me and said, " Sir, this man is great. He does not come here and tell us what he has read in books; he gives it to us hot from his brain." That is what he always did. I therefore, on behalf of all the members, gratefully accept this portrait from Mr. Atkinson, and assure him it will always be esteemed by us as a valuable memorial of one who was not only a great scientific investigator, but a truly great man.

The President: We accept these beautiful gifts from Sir Thomas Callender and Mr. Atkinson with the highest appreciation and the most hearty thanks; and in saying so I know that I am speaking for every individual member of this Institution.

A paper by Messrs. B. A. G. Churcher, Member, and A. J. King, Associate Member, entitled "The Analysis and Measurement of the Noise emitted by Machinery" (see page 97), was then read and discussed.

On the motion of the President a vote of thanks to the authors was carried with acclamation, and the meeting terminated at 8.15 p.m.

INSTITUTION NOTES.

Summer Meeting.

By invitation of the Committee of the Irish Centre the next Summer Meeting of the Institution will be held in Ireland from the 2nd to the 6th June, 1930. Full particulars will be circulated in due course.

National Certificates and Diplomas in Electrical Engineering (England and Wales).

The undermentioned colleges have been approved under the scheme drawn up by the Board of Education and the Institution:—

Approved for Ordinary Grade Certificates (Senior Part-time Course).

Southampton University College.

Approved for Higher Grade Certificates (Advanced Part-time Course).

Crewe Technical Institute.
Sheerness Technical Institute.
Walsall Technical College.

Prizes for Papers by Students, and Graduates up to the Age of 28.

The Council have accepted an offer from a member of the Institution to present this session a Prize (value £10), and a further Prize of a like amount next session, for the best paper submitted by a Student, or a Graduate up to the age of twenty-eight, on the subject of "The Relations between Economics and Engineering."

Papers submitted for the present session's Prize must reach the Secretary not later than the 1st May, 1930. All papers submitted must have been specially written for the purpose and must not have previously been read or published elsewhere.

It should be particularly noted that only Students of the Institution and those Graduates under 28 years of age on the 1st January, 1930, are eligible to compete.

The Council reserve the right to postpone the award and, if necessary, to open a fresh competition in the event of none of the papers submitted being sufficiently meritorious.

The Benevolent Fund.

An appeal to members to support the Fund will be found on the last page of the cover of this issue of the *Journal.*

Lead-Sheathed Cables.

By the decision of the Council the following letter has been sent to the technical Press:—

THE INSTITUTION OF ELECTRICAL ENGINEERS,
SAVOY PLACE, W.C. 2.
9th December, 1929.

DEAR SIR,

SMETHWICK FIRE DISASTER.

The attention of the Council of the Institution of Electrical Engineers has been drawn to newspaper reports of the proceedings at the inquest, which concluded on the 25th September last, upon eleven persons who lost their lives by reason of a fire at premises in Rolfe Street, Smethwick, on the 2nd September.

Some of the evidence purported to show that the fire was due to a defective electrical installation in a neighbouring building, and in this connection one of the witnesses condemned the use of lead-covered rubber-insulated cables for the wiring of public buildings. This statement has caused great uneasiness in the minds of consulting engineers, architects, electrical contractors and others, inasmuch as the use of lead-covered rubber-insulated cables is permitted by, and the proper methods of installation of such cables are set out in, the "Regulations for the Electrical Equipment of Buildings" issued by the Institution. These Regulations are recognized by consulting engineers, electrical contractors, electricity supply authorities and the Fire Offices, as representing the best standard practice, and the Fire Offices in particular recommend their use.

The Council re-affirm, therefore, that they are of the opinion that lead-sheathed cables are both suitable and safe for electrical installations if installed and maintained in accordance with the I.E.E. Wiring Regulations.

From the evidence given, as reported in the newspapers, there is every indication that the electrical installation which, it is suggested, caused the fire at Smethwick, did not comply with these Regulations.

I am, dear Sir, yours faithfully,
P. F. ROWELL,
Secretary.

Proceedings of the Wireless Section.

78th Meeting of the Wireless Section,
6th November, 1929.

Colonel Sir T. F. Purves, O.B.E., President, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 1st May, 1929, were taken as read and were confirmed and signed.

A vote of thanks to Commander J. A. Slee for his services as Chairman of the Wireless Section during the session 1928–29, proposed by Lieut.-Col. A. G. Lee, O.B.E., M.C., B.Sc., and seconded by Major B. Binyon, O.B.E., M.A., was carried with acclamation.

Captain C. E. Kennedy-Purvis, R.N., Chairman of the Wireless Section, then delivered his Address (see page 16).

A vote of thanks to Captain Kennedy-Purvis for his Address was proposed by the President and, after being put to the meeting, was carried with acclamation.

The meeting terminated at 7 p.m.

79th Meeting of the Wireless Section,
4th December, 1929.

Captain C. E. Kennedy-Purvis, R.N., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 6th November, 1929, were taken as read and were confirmed and signed.

A paper by Mr. G. Shearing, B.Sc., and Captain J. W. S. Dorling, R.N., Members, entitled "Naval Wireless Telegraph Communications," was read and discussed.

The meeting terminated at 7.55 p.m. with a vote of thanks to the authors, which was moved by the Chairman and carried with acclamation.

Proceedings of the Meter and Instrument Section.

6th Meeting of the Meter and Instrument Section,
1st November, 1929.

Colonel Sir T. F. Purves, O.B.E., President, took the chair at 7 p.m.

The minutes of the meeting of the Section held on the 5th April, 1929, were taken as read and were confirmed and signed.

The President, after announcing the constitution of the Committee for 1929–1930 (see page 84), then vacated the chair, which was taken by Mr. E. W. Hill, Chairman of the Section, who delivered an Address (see page 24).

A vote of thanks to Mr. E. W. Hill for his Address was proposed by the President and, after being put to the meeting, was carried with acclamation.

The meeting terminated at 8.45 p.m.

7th Meeting of the Meter and Instrument Section,
6th December, 1929.

Mr. E. W. Hill, Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting of the Section held on the 1st November, 1929, were taken as read and were confirmed and signed.

A paper by Dr. C. V. Drysdale, O.B.E., F.R.S.E., Member, entitled "Alternating-Current Potentiometers and their Applications," was read and discussed.

On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 8.55 p.m.

International Illumination Congress, 1931.

An International Illumination Congress, under the auspices of the International Commission on Illumination, will take place in Great Britain during the period 3rd to 13th September, 1931.

Visits will be made to places of interest in England and Scotland and papers dealing with the most varied aspects of lighting will be presented. These will be grouped so as to ensure, as far as possible, that all interests are fully covered at each local centre. The Congress will be followed by the technical meetings of the International Commission on Illumination, which will be held in Cambridge from September 13th to 19th, 1931.

Several committees are already at work on the arrangements, fuller particulars of which will be announced in due course.

The Honorary General Secretary of the Congress is Colonel C. H. Silvester Evans (c/o The Illuminating Engineering Society, 32, Victoria Street, London, S.W.1), to whom all communications should be addressed.

Representatives of the Institution on Other Bodies.

The following is a list of representatives of the Institution on other bodies, and the dates on which they were appointed:—

Bristol University:
Mr. H. F. Proctor (8 Jan., 1925).

British Cast Iron Research Association:
Mr. E. B. Wedmore (25 Sept., 1924).

British Electrical and Allied Industries Research Association:
Capt. J. M. Donaldson, M.C. (8 Nov., 1928).
Mr. P. V. Hunter, C.B.E. (19 Dec., 1929).
Mr. R. W. Paul (21 Jan., 1926).
Dr. A. H. Railing (19 Dec., 1929).
Mr. C. P. Sparks, C.B.E. (20 Nov., 1924).

Sectional Committee on Electric Control Apparatus Research:—
Major H. C. Gunton (2 Feb., 1921).
Mr. W. E. Highfield (19 Mar., 1925).

Sub-Committee on Connections to Large Gas-filled Lamps:—
Mr. C. C. Paterson, O.B.E. (24 Oct., 1929)
Mr. B. Welbourn (24 Oct., 1929).

British Electrical Development Association:
Capt. J. M. Donaldson, M.C. (4 Feb., 1926).
Mr. C. C. Paterson, O.B.E. (14 Feb., 1929).
Mr. H. T. Young (16 Feb., 1928).

Advisory Exhibition Committee:
Mr. Ll. B. Atkinson (30 Sept., 1926).

Electric Vehicle Committee :
Col. R. E. Crompton, C.B. (22 Oct., 1925).
Mr. W. R. Rawlings (22 Oct., 1925).

Sub-Committee on Constitution:
Capt. J. M. Donaldson, M.C. (4 Dec., 1925).

Sub-Committee on Rural Electrical Development :
Capt. J. M. Donaldson, M.C. (20 Oct., 1927).
Mr. R. Grierson (20 Oct., 1927).

British Engineering Standards Association :

Council :
Mr. Ll. B. Atkinson (21 Jan., 1926).
Col. R. E. Crompton, C.B. (21 Jan., 1926).
Mr. C. P. Sparks, C.B.E. (21 Jan., 1926).

Electrical Industry Committee :
Dr. W. H. Eccles, F.R.S. (17 Feb., 1927).
Lt.-Col. K. Edgcumbe, T.D., R.E.T. (Ret.) (5 Mar., 1925).
Mr. F. Gill, O.B.E. (21 May, 1914).
Mr. J. S. Highfield (21 May, 1914).
Mr. R. T. Smith (21 May, 1914).
Mr. W. B. Woodhouse (19 Dec., 1918).

Technical Committee on Electricity Meters :
Mr. C. H. W. Gerhardi (7 Nov., 1929).
Mr. S. W. Melsom (21 Jan., 1926).
Mr. G. F. Shotter (28 Feb., 1929).

Technical Committee on Electrical Accessories :
Mr. H. J. Cash (31 Mar., 1925).
Mr. F. W. Purse (31 Mar., 1925).

Technical Committee on Electrical Instruments :
Lt.-Col. K. Edgcumbe, T.D., R.E.T. (Ret.) (15 Feb., 1923).

Technical Committee on Electrical Nomenclature and Symbols :
Mr. C. C. Paterson, O.B.E. (8 Jan., 1920).

Technical Committee on Nomenclature :
Mr. A. T. Dover (21 Nov., 1929).

Technical Committee on Overhead Transmission Lines Material :
Mr. P. Rosling (5 Mar., 1925).

Technical Committee on Standardization of Wireless Apparatus and Components :
Mr. E. H. Shaughnessy, O.B.E. (30 Sept., 1925).

Sub-Committee on Conduit Fittings :
Mr. H. J. Cash (18 May, 1927).

Sub-Committee on Distribution Boards :
Mr. E. B. Hunter (25 Feb., 1927).
Mr. S. W. Melsom (25 Feb., 1927).

Sub-Committee on Low-Voltage Cut-outs :
Mr. H. J. Cash (22 June, 1926).
Mr. E. B. Hunter (25 Feb., 1927).
Mr. S. W. Melsom (25 Feb., 1927).

Sub-Committee on Mains Supply Units :
Mr. R. Grierson (31 Oct., 1928).
Mr. F. W. Purse (16 Oct., 1928).

Sub-Committee on Prime Movers for Electrical Plant :
Mr. J. Rosen (20 Oct., 1927).

Sub-Committees on Switches, Ceiling Roses, Wall-plug Sockets and Connectors for Portable Apparatus :
Mr. H. J. Cash (23 Jan., 1924).
Mr. F. W. Purse (23 Jan., 1924).

Sub-Panel on Graphical Symbols for Interior Installations :
Mr. J. R. Cowie (13 Nov., 1924).

Illumination Industry Committee :
Lt.-Col. K. Edgcumbe, T.D., R.E.T. (Ret.) (28 Feb., 1924).
Mr. P. Good (28 Feb., 1924).
Mr. H. T. Harrison (28 Feb., 1924).
Prof. J. T. MacGregor-Morris (28 Feb., 1924).
Mr. J. M. G. Trezise (19 Mar., 1925).

Technical Committee on British Standards in Colonial and Foreign Trade :
The President (*ex-officio*).

Technical Committee on Coal :
Mr. W. M. Selvey (19 Jan., 1928).

Technical Committee on Colliery Requisites :
Mr. C. T. Allan (3 July, 1924).

Glasgow Regional Committee :
Mr. F. Anslow.

Manchester Regional Committee .
Mr. W. T. Anderson.

Newcastle Regional Committee :
Mr. S. A. Simon.

Sheffield Regional Committee :
Mr. M. Wadeson.

Technical Committee on Petroleum Products :
Mr. H. W. Clothier (1 Feb., 1923).

Technical Committee on Pipe Flanges :
Mr. W. M. Selvey (14 April, 1921).

Technical Committee on Railway Signalling Apparatus :
Mr. A. F. Bound (24 Oct., 1929).

Technical Committee on Rating of Rivers :
Mr. G. K. Paton (20 Oct., 1927).

Sub-Committee on Mining Electrical Plant :
Mr. C. P. Sparks, C.B.E. (23 April, 1925).

Sub-Committee on Portable Railway Track :
Mr. R. T. Smith (25 Oct., 1928).

Sub-Committee on Rubber Belting :
Mr. C. Rodgers, O.B.E., B.Sc., B.Eng. (5 Jan., 1928).

Sub-Committee on Tubular Tramway Poles :
Mr. T. L. Horn (4 Feb., 1926).

City and Guilds of London Institute, Fellowship Committee:
Dr. W. H. Eccles, F.R.S. (19 April, 1928).

Council for the Preservation of Rural England:
Mr. J. M. Kennedy (10 Jan., 1929).

Engineering Joint Council:
Col. Sir T. F. Purves, O.B.E. (24 Oct., 1929).
Sir Archibald Page (2 Feb., 1928).

Imperial College of Science and Technology, Governing Body:
Mr. W. M. Mordey (12 April, 1923).

Imperial Minerals Resources Bureau Conference, Copper Committee:
Mr. B. Welbourn (18 Sept., 1919).

Institute of Metals, Corrosion Research Committee:
Mr. W. M. Selvey, (19 July, 1923).

Institution of Civil Engineers, Engine and Boiler Testing Committee:
Mr. R. A. Chattock (19 Oct., 1922).
Mr. C. P. Sparks, C.B.E. (19 Oct., 1922).

International Association for Testing Materials:
Mr. J. M. Kennedy (5 July, 1928).

International Illumination Commission, British National Illumination Committee:
Lt.-Col. K. Edgcumbe, T.D., R.E.T. (Ret.) (27 Nov., 1913).
Mr. P. Good (18 Sept., 1919).
Mr. H. T. Harrison (27 Nov., 1913).
Prof. J. T. MacGregor-Morris (27 Nov., 1913).
Mr. J. M. G. Trezise (19 Mar., 1925).

International Scientific Unions:
Committee on International Union in Physics:
Dr. A. Russell, F.R.S. (18 Mar., 1920).

Committee on International Union in Radio-Telegraphy:
Dr. W. H. Eccles, F.R.S. (18 Mar., 1920).
Prof. G. W. O. Howe, D.Sc. (18 Mar., 1920).
Prof. E. W. Marchant, D.Sc. (18 Mar., 1920).

Leeds Municipal Technical Library Committee:
Mr. W. B. Woodhouse (19 Dec., 1918).

Loughborough Technical College, Advisory Committee:
Mr. Ll. B. Atkinson (11 April, 1929).

Metalliferous Mining (Cornwall) School, Governing Body:
Mr. L. A. Hards (1 Dec., 1927).

Middlesbrough Technical College, Governing Body:
Mr. E. Edwards (1 Oct., 1925).
Mr. J. M. Gibson (1 Oct., 1925).

National Certificates and Diplomas in Electrical Engineering, Joint Committee (England):
Mr. W. E. Highfield (5 Jan., 1928).
Prof. E. W. Marchant, D.Sc. (5 Jan., 1928).
Mr. W. M. Selvey (5 Jan., 1926).

National Physical Laboratory, General Board:
Dr. W. H. Eccles, F.R.S. (21 Oct., 1926).
Dr. A. Russell, F.R.S. (22 Nov., 1923).

National Register of Electrical Contractors:
Col. R. E. Crompton, C.B. (18 Feb., 1926).
Mr. P. V. Hunter, C.B.E. (18 Feb., 1926).
Mr. W. R. Rawlings (18 Feb., 1926).
Mr. W. M. Selvey (18 Feb., 1927).

Professional Classes Aid Council:
Mr. P. F. Rowell (20 April, 1928).

Radio Manufacturers' Association, Committee on Battery Eliminators:
Mr. J. R. Dick, B.Sc. (3 April, 1928).

Royal Engineer Board:
Mr. W. B. Woodhouse (19 Mar., 1925).

Royal Society:
Alloys of Iron Research Committee:
Mr. J. Swinburne, F.R.S. (15 Feb., 1923).

National Committee on Physics:
Dr. A. Russell, F.R.S. (16 Dec., 1920).

National Committee on Radio-Telegraphy:
Col. A. S. Angwin, D.S.O., M.C. (7 April, 1927).
Prof. C. L. Fortescue, O.B.E., M.A. (20 Oct., 1927).

Smoke Abatement League of Great Britain:
Mr. H. C. Lamb (8 April, 1926).
Mr. S. J. Watson (8 April, 1926).

Union of Lancashire and Cheshire Institutes (Panel for Engineering):
Mr. A. P. M. Fleming, C.B.E., M.Sc. (28 Feb., 1924).
Prof. Miles Walker, D.Sc. (28 Feb., 1924).

War Office Mechanical Warfare Board:
Dr. W. H. Eccles, F.R.S. (19 Jan., 1928).

Women's Electrical Association:
Mr. A. P. M. Fleming, C.B.E., M.Sc. (18 Dec., 1924).

Women's Engineering Society:
Mr. A. P. M. Fleming, C.B.E., M.Sc. (25 Sept, 1924).

World Power Conference (British National Committee):
Mr. B. Welbourn (24 Oct., 1929).

LOW-TEMPERATURE CARBONIZATION OF FUEL, WITH SPECIAL REFERENCE TO ITS COMBINATION WITH THE PRODUCTION OF ELECTRICITY (AMERICAN PRACTICE).

By S. McEwen.

[*Paper received* 1*st October*, 1929; *read at a Joint Meeting of* The Institution *and the* Institute of Fuel 21*st November*, *and before the* Tees-Side Sub-Centre 4*th December*, 1929, *also before the* Mersey and North Wales (Liverpool) Centre 20*th January*, 1930.]

Summary.

In this paper consideration is given to the possibility that the pre-treatment of coal with recovery of by-products may secure an economic advantage in the production of electricity in the United States of America.

Reference is made to the trend of opinion in the minds of power station engineers and to the great interest which is maintained in the subject.

The economic possibilities are reviewed and stress is laid on the necessity for securing a maximum revenue from the sale of such gas as is produced by the process of pre-treatment, and it is claimed that this result can be obtained only by co-operation with public service companies supplying gas to domestic and industrial concerns.

The installation of the McEwen-Runge process at the Lakeside station of the Milwaukee Electric Railway and Light Co. is described and an account is given of its development so far as it has been continued in America, the earlier experimental work which originated in England being omitted. Particulars are given of the progress which has been made, together with an indication of the direction which future development will follow.

In America, the measure of interest in the pre-treatment of coal as a preliminary to combustion for the purpose of generating electric power is evidenced by the fact that the Prime Movers Committee have issued serial reports under the title "Distillation Products of Coal." A sub-committee was appointed to deal with this subject.

The first report was issued in July 1928, and announced that the interest of American engineers in the distillation products of coal is increasing. The report constitutes a review of the better-known processes, both of American and European origin, together with statements referring to the advance in theoretical knowledge of the subject. The general position was summed up in the following statement:—

"There have been no startling developments in any of the processes during the past year. Steady progress has been made in the commercialization of certain of these processes and these advances are being closely followed by interested engineers."

A year later, in June 1929, a further serial report was issued wherein the developments of the past year were reviewed. The following are extracts from that report:—

"From the purely commercial standpoint, for conditions in this country it appears that no process has as yet proved itself in practice, particularly for use in connection with steam power plants. It is, of course, such a development that most interests the engineer entrusted with the design of power plants in his search for the process making the highest economic use of fuel.

"Power plant engineers in this country centre their interest on the McEwen-Runge plant installed at Milwaukee."

In view of this statement by the Prime Movers Committee, no apology need be offered for dealing in this paper primarily with the McEwen-Runge process. Before proceeding to describe this process and giving an account of the progress which has been made in its development, it is desirable that the economic possibilities in connection with the pre-treatment of coal should be realized and the conditions which are essential for commercial success should be clearly understood. It is not merely sufficient to achieve a technical success, for a process which is both technically and commercially successful when applied to the pre-treatment of coal with domestic fuel as one of the products might not be commercially successful if the solid fuel were utilized for power production instead of for domestic purposes. Fuel for the latter purpose can be sold at a high price, generally very much higher per unit of weight than that of the coal from which it was produced, but the power station engineer of to-day is only concerned with heat units; he is not so much concerned with the physical condition in which the fuel is supplied to him. He has methods at his disposal which will enable him to convert an equally high percentage of those heat units into electrical energy whether the fuel is in the form of powder, grains or lumps. The pre-treatment of coal with a recovery of by-products, which is to be followed by the combustion of the solid residue, is not favoured by any appreciation in the value of the solid residue; the latter has to be sold to the power producer at a price per heat unit which is equivalent to the price of a heat unit in the raw coal. The revenue obtained from the sale of the liquid and gaseous by-products has to pay the whole cost of pre-treatment and, after an allowance for the loss of weight of the solid residue as compared with the original coal, provide an adequate profit to warrant the undertaking. It is for this reason that a low-temperature process operated in conjunction with a plant for electric power generation has a much smaller margin for profit than is the case with low-temperature processes which yield, as one of the main products, a high-grade domestic fuel. To secure an equivalent profit it is essential that the pre-treatment plant for use in conjunction with a power plant be cheaper to operate, have a lower capital cost and secure the maximum possible revenue from all of the by-products. These conditions involve the production of gas which can be sold for town supply, because conditions in America indicate that should the gas be burned under the boilers and the B.Th.U. in that gas be credited to the carbonization plant at a rate per B.Th.U. slightly above that of the original coal, the pre-treatment process would be handicapped to the point of economic failure. This conclusion points to the necessity for a working alliance between the electric power producer and the town gas distributor.

It may be said that it is not necessary to develop a low-temperature carbonization process in order to give effect to an alliance between electric power and town gas undertakings, and it is possibly doubtful whether so much interest would have been taken by power station engineers in low-temperature carbonization were it not for the fact that the coke produced by high-temperature processes is not favoured by power station engineers as a fuel. The justification for the development of low-temperature carbonization in this connection lies in the fact that semi-coke is an ideal fuel for combustion, while the net revenue from the by-products of a low-temperature process promises to be greater than that from the by-products of a high-temperature process.

Many investigations have been made from time to time for the purpose of determining whether the cost of generating a unit of electric power can be reduced by pre-treating coal, and perhaps one of the most interesting studies which has been made available through the technical Press is that embodied in the report which was made to the E. L. Phillips Co. of New York, a summary of which has been published* by W. R. Knapp and P. McMichael. Eight studies were made of different combinations to show the possibility of obtaining cheaper power by pre-treating coal. These studies cover combinations of a power station with standard coke-oven plants and with complete gasification plants, showing the cost of power when the various products are either consumed as fuel for power production or sold for public service. The study purports to include low-temperature carbonization as one of the possible combinations alternative to high-temperature carbonization, but the application of the low-temperature system is contrary to the best practice and, therefore, has little significance. The report, however, is of great value in showing the importance of securing a good revenue for the sale of gas to ensure a profitable combination of pre-treatment and power generation. Very definite information of costs, yields and revenue from high-temperature coke-oven plants was available to Messrs. Knapp and McMichael, this being an established industry, whereas no similar information regarding the low-temperature carbonization industry was available. The most profitable combination is shown in Table 1.

TABLE 1.

	Steam generated with	
	Pulverized low-grade coal	Pulverized coke and breeze (Total oven gas sold)
Capital investment:—	$	$
Power plant	17 073 000	17 073 000
Gas plant	—	5 607 000
Total	$17 073 000	$22 680 000
Cost per kWh produced:—	mills	mills
Operation: labour, maintenance and supplies ..	0·595	1·460
Interest and depletion ..	0·048	0·149
Fixed charges, 15 per cent	3·248	4·315
Coal	1·324	2·221
Total operation expense	5·215	8·145
Revenue from by-products	—	3·669
Net operation expense..	5·215	4·476
Change in cost of power ..	—	+ 0·739
Additional investment:—		$
Gross amount	—	5 607 000
Change in cost of power ..	—	+ 582 927
Return on additional investment	—	per cent 10·38

Table 1 shows that it is profitable to combine pre-treatment of coal with power generation, but the figures are based upon the assumption that high-temperature oven coke can be efficiently burned under the boilers in the power station, and it is also assumed that the coal to be carbonized in coke ovens would have to be of a higher grade and more costly than the low-grade coal suitable for direct firing under the boilers. Without referring more specifically to studies of the various combinations, it may be said that Table 1 clearly shows that there is either absence of profit or considerable loss unless the whole of the gas made is sold for town supply.

The important position which the revenue from the sale of gas occupies in the economics of pre-treatment may be realized if the revenue from by-products is analysed per ton of coal treated, which is possible with the aid of the data given in the published summary by Messrs. Knapp and McMichael.

TABLE 2.

Costs		Revenue	
	$		$
Coal	2·650	Coke and breeze	1·805
Operation, including labour, supplies, heating and maintenance ..	1·356	Tar	0·600
Capital and overhead charges ..	1·600	Gas	3·600
		Light oil ..	0·300
		Ammonium sulphate ..	0·375
Total costs ..	$5·606	Total revenue	$6·680

Net profit per ton of coal treated = $1·07.

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* *Power*, 1929, vol. 69, p. 665.

The revenue from the sale of gas is seen to be $3·60 for each ton of coal treated, a figure in excess of the original cost of the coal per ton, and it is based upon a selling price for the gas of 30 cents per 1 000 cubic ft. of 530-B.Th.U. gas. If this gas were burned under the boilers it would have a value per B.Th.U. only slightly above that of 1 B.Th.U. in coal and the revenue would be reduced from $3·6 to $0·6, and the profit of $1·07 per ton would be converted into a loss of nearly $2 per ton.

Since it has been clearly established that in America a very high revenue can be secured by the disposal of gas for public service, it would follow that the ideal pre-treatment process would be one yielding the maximum quantity of saleable gas, unless it could be established that a reduction in the quantity of gas produced was accompanied by an improvement in the quality of other products with a proportionately greater revenue therefrom. If a yield of the maximum quantity of gas under high-temperature conditions results in the production of a solid residue of little value to the power station engineer, then the pre-treatment process must be varied to yield a residue which will be acceptable to him. It is also important to establish the relative value of gas and low-temperature tar, since one of the characteristics of a low-temperature system is a high yield of liquid by-products at the expense of gas. For a study of these relative values it is convenient to set out the realizable value of the various products in cents per 100 000 B.Th.U.

Dealing first with high-temperature carbonization, and using the figures reported by Messrs. Knapp and McMichael, we find the revenue per 100 000 B.Th.U. from each product to be as given in Table 3.

TABLE 3.

Product	Price and particulars	Revenue per 100 000 B.Th.U.
		cents
Coal ..	$2·65 per ton (13 900 B.Th.U. per lb.)	0·9
Coke ..	$2·37 per ton (13 170 B.Th.U. per lb.)	0·9
Tar ..	6 cents per gal. of 8 lb.	4·42
Gas ..	30 cents per 1 000 cub. ft. (530 B.Th.U. per cub. ft.)	5·66
Light oil..	10 cents per gal. of 6½ lb.	7·7

It is customarily claimed for a low-temperature process that the high yield of liquid by-products more than compensates for the low yield of gas, but, if this claim is to be justified, then the realizable value of the tar per 100 000 B.Th.U. must be sufficiently higher than that secured by high-temperature tar to make it equal to the value of gas and, in addition, to compensate for the volatile matter allowed to remain in the semi-coke which brings a low rate of revenue.

For tar to secure the same revenue as gas per 100 000 B.Th.U. it must realize at least 7·7 cents per American gallon, and a higher revenue than this must be obtained if compensation has to be made for the unextracted volatile matter.

It is not difficult to show that low-temperature tar can be made to realize a much higher figure than the 7·7 cents per gallon just referred to. The treatment of this tar by processes known to-day in America will result in the sale of water-white tar acids, solvent naphtha and neutral oils, but this raises the important question as to whether the power station engineer, working possibly in conjunction with a gas-distribution company, will consider it proper to include in his equipment a refinery for the production of marketable products from tar. If the refining profits be included in the revenue for tar, there is no question whatever that a high price may be established for the tar. If, however, it be deemed that the refining of tar should be the business of a chemical company separate and apart from power or gas station, then the gross trading profit of the refinery has to be subject to overhead charges and profit which will reduce the net value ex the carbonizing works by as much as 20 to 25 per cent.

TABLE 4.

Product	Amount and price	Revenue
		$
Gas ..	8 000 cub. ft. of 530-B.Th.U. gas at 30 cents per 1 000 cub. ft.	2·40
Tar ..	24 gal. at 8 cents per gal.	1·92
Light oil..	2·75 gal. at 10 cents per gal.	0·27
Coke ..	1 430 lb. at a price per B.Th.U. equivalent to that of the coal	1·73
	Total	$6·32

Even on the assumption that the refining profits are not to be credited to the power plant, it has been established in America that the net value at the carbonizing plant is in excess of 8 cents per gallon.

The low-temperature gas produced has a high heating value of approximately 830 B.Th.U. per cub. ft. and, therefore, to make town gas of 530 B.Th.U. per cubic ft. it is necessary to blend with this rich gas some diluent gas produced from the original coal, resulting in the production of a larger volume of the lower-grade gas per ton of coal treated.

The revenue from the pre-treatment of coal by low-temperature carbonization may therefore be set out to compare with the revenue from high-temperature carbonization, the latter based on the data given by Messrs. Knapp and McMichael. In Table 4 it is assumed that a certain part of a ton of coal is gasified to make water-gas to serve as a diluent for the rich low-temperature gas.

Table 4 gives particulars of the revenue from pre-treatment by low-temperature carbonization.

Comparing Table 4 with Table 3, it will be seen that the total revenue is 36 cents lower, a difference which is accounted for by the fact that with low-temperature carbonization no revenue is obtained from the sale of ammonium sulphate. With the prices now ruling for ammonium sulphate it is doubtful whether the revenue from this source is not practically balanced by the cost of recovery.

By low-temperature carbonization, therefore, it is possible to secure a net revenue for by-products at least equal to that of high-temperature carbonization and, further, to produce a solid fuel which would not only be acceptable to the power station engineer but would be preferred to raw coal for the reason that it is more readily combustible and can be burned at a greater rate per unit of combustion space with higher combustion efficiency.

One other possibility in favour of low-temperature carbonization is that of operating and capital costs being reduced as compared with those of a high-temperature system.

In designing and developing the McEwen-Runge process, the objective aimed at was a system which would have a very high capacity per unit, could be constructed cheaply, and could be operated with a minimum of labour. It was further decided that it would be necessary to produce town gas for sale.

The McEwen-Runge process has been described in various publications, but for the sake of clarity it may be well to repeat here some of its essentials. The process consists in carbonizing pulverized bituminous coal while that coal is in suspension in a hot gas. In practice the pulverized coal from the ordinary preparation plant of a pulverized-fuel-fired power station is intercepted on its path from the preparation house to the boiler house and is allowed to fall by gravity in a shower through a vertical tower up which heated gases rise, so that there is an exchange of heat from the gases to the coal, with the result that carbonization is effected. By this system it is possible to reduce the time normally required for carbonization from hours to seconds, making it possible to secure very high capacity from a relatively small plant. The resultant carbonized residue, being still in a finely-divided condition, is available for supply to the boilers, where it can be burned as pulverized fuel

One of the problems encountered at the outset was to devise a method of treatment on the lines just indicated which would result in the production of a final permanent gas rich enough to be suitable for town supply. It was known that if products of combustion were utilized as the heating medium and the coal were raised from atmospheric temperature to the carbonizing temperature with the unaided use of hot products of combustion, the resultant permanent gas would have a very low calorific value and would be useless except to be burned in furnaces.

As a result of extensive investigation and the preparation of a large number of heat balances, it was found to be theoretically possible to produce a permanent gas rich enough for town supply by including in the system pre-heating of the coal prior to carbonization, and by the introduction of heat exchangers which would serve to extract the sensible heat from the semi-coke and utilize the heat so extracted in the process of carbonization.

The plan substantially was to pre-heat the coal while in suspension in a vertical retort to a temperature of about 500° F., at which temperature it was assumed no valuable by-products would be lost and the coal would be merely affected to the extent of the removal of a certain amount of combined water and carbon dioxide. The pulverized coal at a temperature of 500° F. would then have to be raised, in the carbonization retort proper, to a temperature of 1 000° F. It was believed that the heat required to raise 1 lb. of coal through the first 500 degrees F. would be greater than that required to heat it through the second stage of 500 degrees, as the earlier stage was likely to be endothermic while the latter stage would be slightly exothermic. The reduction in the temperature of the hot semi-coke from 1 000° F. to about 300 or 400° F. provided, by means of the exchanger, a quantity of heated gas which had to be boosted in temperature by a fresh source of heat to provide the gaseous heating medium for carbonization.

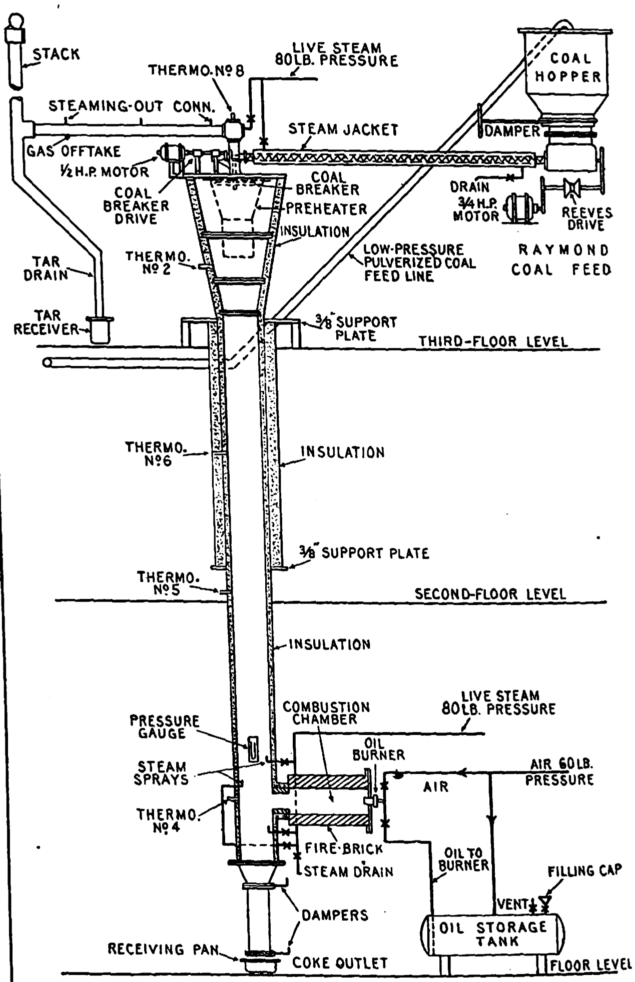
STACK
THERMO. Nº 8
LIVE STEAM 80LB. PRESSURE
COAL HOPPER
STEAMING-OUT CONN.
STEAM JACKET
DAMPER
GAS OFFTAKE
½ H.P. MOTOR
COAL BREAKER DRIVE
COAL BREAKER
PREHEATER
INSULATION
DRAIN
¾ H.P. MOTOR
REEVES DRIVE
TAR DRAIN
THERMO. Nº 2
LOW-PRESSURE PULVERIZED COAL FEED LINE
RAYMOND COAL FEED
TAR RECEIVER
⅜" SUPPORT PLATE
THIRD-FLOOR LEVEL
THERMO. Nº 6
INSULATION
⅜" SUPPORT PLATE
THERMO. Nº 5
SECOND-FLOOR LEVEL
INSULATION
COMBUSTION CHAMBER
LIVE STEAM 80LB. PRESSURE
PRESSURE GAUGE
OIL BURNER
STEAM SPRAYS
AIR
AIR 60LB. PRESSURE
THERMO. Nº 4
FIRE-BRICK
STEAM DRAIN
OIL TO BURNER
FILLING CAP
DAMPERS
VENT
OIL STORAGE TANK
RECEIVING PAN
COKE OUTLET
FLOOR LEVEL

FIG. 1.—General arrangement of experimental retort.

These possibilities having been established by calculations, it was then necessary to establish them by practical trial.

The first stage of the development was to determine that pulverized fuel could be carbonized by allowing it to fall in suspension through a vertical retort, and to obtain some data as to the rate of carbonization and the space which had to be provided for a given capacity. The first retort to be built is shown in Fig. 1. This retort was 30 ft. in height and 1 ft. in diameter and was operated over a period of several months, and it was established that pulverized coal could be efficiently carbonized at the rate of 200 lb. per hour. It served to prove that there need be no fear of the coal adhering to the sides of the retort to such an extent as would interfere with satisfactory commercial operation and, further, it demonstrated that the resultant semi-coke was in a condition suitable for direct firing in a furnace equipped for the combustion of pulverized fuel. It also provided sufficient evidence that the gases leaving the retort did not contain any excessive quantity of dust. In other words, it established the fact that it was possible to adopt this method of carbonizing pulverized fuel in suspension without any prohibitive loss in the form of dust, and that it should be possible to recover the condensable liquid by-products free from such dust as would impair their commercial value.

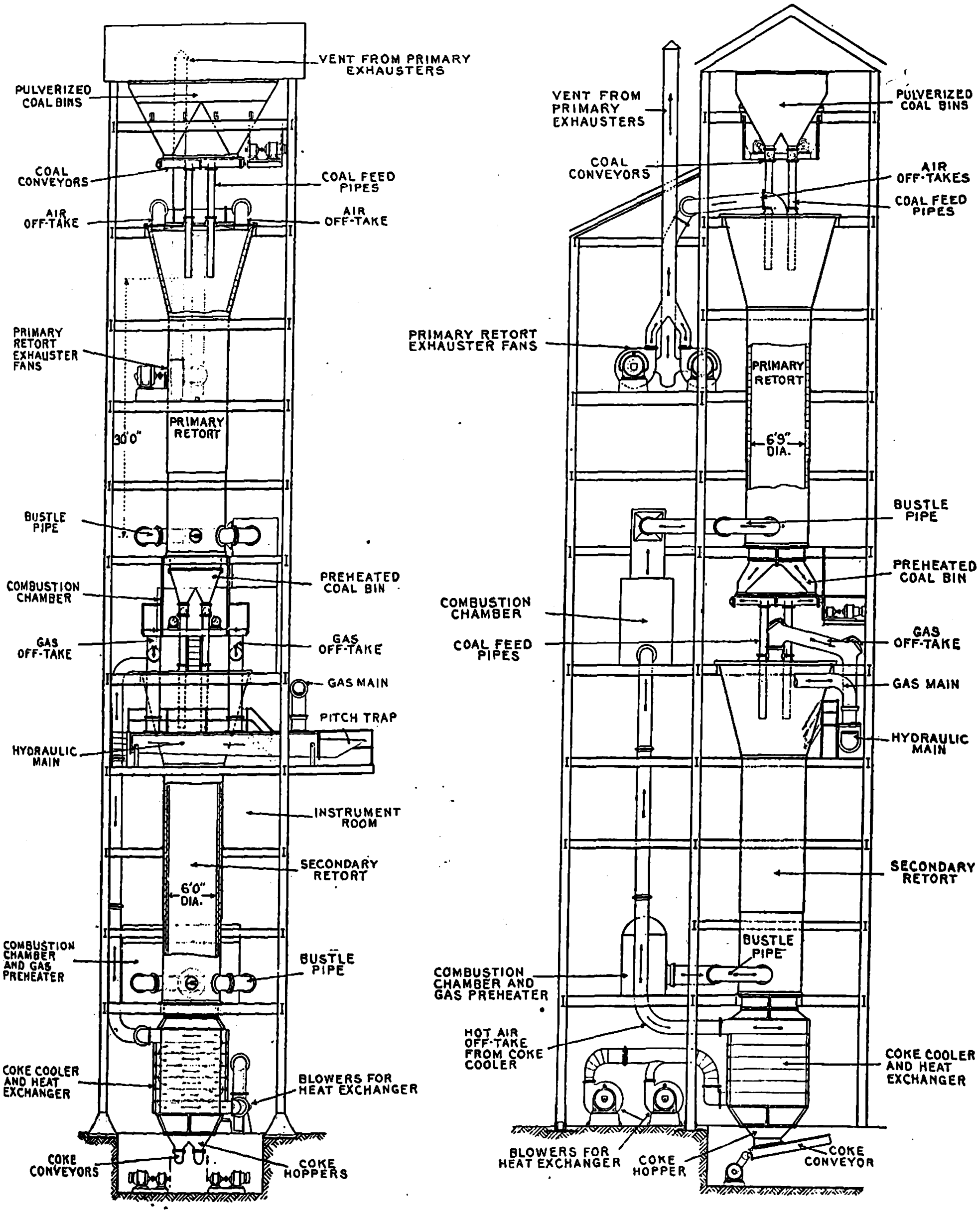
VENT FROM PRIMARY EXHAUSTERS
PULVERIZED COAL BINS
COAL CONVEYORS
COAL FEED PIPES
AIR OFF-TAKE
AIR OFF-TAKE
PRIMARY RETORT EXHAUSTER FANS
PRIMARY RETORT
30'0"
BUSTLE PIPE
COMBUSTION CHAMBER
PREHEATED COAL BIN
GAS OFF-TAKE
GAS OFF-TAKE
GAS MAIN
PITCH TRAP
HYDRAULIC MAIN
INSTRUMENT ROOM
SECONDARY RETORT
6'0" DIA.
COMBUSTION CHAMBER AND GAS PREHEATER
BUSTLE PIPE
COKE COOLER AND HEAT EXCHANGER
BLOWERS FOR HEAT EXCHANGER
COKE CONVEYORS
COKE HOPPERS
VENT FROM PRIMARY EXHAUSTERS
PULVERIZED COAL BINS
COAL CONVEYORS
AIR OFF-TAKES
COAL FEED PIPES
PRIMARY RETORT EXHAUSTER FANS
PRIMARY RETORT
6'9" DIA.
BUSTLE PIPE
PREHEATED COAL BIN
COMBUSTION CHAMBER
COAL FEED PIPES
GAS OFF-TAKE
GAS MAIN
HYDRAULIC MAIN
SECONDARY RETORT
BUSTLE PIPE
COMBUSTION CHAMBER AND GAS PREHEATER
HOT AIR OFF-TAKE FROM COKE COOLER
COKE COOLER AND HEAT EXCHANGER
BLOWERS FOR HEAT EXCHANGER
COKE HOPPER
COKE CONVEYOR

FIG. 2.—Arrangement of full-size retort.

The next stage in the development was to design and construct a large-scale commercial plant which, based on the factors established with the small plant, should be capable of carbonizing 200 tons of coal per day. The arrangement ultimately installed is shown in Fig. 2. It included an upper retort for the pre-heating of the pulverized coal to a temperature of 500° F. and a secondary or carbonizing retort which would raise the coal to 1 000° F., and below the secondary retort a heat exchanger which would serve to cool the coke and enable the sensible heat recovered to be returned to the system. The whole equipment was designed to be entirely automatic; the whole of the feeders, the temperature regulators and all other controls were centred in an instrument room so that one man could attend to the complete sequence of operations. The pulverized semi-coke from the heat exchanger was delivered to a pump and thence transported to the boiler house.

As might have been anticipated and, as is invariably the case in the development of all processes embodying some hitherto untried methods, a number of difficulties were encountered. In the first place it was found that the pre-heating of the coal to a temperature approximating to that desired resulted in the loss of valuable volatile matter. This required a great deal of investigation and a great deal of attention was devoted to this first stage of the process. The results are fully described in a paper read by Dr. Soule before the American Society of Mechanical Engineers in February 1928. The composition of the gaseous heating medium was varied over a fairly wide range. Gases containing different percentages of free oxygen were used, also gases which were neutral and contained no oxygen. It was finally concluded, however, that it would not be economic to heat the coal above 350° F., as beyond that temperature the loss of valuable volatile matter was greater than any benefit which could be derived from pre-heating.

Another difficulty which was encountered related to the operation of the heat exchanger, the object of which was to recover the sensible heat from the semi-coke. The heat exchanger originally designed became choked and, owing to the existence of a number of leaks difficult to detect and isolate, air was admitted which resulted in local combustion with the rapid destruction of the pre-heater elements. A very large number of changes were made until the engineers were driven to the conclusion that the cooling of the semi-coke was in itself a sufficiently difficult problem to solve without the added difficulty of endeavouring to recover the sensible heat from the coke. Ultimately, but not until after the expenditure of long and sustained effort, coke coolers were installed in which the cooling medium was water and the whole of the sensible heat of the coke was dissipated. It was found that unless the semi-coke was thoroughly cooled the problem of transporting it to the boiler-house bunkers was too great for practical solution.

Finally, therefore, the process was simplified in order to maintain continuous operation and obtain commercial results which would more clearly indicate the next stage of development. The two retorts were united and made into one. An independent coke cooler was installed in which water was the cooling medium, and by this means it was found possible to operate the plant over a long period and to transport pulverized coal continuously to the boiler house, where it was consumed in the boilers. It became clear from this operation that, while the semi-coke prepared in the manner described constituted an ideal fuel for the boiler house, permitting an increased rate of combustion per cub. ft. of combustion space and giving a high combustion efficiency, the permanent gas made was of too low a calorific value to be useful for public service. The actual value of the gas manufactured reached 275 to 300 B.Th.U. per cub. ft.

The following analyses and tests may be of interest.

Analysis of coal :—

Moisture	0·75 per cent
Volatile matter	31·55 ,,
Fixed carbon	60·60 ,,
Ash	7·10 ,,
Calorific value	14 039 B.Th.U. per lb.

Sizing test on coal :—

Through 200 mesh ..	65·30 per cent
,, 100 ,, ..	83·50 ,,
,, 48 ,, ..	97·97 ,,
,, 28 ,, ..	99·3 ,,
,, 20 ,, ..	100·0 ,,

Analysis of semi-coke :—

Volatile matter	12·0 per cent
Ash	10·3 ,,
Calorific value	13 800 B.Th.U. per lb.

Sizing test on semi-coke :—

Through 200 mesh ..	50·0 per cent
,, 100 ,, ..	62·0 ,,
,, 48 ,, ..	73·8 ,,
,, 20 ,, ..	91·0 ,,
,, 10 ,, ..	98·4 ,,

Analysis of gas :—

CO_2	6·6 per cent
O_2	0·2 ,,
Illuminants	3·2 ,,
H_2	13·8 ,,
CO	6·4 ,,
C_2H_6	0·7 ,,
CH_4	12·4 ,,
N_2	56·7 ,,
Calorific value	279 B.Th.U. per cub. ft.

Having solved the engineering problems of showering the coal continuously through a vertical retort at a rate which gave the full estimated capacity of the retort, namely, 200 tons per day; having also solved the problem of cooling the hot semi-coke and having established that the semi-coke dust was an ideal fuel for combustion, it then became necessary to select the best method for increasing the calorific value of the gas and making it suitable for town supply.

Here it may be mentioned that the McEwen-Runge plant which was installed at the Lakeside station of the Milwaukee Electric Railway and Light Co. was in a favourable position to dispose of its gas, since the Lakeside installation was under the control of the North American company which also owned a gas works in the near neighbourhood, and it was the intention to supply gas in bulk from this McEwen-Runge plant had its quality been as suitable as was anticipated. As a result of the practical experience gained at Milwaukee and resulting from conversations with those in charge of the gas works, it became apparent that even had the plant functioned in accordance with the original plan and gas of the desired calorific value been obtained, the gas would still have been of doubtful value owing to its high specific gravity due to the large percentage of inert gas which it would have contained. It was necessary, therefore, to reconsider the whole problem of the composition of the gaseous heating medium, so that it would be possible to produce a gas not only rich enough as regards calorific value, but also one of a specific gravity which complied with the normal requirements of a public service company.

It was foreseen that this result was not beyond the bounds of possibility, since a very rich gas could be made by utilizing superheated steam as the heating medium. Alternatively, pre-heated blue water-gas could be utilized with or without the admixture of superheated steam. Other combinations have presented themselves and preparations are now in hand for the last stage of development, which is to secure a standard gas for public service.

There are one or two factors in connection with the pre-treatment of coal in conjunction with power generation which may be mentioned. It has been said that a pre-treatment plant should be capable of being operated at a varying capacity to suit the hourly demand for power, or alternatively that pre-treatment plant could only be applied to a base-load power station. This, however, is scarcely the case, since the pre-treatment plant can be operated at a uniform capacity per day of 24 hours, variations in demand for power being provided for by adequate storage bunkers for the pulverized semi-coke. This semi-coke can be stored indefinitely and is unlike pulverized raw coal in this respect. The variation in demand for town gas, which follows very closely the variation in demand for electricity, can also be provided for by adequate holder capacity. Seasonal variations can, of course, always be allowed for by having a sufficient number of units in the pre-treatment plant, one or more of which can be put out of commission during the season of light load.

It is an interesting fact that at the present time, in the large American towns, the demand for gas and the demand for electric power bear such a relation to each other that the demands are met by the yields of gas and power which it is possible to obtain by the pre-treatment of coal.

[The discussion on this paper will be found on page 229.]

LOW-TEMPERATURE CARBONIZATION OF FUEL, WITH SPECIAL REFERENCE TO ITS COMBINATION WITH THE PRODUCTION OF ELECTRICITY (GERMAN PRACTICE).

By Prof. P. Rosin, Dr.Ing.

(*Paper received* 12*th October*, 1929, *and read at a Joint Meeting of* THE INSTITUTION *and the* INSTITUTE OF FUEL, 21*st November*, 1929.)

SUMMARY.

The paper deals with the economics of the production of power and valuable by-products from brown coal, which is very plentiful in Germany but has an extremely low calorific value.

Germany's coal industry is characterized by the competition between two different fuels, namely, pit coal and brown coal. The pit coal is similar to that in England in its technical qualities, whilst brown coal represents a very inferior coal until it has been treated in order to improve its quality. It contains from 50 to 60 per cent of water and 3 to 10 per cent of ash, and its calorific value is only about 1 800 to 2 500 kg-cal. per kg. On the other hand, brown coal can be obtained so cheaply from very large open workings that its cost per calorie at the mine is much lower than that of pit coal. On account of its high water-content the transport of raw brown coal to any distance is uneconomic. Before it can be transported, therefore, it must be dried and converted into briquettes containing about 15 per cent of water. On the other hand, the transport of pit coal over long distances is rendered possible owing to low railway tariffs and favourably situated water-highways. For these reasons the production of electricity in Germany proceeds along two different lines. First there are the pit-coal power stations in the coal-bearing areas themselves, and in all those districts where no other economic fuel is available, that is, at the collieries and in most of the municipal electricity works. Secondly there are the brown-coal power stations in the immediate vicinity of the large open workings. The latter are being developed into very large power houses under Government or industrial control for overland distribution. As most of the German power houses have to operate with cooling towers, and as there are enough small rivers and streams in the neighbourhood of the brown-coal districts to supply a sufficient quantity of water, the main consideration in the planning of steam power works is the transport of fuel and electricity. On account of the low cost of production of brown coal, the power works using this fuel have in recent years gained a considerable advantage over those dependent upon pit coal. Whilst only 23 per cent of the electricity produced in Germany during 1914 in public electricity works was generated from brown coal, this percentage had increased in 1922 to 41 per cent and at the present day is probably over 60 per cent.

In 1913 the total energy production of public electricity works in Germany was only about 2 200 million kWh. This figure had, however, increased in 1927 to 12 400 millions, and in 1928 showed a further increase to a total of approximately 14 500 millions.* A similar amount of electrical energy is being produced each year in the industrial power plants, so that the total production in Germany this year will probably exceed 30 000 million kWh. This corresponds to about 500 kWh per head of the population. Of the 30 000 million kWh referred to, the public and industrial brown-coal stations produced about 10 000 millions, and for this purpose consumed from 25 to 30 million tons of brown coal. The six most important German electricity works using brown coal produced some 6 000 million kWh per annum, the plant installed in these works being of 2 050 000 kW capacity and consuming from 18 to 20 million tons of raw brown coal. This development will still further increase, for the tendency in Germany, as in England and America, is to concentrate production in large super-power stations having a high load factor and consequent low cost of production. Although the production of brown coal already amounts to 170 million tons a year, brown coal will still be available in Germany for several hundred years as a cheap fuel, whilst the cost of mining pit coal will probably become greater on account of the increasing depth from which it must be obtained, and the fact that underground working is becoming more expensive.

Although coal is plentiful in Germany the country is entirely devoid of natural oils, so that the study of low-temperature carbonization is of as much interest to Germany as it is to England. Dr. Heinze submitted to the Fuel Conference held in connection with the World Power Conference (1928) in London, a report† on the position of the German low-temperature carbonization processes. Although a year has passed since the publication of this report it is still quite up to date, as no new processes have been developed in the meantime. On the other hand, many very valuable technical and economic data have been collected during the last year in connection with the subject, owing to experience having been obtained from the operation of the new large brown-coal low-temperature carbonization plants which, having attained full production, are, taken together, now treating about 3 000 tons of raw brown coal per day, and the first really large low-temperature plant in the world has started in Wölfersheim. The data now available from these plants therefore enables the author to set out the German views and opinions of the relations between low-temperature carbonization and the production of electricity, as well as to forecast probable further developments.

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* PEUCKER: "The Use of Brown Coal in German Public Electricity Works," *Braunkohle*, 1929, p. 572.

† HEINZE: "The Present State of Low-Temperature Carbonization in Germany," *Transactions of the Fuel Conference*, 1928, vol. 3, p. 1015.

The appreciation of low-temperature carbonization as an economic factor has undergone a considerable change in the course of the last few years. It was originally intended as a means of producing oil, low-temperature tar being the main product, whilst the semi-coke and gas were regarded as by-products. This view has undergone a complete change on account of the many disappointments and economic failures of low-temperature processes using German coal. German pit coal does certainly not contain sufficient tar for its sale alone to cover the cost of carbonization, and the author believes that this is true for all countries except in connection with Cannel coal, which is, however, only found in small quantities. The profit on the low-temperature carbonization of pit coal must therefore be derived from the sale of semi-coke. Besides being a smokeless lump fuel, it sells as artificial anthracite for domestic purposes at much higher prices than those obtained for raw coal. The economic basis of the low-temperature carbonization of pit coal in Germany is therefore the production of such semi-coke of high value from cheap slacks, and resolves itself into a question of the difference in value between the original coal and the smokeless lump semi-coke made from it, the calorific values of both being approximately alike. The value of the tar obtained from the low-temperature carbonization of pit coal, for which the price under most favourable conditions will not be higher than that of fuel oil or Diesel oil, is generally not sufficient to cover the capital charges and working expenses of the carbonization plant, and consequently the economic utilization of the gaseous products of distillation, which were formerly almost entirely neglected, is now attracting considerable attention. As it has a very high calorific value this gas should be a welcome contribution to the public gas supply, but up to now its utilization has not assumed any practical significance in Germany. It will be seen, therefore, that the production of oil from pit coal is now a secondary consideration, the main product being semi-coke for domestic purposes, with tar and gas as by-products. It is, however, considered that the gas will, in the near future, be looked upon as being of greater importance than the oil. The type of pit coal most suitable for low-temperature carbonization is therefore principally small coking coal containing over 6 per cent of tar, the caking characteristics being such as to enable lump semi-coke to be produced. Ranking far behind this comes the fine-grained non-coking pit coal, the tar percentage of which would have to be so high as to guarantee a profit by itself, as with this class of fuel the carbonization process improves neither the size nor the calorific value. However, this class of coal exists in Germany in small quantities only, but there are other classes of pit coal, also very limited in quantity, which, containing much ash, make a very poor fuel in the crude state, but which can be improved as regards their combustion properties by low-temperature carbonization.

As already explained by the author last year at the Fuel Conference in connection with the World Power Conference in London,* the co-ordination between low-temperature distillation and the production of electricity is only remunerative, generally speaking, if, on account of the revenue derived from carbonization, the cost per unit becomes less than when the most reasonably priced fuel which the electricity works concerned can purchase is used. This means that the initial cost of the complete combustion plant must be so low that the semi-coke burnt under the power station boilers will be cheaper than any other competitive fuel which the power works could use. A power station will never pay the same price for semi-coke as will the domestic market, and it does not necessarily require a large smokeless fuel, as it can produce current at a lower cost and in a perfectly simple manner from fine-grained raw coal, and could probably purchase and use those classes of coal which are unsuitable for low-temperature carbonization at a price lower than that which the carbonizing plants would have to pay for their supplies. An electric power station combined with a carbonization plant using pit coal can therefore only be considered economic if a non-coking coal contains so much tar and gas that its sale would cover all the capital charges and working expenses of carbonization, besides leaving an adequate profit without any increase in the fuel costs to the boilers. Hitherto such pit coal has not been found in Germany, and for that reason German pit-coal carbonization power stations cannot be operated on a remunerative basis until the initial costs of the carbonizing plant have been reduced to a fraction of those obtaining at present, or until totally different price conditions obtain in the oil market.

The low-temperature carbonization of pit coal in Germany is at present only possible for the production of semi-coke for domestic purposes, and the only progress made last year in this connection is the extension of the carbonizing plant at the Mathias Stinnes Colliery at Karnap, where two additional carbonization retorts have been added to the one originally installed, so that the whole plant now deals with a daily through-put of from 250 to 300 tons. This, the only large plant working economically in Germany, operates on the K.S.G. (Kohlenscheidungs-Gesellschaft) system, similar plants having also been erected, or being in course of construction, in England and America, so that it is not necessary to deal with details of them in this paper.

The independent pit-coal carbonization plants known to the author cost on an average £250 per daily ton of raw coal through-put, one ton yielding about 16 cwt. of semi-coke, the calorific value of which is approximately 7 000 kg-cal. per kg. If the power station operates with the highest fuel economy, 1 kg of semi-coke will at most produce 2 kWh, corresponding to 1 600 kWh per ton of carbonization coal. The installation of a carbonization plant in connection with a power station therefore means an increased capital cost of at least £3 5s. per kW installed, but in most cases even more. The whole of the charges due to this extra capital cost, together with the working expenses, would have to be covered by the profit derived from the tar and gas. For this reason all the important projects relating to low-temperature carbonization power stations using pit coal in Germany have had to be postponed, as they offer no prospect of remunerative operation at present, and only in special cases could non-independent carbonization plants directly connected to boilers be considered, the capital cost of which would not have to exceed about £75 per installed daily ton of raw coal through-put.

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* P. Rosin: "The Possibilities of Co-ordination between Coal Processing and the Production of Electricity," *Transactions of the Fuel Conference*, 1928, vol. 8, p. 925.

In this connection it should be mentioned that a certain inferior slatey coal containing a high percentage of ash, for which there is at present no market, is found in the neighbourhood of Polish Upper Silesia. The combustion of this coal under boilers shows an efficiency of only 40 to 50 per cent, even with mechanical step-grates, whilst trials made on chain-grate stokers have shown that it is difficult to keep a fire alight at the arch, in addition to which the clinkering is very serious. Various mines (Prinzen-grube, Mittel-Laziska, Trautscholdsegengrube of the Prince Pless Mines administration, Kattowitz) have therefore adopted the method of utilizing this coal at their own power stations by means of the patent boiler furnaces combined with the carbonization retort developed by the Julius Pintsch A.-G. of Berlin,* from which primary tar is obtained. In this process the coal is carbonized in the apparatus installed in front of the boiler, from which it is discharged on to the grate where it is burnt. It is conveyed from the bunker through the carbonization shaft to the travelling grate. An exhauster draws part of the hot combustion gases out of the boiler furnace through the carbonization shaft and, in consequence of the reduction of pressure in the shaft, fresh air enters from the front, also producing hot gases owing to the combustion of a small part of the coal. These hot gases rising in the carbonization shaft carbonize the descending coal, their volume being adjusted by regulation of the fan. The residue, a kind of semi-coke, falls whilst still hot on to the chain grate and immediately commences to burn. The tar in the mixture of combustion and carbonization gases drawn from the carbonization shaft is condensed in normal water-cooled condensers, and the vapour-free gas mixture, which still has a calorific value of over 1 000 cal. per m^3, is conveyed to the boiler furnace and consumed.

On account of the fact that semi-coke falls upon the grate whilst hot and in a very reactive condition, the flame does not go out and combustion proceeds in a very satisfactory manner with an efficiency which, related to tar and steam, may be as high as 80 per cent.

The working figures are as follows:

Boiler heating surface ..	.. 550 m^2
Calorific value of coal ..	.. 4 500 kg-cal. per kg
Ash content of coal ..	.. 30–42 per cent
Coal charge	.. 80–100 tons in 24 hours
Average steam production	.. 28 kg per m^2 per hour
Evaporation figure ..	.. 4 to 5
Tar production	.. 7–7·5 per cent of the weight of coal
Average CO_2 contents of flue gases	14 per cent

It will be seen that in such plants it is possible to treat only non-caking pit coal over a 15-mm screen, brown-coal briquettes, or other fuel of similar size, not containing more than 20 to 25 per cent of water. Coking pit coal becomes too sticky under treatment to travel by gravity through the shaft, whilst with fine-grained material uniform carbonization cannot take place, on account of holes being formed in the column of fuel through which the hot gases flow, without carbonizing the entire mass of coal. Very wet fuel requires such an amount of heat that under certain circumstances there is no coke left for combustion under the boiler. With this equipment it is found that should, for any reason, the supply of suitable fuel for carbonization temporarily fail, the boiler can be fired with other types of coal until the normal supply for carbonization purposes is once more available. For this process grates are necessary which will convey the semi-coke in a glowing condition from the carbonization shaft into the boiler furnace, i.e. some type of travelling or chain grate. As regards boiler systems the inclined-tube type of boiler is the most suitable, because with these boilers the carbonization shaft can be constructed of a suitable height on account of the great height of the boiler, and any defective tubes can be replaced upwards, whereas in the case of cross-drum boilers such replacement must be done towards the front, which would necessitate the carbonization shaft being so constructed that it could be moved sideways. Naturally, this combination of carbonization with steam production is applicable only to boilers in base-load power stations. Approximately 5 000 m^2 of boiler heating surface are in use or in course of erection at the Upper Silesian mines referred to above.

The position as regards German brown coal is, however, quite different from that which applies to pit coal. Here the tar and not the coke is the main product of carbonization, as the value of the tar produced is more than 2½ times that of the coke. The composition of a brown coal which would be considered suitable for carbonization would be approximately as follows:—

Water	.. 45–55 per cent
Ash	.. 5–8 per cent
Tar	.. Over 7 per cent
Semi-coke	.. 20–25 per cent
Carbonization gas ..	.. 50–70 m^3 per ton

On account of the high water-content, carbonization must be preceded by some drying process in order to yield a high through-put from the expensive carbonization plant. This pre-drying is accomplished either in tube dryers with back-pressure steam of 1 to 2 atmospheres, or in rotary dryers heated by flue gas. A good brown-coal tar yields on an average the following:—

Benzol (gasoline)	.. 3 per cent
Solar oil (gas oil)	.. 2 per cent
Fuel oil	.. 65 per cent
Paraffin	.. 12 per cent
Tar coke	.. 4 per cent
Refined residues such as acid resins and creosote sodium	.. 8 per cent

As the raw coal is broken up previous to drying and as the dried coal breaks up still further during the carbonizing process, the semi-coke obtained will all pass through a 10-mm mesh screen. The whole of the ash of the raw coal is transferred to the semi-coke, so that the ash content of the coke is between 20 and 40 per cent, but it is a free-burning smokeless fuel. It has, however, a great tendency to self-ignition.

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* *Zeitschrift des Vereins Deutscher Ingenieure*, 1922, vol. 66, p. 869; also *Die Wärme*, 1927, no. 50, and *Braunkohle*, 1928, no. 2.

The gas from the carbonization of this fuel has a calorific value of 4 000 cal. per m^3, but in this condition it contains up to 40 per cent of CO_2 and 10 per cent of H_2S. If purified, however, its calorific value is 8 000 cal. per m^3.

Brown coal can be completely carbonized at 450°C. The higher the furnace temperature the more the tar is cracked, causing the tar yield to fall whilst the yield of gas increases, and at the same time the amount of low-boiling-point components such as light oil and benzol is increased, and a tar is obtained in which the waxes and resins have become decomposed, thus rendering its further treatment more easy. The old carbonization furnaces operated at temperatures of over 600°, whereas the new ones are not heated above 500° C. and give tar yields of over 90 per cent of those obtained in laboratory apparatus.

The carbonization industry in Central Germany is over 70 years old. In 1928 about 2½ million tons of brown coal were carbonized, giving 522 000 tons of semi-coke. This year it is estimated that a further 20 per cent increase is to be expected. The production of low-temperature tar from brown coal is expected to amount this year to over 200 000 tons. During the past few years there has been a very great increase in this industry, due to the extension of the Geissen furnaces, which now carbonize about 3 600 tons of raw coal daily. This year no new carbonization plants have so far been built or ordered in Germany, on account of the experience obtained from these new works. After some years of rapid expansion it is now necessary to call a halt, during which the newly erected plants must be adjusted for efficient operation and a close study of detail made. At the same time, the development of the market conditions has to be awaited and the effect of the sudden increase in production noted. Whilst the future development will be favourably affected, owing to the fact that the new hydrogenating processes enable brown-coal oils to be transformed in bulk into motor spirit, the position is not yet clear as to what effect the increased production of paraffin will have on the German market, which is now almost saturated by the present output. On the other hand, the gas produced has now been successfully purified by the elimination of CO_2 and H_2S, due to pressure washing, so that it can be used for town gas supply. The Edderitz mines near Koethen are now supplying the surplus gas from the carbonization plant to Dessau for the Continentale Gasgesellschaft, which is the first long-distance gas transmission of this kind and has been in successful operation for several months.

On the other hand, the marketing of the increased quantities of semi-coke produced by this means has now become a difficult problem. The original carbonization works sold their coke, which contained 20 to 25 per cent of water due to being quenched, in small quantities for domestic purposes. This fuel is used in special stoves in small amounts, more particularly by the poorer classes of the population. This source of disposal, however, cannot be further developed, but has, in fact, decreased somewhat in recent years. It has not, so far, been possible to make briquettes from brown-coal semi-coke on an economical basis and, in any case, such briquettes would not be very suitable for domestic purposes on account of the high ash-content. The gasification of the very fine coke breeze containing a high percentage of ash is also a difficult matter. It is, therefore, necessary to endeavour to introduce it as an industrial fuel for steam boilers or furnaces. Until recently there were no grates on which this fine breeze could be burnt efficiently, but recently suitable travelling grates have been constructed which give successful results.* Previous to the introduction of this new type of grate the burning of the coke in pulverized form offered the best solution for boilers and cement kilns, but this method can only be satisfactorily adopted if the coke is dry-quenched, as wet coke cannot be pulverized and re-drying increases the cost beyond economical limits. Dry quenching, therefore, has now been developed and it is interesting to note that this method obviates at the same time the dangerous tendency to self-ignition.† Even so, the pulverizing of brown coal semi-coke is by no means easy, as the output of the mills is less than when raw coal is being ground, in addition to which the wear and tear is very heavy. If used in the pulverized form in boilers, the high ash-content causes much more trouble than when the fuel is burned on grates, and this necessitates very efficient cooling of the combustion-chamber walls. It is also essential to make use of highly pre-heated air in order to ensure good ignition of a fuel so low in volatile matter as this. In order to avoid sintering and to allow the boilers to operate continuously for long periods, it is necessary to space the tubes farther apart than usual. If the fuel is burned on grates the expensive grinding plant is eliminated, clinkering troubles in the combustion chamber and sintering at the tubes are reduced, and moisture in the fuel is not so detrimental.

The use of the new large carbonization plants calls for an immediate solution of the problem of the disposal of waste liquor containing sulphuretted hydrogen, phenols and fatty acids in addition to ammonia. The authorities do not permit this waste liquor to be run to waste unpurified, but the author's recent work has shown one way of purifying it and removing the phenol content from it.‡

The necessity of reducing the capital cost and working expenses of plant in connection with the carbonization of brown coal is daily becoming more obvious, as the coal deposits which are rich in tar and can be obtained cheaply in open workings are now becoming exhausted. It is therefore necessary either to carbonize the brown coal containing a low percentage of tar which is available from open workings, or to adopt mining methods for obtaining the richer brown coals, in which case the cost is fully twice as great. The cost of the raw material is the most important factor to be taken into account in estimating the earning capacity of a carbonization plant, particularly as the fuel contains 50 per cent of water, which is not only worthless but requires the installation and operation of expensive drying equipment.

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* *Braunkohle*, 1929, pp. 161, 164 and 170.

† P. Rosin: "The Spontaneous Combustion of Semi-Coke from Brown Coal: its Causes and Prevention," *Fuel*, vol. 8, no. 2.

‡ *Zeitschrift für Angewandte Chemie*, 1929, nos. 40–42; also *Braunkohle*, 1929, nos. 41 and 42.

In the earlier part of this paper mention was made of the importance of brown coal to the German electrical industry. The large brown-coal power stations make use of a certain amount of coal in which the percentage of tar is such that its carbonization is well worth considering. On the other hand, there are the independent carbonization works which already have a surplus of semi-coke very difficult to dispose of. These works dry the coal in many cases by means of back-pressure steam previous to carbonizing, this back-pressure steam having by previous expansion produced more electrical energy than is required by the carbonization works for its own purposes. For this reason the idea has been conceived of establishing brown-coal carbonization power stations in which the coal would be wholly or partly carbonized previous to combustion, and better use made of its valuable tar contents than by combustion only. It will be seen, therefore, that this idea first assumed tangible form in Germany and was developed there for the first time on a large scale. The pioneer of this method is the Hessen-Frankfurt A.-G. (Hefrag) with its brown-coal carbonization stations at Wölfersheim. This was the first carbonization power station in the world, having been founded jointly by the Government of Hesse and the municipality of Frankfurt. The author has to thank the managing director (Dr. Czakó) of Wölfersheim, to whom he is indebted for the following particulars.*

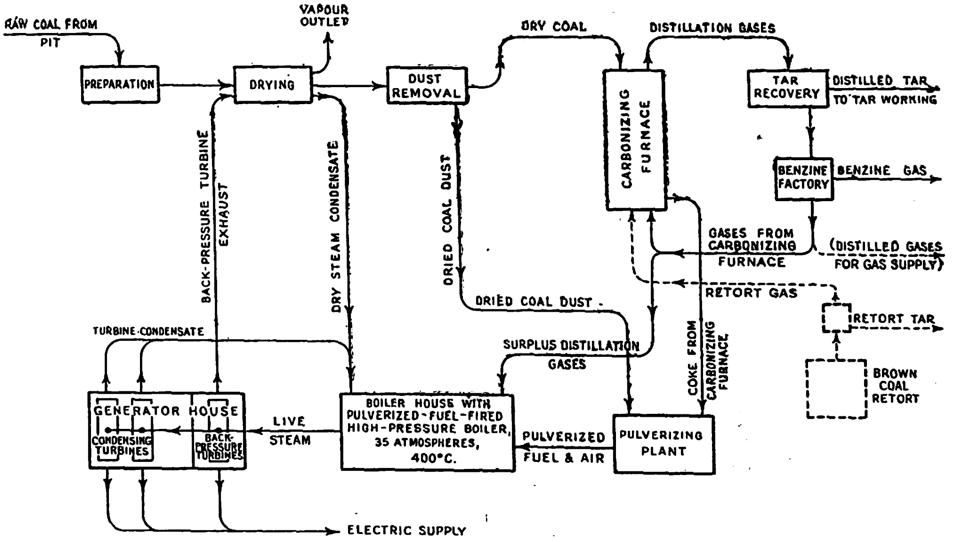
RAW COAL FROM PIT
VAPOUR OUTLET
PREPARATION
DRYING
DUST REMOVAL
DRY COAL
DISTILLATION GASES
CARBONIZING FURNACE
TAR RECOVERY
DISTILLED TAR
TO TAR WORKING
BENZINE FACTORY
BENZINE GAS
GASES FROM CARBONIZING FURNACE
(DISTILLED GASES FOR GAS SUPPLY)
RETORT GAS
RETORT TAR
BROWN COAL RETORT
BACK-PRESSURE TURBINE EXHAUST
DRY STEAM CONDENSATE
DRIED COAL DUST
DRIED COAL DUST
TURBINE-CONDENSATE
SURPLUS DISTILLATION GASES
COKE FROM CARBONIZING FURNACE
GENERATOR HOUSE
CONDENSING TURBINES
BACK-PRESSURE TURBINES
LIVE STEAM
BOILER HOUSE WITH PULVERIZED-FUEL-FIRED HIGH-PRESSURE BOILER, 35 ATMOSPHERES, 400°C.
PULVERIZED FUEL & AIR
PULVERIZING PLANT
ELECTRIC SUPPLY

Diagram of a combined steam and brown-coal carbonization plant.

The illustration shows the general process of a brown-coal carbonization power station. The raw coal drawn from open workings undergoes a process of preparation called the wet service. In the course of this preparation the coal is broken up and screened, and the coarse wooden and clay components are removed. Following this the coal undergoes a drying treatment in the course of which the percentage of moisture is reduced from about 55 per cent to 15 per cent. The drying is carried out in tube dryers heated by exhaust steam from back-pressure turbines of the power plant. After being dried the coal is freed from dust in a separating plant and goes to the carbonization furnaces where it is carbonized at about 500° C. These furnaces work on the retort principle, so that pure gas is obtained from the coal. This gas is first of all freed from tar by gradual cooling, condensation and electrical precipitation, after which the light vapours are scrubbed out in the benzol scrubbers. The gas from which the tar and benzol have been removed can then be used for heating the carbonization retorts themselves, the surplus being taken to the boilers as additional fuel, or it can be made available, after necessary purification, for gas supply in the immediate neighbourhood, or pumped through pipe lines to any convenient distance. When the gas is disposed of in the latter manner the retorts of the carbonizing plants are heated by producer gas made from brown coal, from which a further supply of producer tar is also obtained.

The new works have been erected by the side of an old brown-coal power station, and the present daily through-put amounts to 1 000 tons per day for the first instalment. Most of the coal is obtained by cable dredger in open workings and is brought by the mine railway in self-unloading wagons which discharge over the draw-off bunker. From the latter it falls directly on to low-lying conveyor belts which carry it over the inclined raw-coal bridge to the preparation plant. The wet-service plant consists of two parts, each of 700 tons through-put in 16 hours. The coal which is broken up here, screened so that it will all pass a 1-in. mesh, runs over an inclined wet-coal bridge leading at right angles into the bunkers of the dry service. From there it is distributed over the 5 steam-heated tube-dryers, each dryer having a heating surface of 1 820 m^2, the dust being extracted by electrical means from the vapours as they leave the dryers. The dry coal is then taken on an inclined-belt conveyor to the carbonization house, where it is first of all freed from dust (amounting to about 10 per cent) by means of air separators. In Wölfersheim there are 7 Geissen carbonization furnaces which have been supplied by the Kohlenveredlung A.-G., of Berlin, and the eighth will be erected by the end of this year.

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* "New Brown-Coal Carbonization Works, coupled with Production of Electricity in Upper Hesse." Lecture delivered before the 70th Annual Conference of the German Association of Gas and Water Experts, Berlin, 10th June, 1929.

The report of Dr. Heinze, mentioned above, embodied a complete description of the Geissen furnace, so that it is unnecessary to enter into details here. It is an upright revolving furnace the heating surface of which consists of a cast-iron cylinder built up of separate rings which rotate slowly. Inside this cylinder is a stationary refractory casing up the inside of which the heating gases burn and then flow downwards between the refractory casing and the internal surface of the cylinder. The coal trickles slowly down the outside of the cylinder on the internal louvred surface of the outer casing. The daily through-put of a furnace is 60 to 70 tons of dry coal, corresponding to 120 to 140 tons of wet coal. From the raw gas the tar is extracted by means of gradual cooling and electrical precipitation, the vapour-free gas being then passed on to the benzol-extraction plant by means of a system of pipes running from the carbonization house. The light oil vapours are scrubbed with oil in vertical towers in the benzol plant, the purified gas then passing in its final form to the gas-holder which, having a capacity of 3 500 m^3, acts as a compensator to overcome any fluctuations in the supply and demand. From there it is conveyed along the same pipe bridge back to the carbonizing house, where a portion of it is used for heating the retorts, the surplus acting as additional fuel to the boiler house.

The tar collected in the condensers is conveyed through pipes arranged on the same bridge to the tar storage tanks, which consist of 5 large tanks having a total capacity of 2 700 m^3. From these the tar is loaded into tank wagons and sent away for treatment. Two small tanks having a total capacity of 300 m^3 are used for storing the light spirit. A coke-fed gas producer is used for starting up the plant and it also serves as a stand-by. The semi-coke, which is carbonized at a temperature of about 450° C., is very liable to spontaneous ignition and is dry-quenched by the Rosin process. Cooling is effected by an ample supply of air and a small quantity of steam or fine water spray, the coke being stirred the whole time, with the result that the oxygen in the air saturates the coke during the cooling process, thus making it quite inert. The cooled coke is lifted into the bunkers of the boiler house by means of a suction conveyor plant. In the boiler house there are 4 high-pressure boilers fired by means of pulverized fuel. Each boiler has a heating surface of 750 m^2 and produces steam at a pressure of 35 atmospheres and a total superheat of 400° F. The fuel supplied to these boilers consists of 80 per cent of pulverized coke, the other 20 per cent being the coal dust drawn off from the drying plant. The coke is pulverized in Babcock-Rema unit mills, each of which has a capacity of 4 tons per hour. There are two mills to each boiler, and each blows the dust directly into the furnace without intermediate bunkering.

The power house is equipped with two condensing turbines each of 5 000 kW capacity at 15 atmospheres, and two back-pressure turbines each of 6 500 kW. The total capacity of this first section of the installation is therefore 23 000 kW. The high-pressure steam enters the back-pressure turbines at 33 atmospheres, each turbine being equipped with two runners. In the first stage the steam is expended down to 2 atmospheres and is taken from there as the heating medium for the carbonization plant coal-drying equipment. It is condensed in the tube dryers and returned as condensate at 2 atmospheres to the boiler feed-water tank. In the other stage of the turbine the steam is expanded down to 15 atmospheres and then passes at this pressure into the 5 000-kW condensing turbines arranged behind. One of the back-pressure turbines is always kept as a stand-by so as to ensure an adequate supply of steam at 2 atmospheres pressure for the coal dryers, under all conditions of power-house operation. The condensing turbines are operated in accordance with the load. The low-pressure runner of the back-pressure turbine supplying the steam for the dryers is operated at a steady load day and night, thus taking over the base load of the station whilst the peaks are supplied by the condensing turbines. The current generated is transformed to 20 000 and 100 000 volts and distributed by high-tension overhead transmission lines. The erection of this complete plant was started in the spring of 1928 and completed in March 1929, and all furnaces are now in regular operation. The coal is brought to the station by trains and the wagons are discharged by opening the side doors. The raw-coal inclined bridge leads to the wet plant from which connection is made to the drying plant by means of a second inclined bridge running at right angles to the former. From the semi-coke bunkers the pneumatic conveyor leads past the carbonization house to the top of the boiler-house bunkers, which are some 40 m high. As load fluctuations in the boiler house are unavoidable an adequate coke supply must be kept so as not to interfere with the steady operation of the carbonization equipment. The coke storage is situated below the horizontal portion of the pneumatic pipe bridge and has a capacity of 1 500 tons. Suction nozzles are arranged at various parts of the pipe system so as to pick up coke from any part of the storage space.

All buildings are of steel-frame construction, and particular attention was paid to simplicity of design. The working rooms are adequately lighted by means of numerous horizontal light strips and large window spaces.

It is hoped that the foregoing explanation will give a clear idea of this, the first carbonization power station. Exact operating data are not yet available as the plant has not been at work for a sufficient period.

The following general remarks with regard to the basis of brown-coal carbonization power plants may be of interest.

The capital cost of a new raw brown-coal power station in Germany is about £12 10s. to £15 per kW installed. The addition of a carbonization plant would increase this capital cost by approximately £12 10s. to £17 10s. per kW, depending within these limits on the yield of semi-coke, its calorific value and the consumption of the power plant to which it is attached. On account of this high extra capital cost only base-load power stations can be considered as suitable for such combinations. Assuming that such a plant operates for 3 500 hours a year, a tar yield of 7 per cent from the raw coal makes the revenue from electricity about twice the tar value, on the basis of present tar and energy prices. In this connection it must also be remembered that the price of energy is much less subject to fluctuation than the price of tar. The market price of electricity is, in all probability, the most stable of all market commodities, whilst the oil market is subject to violent fluctuations. For this reason the profit from a carbonization power station must be built up in the first place on the basis of the supply of current, which must be ensured in such a manner that fluctuations in the price of oil would not endanger the general economic stability of the works. This confirms what the author said at the beginning of his report to the World Power Conference, namely, that the kWh is the main product of a combination of carbonization and power stations, and that the requirements of the electricity supply must be the dominant factor of the whole project.

The first carbonization power plant has shown the way to a remunerative combination of electricity production with low-temperature distillation of brown coal. This combination can be more or less close, within the limits of the reasonable balancing of steam, electricity and gas requirements of the individual portions. Theoretically, an extraordinarily close coupling of the individual portions of the plant is possible, enabling an exceptional economy of fuel to be obtained, together with full utilization of nearly all the products in a reciprocal manner. In practice, however, this coupling should not be based on too rigid lines, even at the cost of a somewhat higher heat consumption. Difficulties are unavoidable in all plants and the resultant losses affecting all branches of the works are not necessarily counterbalanced by the attainment of the highest possible thermal efficiency. For this reason, the carbonization power plant should in the first instance be a combination of carbonization and power production from the point of view of space and profit, the operating standpoint of the combined plant being a secondary consideration. This principle will have even greater significance when the coupling becomes a triple one, that is, when the carbonization plant, power station and gas works are combined, to which end Germany is at present making preparations.

[The discussion on this paper will be found on page 229.]

LOW-TEMPERATURE CARBONIZATION OF FUEL, WITH SPECIAL REFERENCE TO ITS COMBINATION WITH THE PRODUCTION OF ELECTRICITY (ENGLISH PRACTICE).

By E. H. SMYTHE and E. G. WEEKS.

[*Paper received* 1*st October*, 1929; *read at a Joint Meeting of* THE INSTITUTION *and the* INSTITUTE OF FUEL 21*st November, before the* EAST MIDLAND CENTRE 26*th November, and before the* TEES-SIDE SUB-CENTRE 4*th December*, 1929; *also before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 20*th January*, 1930.]

SUMMARY.

The paper opens with the statement that Great Britain is dependent almost entirely upon coal for the production of electricity, the amount of water-power available being comparatively small. This being so, the inauguration of the "grid" transmission system and the co-ordination of power production afford favourable conditions for combining the latter with the distillation of coal.

The development of the Babcock process of low-temperature coal distillation is briefly described. So far as the authors are aware, this is the only process of its kind developed in Great Britain. It is suggested that the electric power plant of the future will take in coal as its raw material, but will deliver, in addition to electricity, motor spirit, fuel oil, creosote, pitch and other derivatives of coal tar. A discussion of the actual results obtained from the coal distillation plant at Dunston-on-Tyne follows.

The plant was designed for the production of an ideal power-station fuel, low in volatiles and therefore smokeless, and for the recovery of the more valuable by-products consistent with the production of such a fuel. The broad result obtained is that 16 gallons of tar oils and $\frac{3}{4}$ ton of semi-coke are produced from 1 ton of Northumberland small coal. The paper goes on to discuss the potentialities of low-temperature tar and it is explained that investigation of this aspect of coal distillation is by no means complete. The field of research is said to be one which presents wide possibilities.

In conclusion it is claimed that a new situation exists in which a practical process of coal distillation has been evolved in conjunction with the generation of electricity, and that as a result a definite step forward in the better utilization of our most valuable national asset, namely coal, is now due.

A full description of the coal distillation plant at Dunston-on-Tyne is given as an Appendix to the paper.

The compact nature of the industrial areas of Great Britain and their nearness to each other are two of her physical characteristics, a third characteristic being her complete dependence for power production upon her mineral resources, which means, in effect, upon a cheap and ample supply of coal. Most other countries have the alternative of hydro-electric power to fall back upon in greater or less measure, but Great Britain has to face the fact that the amount of power available from that source is never likely at any given time to be more than 5 per cent of the total power requirements of the country.

The first two of the above characteristics, namely, the compact nature of our industrial areas and their nearness to each other, make it possible to envisage an interconnected electrical system for the whole country —the already well-advertised "grid." The third characteristic makes the economical utilization of coal in combination with the production of electricity of immediate interest. With the creation of the grid transmission system the efficiency of power generation is bound to improve steadily, quite apart from engineering progress, because of the higher load factor at which large "base-load" stations will work, and this condition of high load-factor operation is a feature favourable to the combination of the low-temperature carbonization of coal with the generation of electricity.

In the present paper the Babcock process of low-temperature coal distillation, with the development of which the authors have been associated, is described, together with some details of the results so far attained. So far as the authors are aware, this is the only process developed and in operation in Great Britain with the primary object of combining the low-temperature carbonization of fuel with the production of electricity. Later is given a summary of the conclusions which, in the authors' opinion, may be drawn therefrom.

It is rather more than 10 years since the experiment, as it then was, of distilling coal before utilizing the resultant semi-coke in a boiler furnace was first tried in one of the generating stations of the Newcastle-upon-Tyne Electric Supply Co. The declared aim from the outset was to combine a practical method of coal distillation with the generation of electricity, the main objects being (*a*) to utilize in a more economical way our most valuable raw product, coal, and (*b*) to cheapen the cost of a unit of electricity at the generating station. Right at the beginning of the investigation it was necessary to determine which of many processes suggested was likely to give the best result technically and economically, and, further, the general lay-out of a plant to deal with an entirely new set of conditions presented many problems which had to be solved before any real measure of success could be claimed. The present is not a suitable occasion for a detailed account of the numerous trials and experiments which were found to be necessary due to absence of data and lack of experience, but it will be readily understood that the difficulties were considerable and that their effective solution occupied a great deal of time. A practical solution was not, in fact, reached until after years of painstaking application on an extensive scale of the sometimes wearisome method of "trial and error."

The results eventually attained have, however, confirmed the soundness of the original idea of combining the distillation of coal at low or moderate temperature with the generation of electricity. In the first place, of all the manufacturing processes with which the combination of coal distillation appeared to be a practical possibility, none offered so clear a prospect of success as the large-scale generation of electricity, for few, if any, utilize coal in anything like so large a quantity at one spot. Moreover, in the boiler furnace no use is made, as such, of what have been termed the "high-value heat units" in the coal, namely, those contained in the volatile constituent, as distinct from the "low-value heat units," or those contained in the fixed carbon constituent. Further, electricity supply provides two conditions which are essential if the best results are to be obtained from a coal distillation plant, namely, all-the-year-round continuity of operation and high load-factor working. The supply of waste heat from the boiler flue gases, in addition to steam and electric current required for the working of the distillation plant, are all available at the site.

Present electric power plants take in raw coal and deliver electricity. In the process the whole of the valuable volatile constituent of the coal is consumed. The electric power plant of the future will take in the same raw material, but in addition to electricity it will deliver other useful commodities such as motor spirit, fuel-oil, creosote and pitch. Moreover, the combustion of semi-coke instead of raw coal will at least diminish the ever-present smoke nuisance, and it will be seen from what follows that smokeless fuel and the by-products just mentioned can be produced from the very grade of coal commonly used in power stations.

The analysis of the Northumberland coal which is being treated at the coal distillation plant at Dunston-on-Tyne and also used as the ordinary power station fuel is as follows:—

Analysis of the moisture-free coal.

	Per cent
Carbon	72·75
Hydrogen	4·98
Sulphur (total)	1·26
Nitrogen	1·28
Oxygen	6·96
Ash	12·77
	100·00

The moisture content of the coal varies between 6 and 10 per cent, and the volatile content when containing 6 per cent of moisture is 31 per cent.

The heating value of the raw coal as determined by calorimeter is given below:—

Coal with 6 per cent moisture.

Higher heating value, 11 574 B.Th.U. per lb.
Lower heating value, 11 178 B.Th.U. per lb.

Water-free coal.

Higher heating value, 12 321 B.Th.U. per lb.
Lower heating value, 11 898 B.Th.U. per lb.

The grading of the coal is as follows:—

Percentage retained on 1-in. sieve	= 1·92
Percentage passing 1 in.; ,, ½-in. ,,	= 27·81
,, ,, ½ in.; ,, ¼-in. ,,	= 22·28
,, ,, ¼ in.; ,, ⅛-in. ,,	= 21·85
,, ,, ⅛ in.; ,, $\frac{1}{16}$-in. ,,	= 15·92
Below $\frac{1}{16}$ in.	= 10·22
	100·00

The result of the treatment of this coal is the production of a semi-coke and gas and a variety of by-products, namely motor spirit, white spirit, creosote, pitch and certain low-boiling-point tar acids.

The analysis of the semi-coke is as follows:—

Analysis of the moisture-free coke.

	Per cent
Carbon	74·92
Hydrogen	3·07
Sulphur (total)	1·61
Nitrogen	1·59
Oxygen	2·41
Ash	16·40
	100·00

The average volatile content of the semi-coke is 14 per cent.

The heating value of the semi-coke determined by calorimeter is as follows:—

Semi-coke with 0·74 per cent moisture.

Higher heating value, 12 168 B.Th.U. per lb.
Lower heating value, 11 907 B.Th.U. per lb.

Moisture-free semi-coke.

Higher heating value, 12 258 B.Th.U. per lb.
Lower heating value, 11 997 B.Th.U. per lb.

The fundamental basis of the design of the plant is the production of an ideal boiler fuel and the recovery of the most valuable by-products consistent with the production of such a fuel.

Experience gained in burning semi-coke either on chain-grate stokers or as pulverized fuel has shown that the best efficiency and ease of operation are obtained with a semi-coke having a volatile content of from 12 to 14 per cent. With a fuel of this nature all difficulties of ignition or burning-out are absent, but with semi-coke having a lower volatile content this is not so.

Difficulties have been experienced in maintaining efficient combustion with pulverized semi-coke produced by externally-heated retorts, and it has been ascertained that this is due to the overheating of the coal in contact with the retort walls, so that cracking of the hydrocarbons takes place and loose deposits of amorphous carbon attach themselves to the coke. The result is that in handling the coke and screening it, the outer surfaces of the larger pieces of coke suffer by abrasion, so that the "smalls" of the semi-coke contain a large proportion of graphite and graphite pieces which have a very high ignition temperature. This coke, when pulverized, may therefore require to be mixed with coal in order to maintain satisfactory combustion. In the case of the internally heated retort, however, the temperature of the charge cannot be higher than that of the distilling medium, so that no cracking takes place, no carbon is deposited on the coke surfaces in the form of graphite, and the resultant semi-coke has been found to be an excellent fuel for burning in pulverized form.

Experiments with pulverized semi-coke made by the Babcock process indicate that it is less hygroscopic than pulverized coal, and therefore where the pulverized fuel is used in the bin-and-feeder systems of pulverized-fuel firing there is less risk of trouble due to the fuel packing in the storage bins. Pulverized semi-coke is also less liable to spontaneous combustion than pulverized coal, owing to the lower volatile content and the absence of the lighter volatiles which have been driven off from the coal in the distillation process.

Apart from semi-coke, the result of the distillation of 1 ton of coal after treatment by the Babcock process is shown in Fig. 1, from which it will be seen that the by-products * available for sale after the smokeless fuel and gas have been used for steam-raising purposes are as follows:—

Motor spirit	1 gallon
White spirit	1 ,,
Steam-distilled creosote	6·0 gallons
Heavy creosote	2·4 ,,
Pitch	5 ,,
Air-blown low-boiling-point tar acids	0·4 gallon

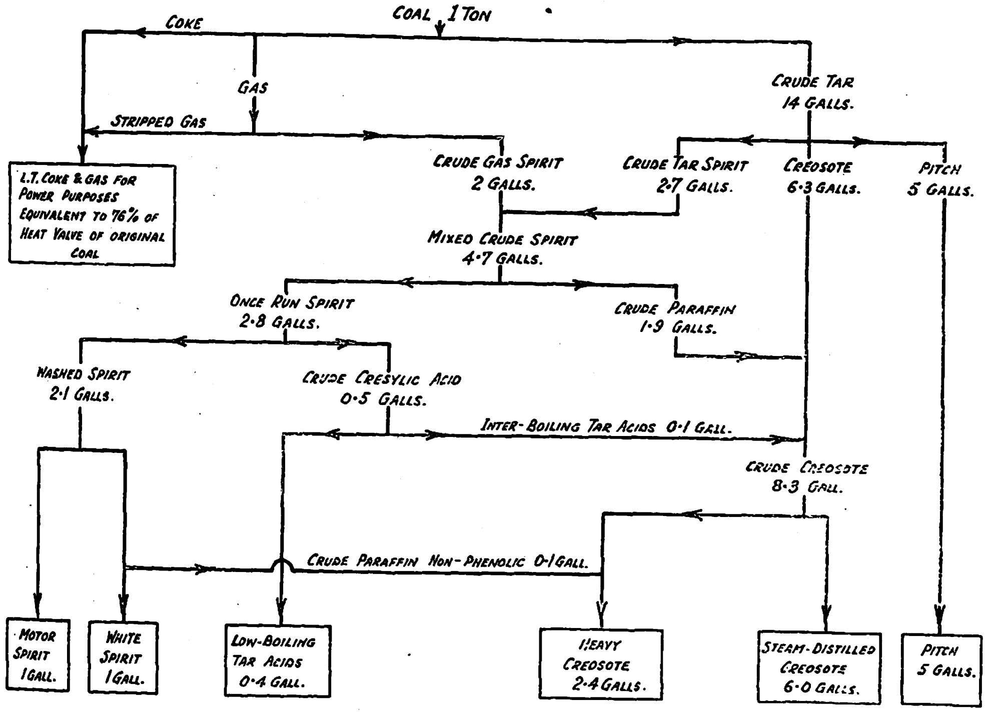
COAL 1 TON
COKE
GAS
STRIPPED GAS
CRUDE TAR 14 GALLS.
L.T. COKE & GAS FOR POWER PURPOSES EQUIVALENT TO 76% OF HEAT VALUE OF ORIGINAL COAL
CRUDE GAS SPIRIT 2 GALLS.
CRUDE TAR SPIRIT 2·7 GALLS.
CREOSOTE 6·3 GALLS.
PITCH 5 GALLS.
MIXED CRUDE SPIRIT 4·7 GALLS.
ONCE RUN SPIRIT 2·8 GALLS.
CRUDE PARAFFIN 1·9 GALLS.
WASHED SPIRIT 2·1 GALLS.
CRUDE CRESYLIC ACID 0·5 GALLS.
INTER-BOILING TAR ACIDS 0·1 GALL.
CRUDE CREOSOTE 8·3 GALL.
CRUDE PARAFFIN NON-PHENOLIC 0·1 GALL.
MOTOR SPIRIT 1 GALL.
WHITE SPIRIT 1 GALL.
LOW-BOILING TAR ACIDS 0·4 GALL.
HEAVY CREOSOTE 2·4 GALLS.
STEAM-DISTILLED CREOSOTE 6·0 GALLS.
PITCH 5 GALLS.

FIG. 1.—Products for sale per ton (2 240 lb.) of coal distilled.

The value of the by-products on the basis of prices now obtainable in this country is as follows:—

Motor spirit	1s. 2d. per gallon
White spirit	1s. 0d. ,,
Air-blown low-boiling-point tar acids	1s. 8d. ,,
Steam-distilled creosote	8d. ,,
Heavy creosote	4½d. ,,
Pitch	2·84d. ,,

It will thus be seen that from 1 ton of coal costing 11s., by-products are produced having a value of 8s. 11d.

The distribution of 1 ton of coal after distillation may conveniently be summarized in the following form:—

	Weight	Heat value	Cash value (1 ton of coal = 100)
	per cent	per cent	per cent
Coke and gas for steam-raising purposes ..	76	76	76
Oils	7·36	11	81
Loss and used on process	16·64	13	—
	100	100	157

While the by-products mentioned above include those actually being made and sold at the Dunston distillation plant, they do not by any means represent the complete scope of what may be done to meet the requirements of the market. For example, it may be preferable to concentrate on the bulk production of any one product, thus reducing the amount of refining plant necessary.

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* Commercial uses of by-products:—

Motor spirit.—For use in internal-combustion engines. The spirit possesses excellent anti-knock properties.
White spirit.—As a turpentine substitute for paint manufacture; for general use as a solvent; and as a cheap fuel for internal-combustion engines using heavy petrol or paraffin oil.
Steam-distilled creosote.—For the manufacture of special disinfectants, fungicides and weed killers. The residuals may be used as a "brick" oil or as charging stock in oil-cracking processes for the production of motor spirit.
Low-boiling-point tar acids.—For the manufacture of disinfectants, sheep dips, etc., also artificial resins and insulating compounds.
Heavy creosote oil.—For timber preservation; as a wash oil for benzol recovery plants; for the manufacture of disinfectants; for use as Diesel-engine fuel; and as charging stock in oil-cracking process for the production of motor spirit.
Pitch.—For cable-laying; for the manufacture of paint or varnish, and artificial resins; and for briquetting purposes.

Further, an alternative scheme for utilizing low-temperature tar oils is to subject them to cracking with a view to the production of motor spirit. Investigation has shown that by this means the tar oils produced at Dunston will give a yield of motor spirit amounting to approximately 30 per cent of the total quantity treated, the residue being available as fuel oil, in addition to residual coke of high calorific value. Activities of this nature will, of course, necessitate the installation of cracking plants specially designed for dealing with low-temperature tar oils.

Recent developments have rendered it possible to treat heavier oils containing a larger percentage of carbon than the natural oils treated by the cracking plants now widely established in the United States and elsewhere. There is therefore no reason for anticipating any difficulty in the way of recovering considerably larger quantities of motor spirit from low-temperature oils than is possible by other means, but here, again, an essential feature is that large quantities of low-temperature oils should be available as it is only possible to treat large quantities commercially.

A further outlet for the use of low-temperature oils is in connection with the hydrogenation of coal. It has been found that these oils constitute a suitable medium for mixing with the coal transformed by this process, and it is believed that considerable quantities of low-temperature tar oils are actually being used for this purpose in coal hydrogenation installations.

So much for results, actual and prospective. The coal distillation plant employing the Babcock process and installed at the Dunston power station of the Newcastle-upon-Tyne Electric Supply Co. is described in an Appendix to this paper. The next succeeding paragraphs summarize what has so far been achieved and offer some comment on the probable future, as the authors see it, of coal distillation at low temperature.

It is claimed that a new situation exists in which a practical process of coal distillation has been evolved in conjunction with the generation of electricity. This development has been carried out primarily for the better utilization of the constituent parts of raw coal, but there are also the prospects (*a*) of cheapening the unit of electrical energy, and (*b*) of providing a smokeless fuel which has proved itself to be eminently suitable for burning on a large scale in boiler furnaces. A good deal of success has recently been achieved in the direction of improving the combustion of raw coal, but all the energy has been confined to that one direction. Under the new conditions, the advance which has been made will be consolidated and combined with better utilization of the raw coal and the production of an improved boiler fuel.

The claim outlined above is based upon results obtained during three years of continuous operation under day-to-day working conditions. The plant has, moreover, two important advantages. In the first place it occupies little ground space, and secondly, as is shown by Fig. 6, it can be conveniently worked in with the design of the boiler-house plant of a modern power station. The further conditions of reasonable first cost, reliability and low working cost, have also been met.

It may be said that no details of first cost are given in the present paper. The attempt here made is to give a description, necessarily brief, of the plant and process as they exist to-day in practical form at the end of a long development. The expenditure on the existing plant, many of the details of which had to be designed as the work progressed, would form no reliable guide, but at the same time the experience gained has been such that there is no practical difficulty in the way of preparing a close estimate for a plant of any desired through-put. The capacity of the existing plant at Dunston is now being increased by the installation of a further retort capable of treating 60 tons per day, and this new retort will soon be in operation. A design has been prepared (Fig. 6) involving the employment of three separate retorts, each with a through-put of 160 tons per day.

The investigation of the commercial utility of the by-products derivable from low-temperature tar oils is by no means complete, and the field of research is one which presents wide possibilities. The position might, in fact, be compared with the state of affairs that existed in a number of industries, for example the gas industry, until chemical research led to discoveries which resulted in the birth of vast new industries solely concerned with the transformation of what were once regarded as waste products into commodities of essential value. The manufacture of aniline dyes, synthetic nitrates and synthetic resins are notable examples of what has been achieved in this respect, and it is not unreasonable to assume that important new uses will also be found for the by-products derivable from low-temperature tar as soon as larger supplies than have hitherto been possible appear on the market. The result of recent research work on these tars points definitely to further developments of commercial importance.

Having regard to the practical and technical efficiency here claimed for the process of coal distillation, it may be said that the progress made up to the present time, measured in terms of the tons of coal distilled per day, is disappointingly small. The fact must be admitted, but the explanation is fairly simple. The utilization of coal for power generation in the way advocated in this paper amounts, in effect, to a new industrial process, and new industrial processes are notoriously slow in establishing themselves against old and well-tried methods. For example, the operation of winning coal was for long years purely a manual process. So far as the actual process of coal-getting is concerned, the coal mines of Great Britain were worked almost entirely by man-power until the beginning of the present century. Even now there are few mines in which the coal is mechanically cut and in which its transport from the coal face to the pit bottom is worked throughout by mechanical means, a fact which may surprise a mechanical engineer used to handling surface transport problems. So it may well be with the fuel technologist of the not very-distant future. He will be unable to suppress his astonishment that for the first quarter of the twentieth century, during the development of the power industry into one of the most progressive industries in the country, measured either by physical growth or technical achievement, raw coal to the extent of many million tons per annum continued to be burnt under boilers.

The authors consider that the effective combination of coal distillation with the generation of electricity is already a practical and commercial possibility, and that by this means a decisive step forward in the direction of the better utilization of our most valuable national asset, namely coal, is now due.

APPENDIX.

DESCRIPTION OF THE COAL DISTILLATION PLANT AT DUNSTON-ON-TYNE.

The coal distillation plant at the Dunston power station is now in its third year of continuous operation. It is composed of two retorts, operating in conjunction with a Babcock boiler of 30 000 lb. of steam per hour evaporative capacity.

The general lay-out of the complete installation is shown in Figs. 2 and 3. Fig. 2 indicates the general features of the plant. On the extreme left of the lower portion is seen the cross-section of the boiler house. The dimensions of this house are 102 ft. long by 40 ft. wide and the height from the firing floor to the flat concrete roof on which are placed the boiler fans and chimneys is 52 ft. In the centre of the house, coal bunkers equipped with scraper coal conveyors are provided for the storage of coal or coke for use in the boilers.

The existing retort and boiler plant is located on the west side of the house and consists of one C.T.M. type boiler which is fitted with two Babcock and Wilcox compartment type chain-grate stokers supplied with hot forced draught obtained from a corrugated plate air-heater located immediately above the boiler. The two retorts (shown by thick lines) are located immediately in front of the boiler and are arranged to deliver coke to each stoker by means of enclosed screw conveyors. It will be noted that the space occupied by the retort plant is relatively small, about the same as is usually provided for the withdrawal of chain-grate stokers for repairs and overhaul. Hoppers for receiving ashes and riddlings from the stokers are located in a basement below the firing floor, and a standard Babcock and Wilcox vacuum ash plant with ash breaker is installed. The east side of the boiler house contains a Babcock and Wilcox pulverized-fuel boiler complete with a unit pulverizing plant of the Fuller-Bonnot type. This boiler, which has a heating surface of 5 486 sq. ft., is fitted with Luloff water-cooled walls in the sides and back of the combustion chamber and is surmounted by a feed-water economizer and plate type air-heater.

The pulverized fuel is fed into the combustion chamber through a standard Babcock and Wilcox Lodi type burner which receives its supply of hot air from the air heater on the top of the boiler. The pulverized-fuel boiler is at present being fired with pulverized coal, but provision has been made for this boiler to be fired by semi-coke on the completion of a new retort which is now in process of erection.

The top portion of Fig. 2 shows on the left the lay-out of the two existing retorts each of which are capable of treating 30 tons of Northumberland coal per 24 hours. The new retort already referred to is shown on the right-hand side of this part of the illustration. This new retort will be capable of handling 60 tons of coal per day and is therefore of twice the capacity of each of the existing retorts.

Semi-coke from the new retort will be transported by conveyors to the storage bunker over the pulverized-fuel boiler in the adjacent boiler house, and will then be pulverized and consumed in the furnace of the pulverized-fuel boiler. It is intended, therefore, that in the near future both boilers will be fired with semi-coke under two different systems of firing, i.e. the existing retorts will continue to supply coke to the chain-grate stokers of the stoker-fired boiler, while the new retort will supply coke to the pulverized-fuel boiler via a Fuller-Bonnot mill and Lodi burner. On the right of the lower portion of Fig. 2 is shown the side elevation of the new 60-tons-per-day retort plant. The new retort and its auxiliaries are shown in thick lines, while the existing building, coal bunkers and conveyors are indicated by faint lines. The boilers are designed to generate steam at 250 lb. per sq. in. pressure and a total temperature of 702° F. The steam is conveyed to the main power station, for use in the turbines, by an overhead pipe line as indicated on the site plan shown in Fig. 3.

The coal used in the process is similar to that ordinarily supplied for burning in the furnaces of the power station boilers and is obtained from several local Northumberland collieries. The coal is delivered by railway trucks to two hoppers from which bucket elevators lift it to the coal-screening plant, where the fines are removed and afterwards transported to other boilers in the power station by way of trucks on sidings, as shown in Fig. 3. In cases where the coal is suitable, screening may be dispensed with and the raw coal delivered direct to the retorts. The coal passing over the coal screen is conveyed by scraper conveyors to bunkers located immediately above the retort plants.

In the Babcock process the distillation of the coal is effected by passing hot gases in intimate contact with the fuel, no external heating being employed. This facilitates continuity in operation and renders possible the economic construction of large units of simple construction, with consequent low capital and operating costs. The method of operation is shown diagrammatically in Fig. 4. The coal, which is stored in bunkers, is dried and preheated before entering the retorts, as it has been found essential with certain coals to drive off the moisture and heat the coal before it enters the retort, otherwise the effects of condensation of the oil vapours in the retort gases may impede the flow of distilling gases through the coal. For this reason the coal, immediately it leaves the bunker, is passed through a preheater consisting of a chain grate enclosed in a brick chamber. The coal is conveyed in a layer approximately 3 in. thick on the chain grate, while waste flue gases at a temperature of 200° C. drawn from the flues of the boiler plant are passed through it, thus heating the coal by direct contact with hot inert gas.

The time taken to preheat the coal used at Dunston is approximately 15 minutes, and the preheating is carried out without effecting any distillation of oils.

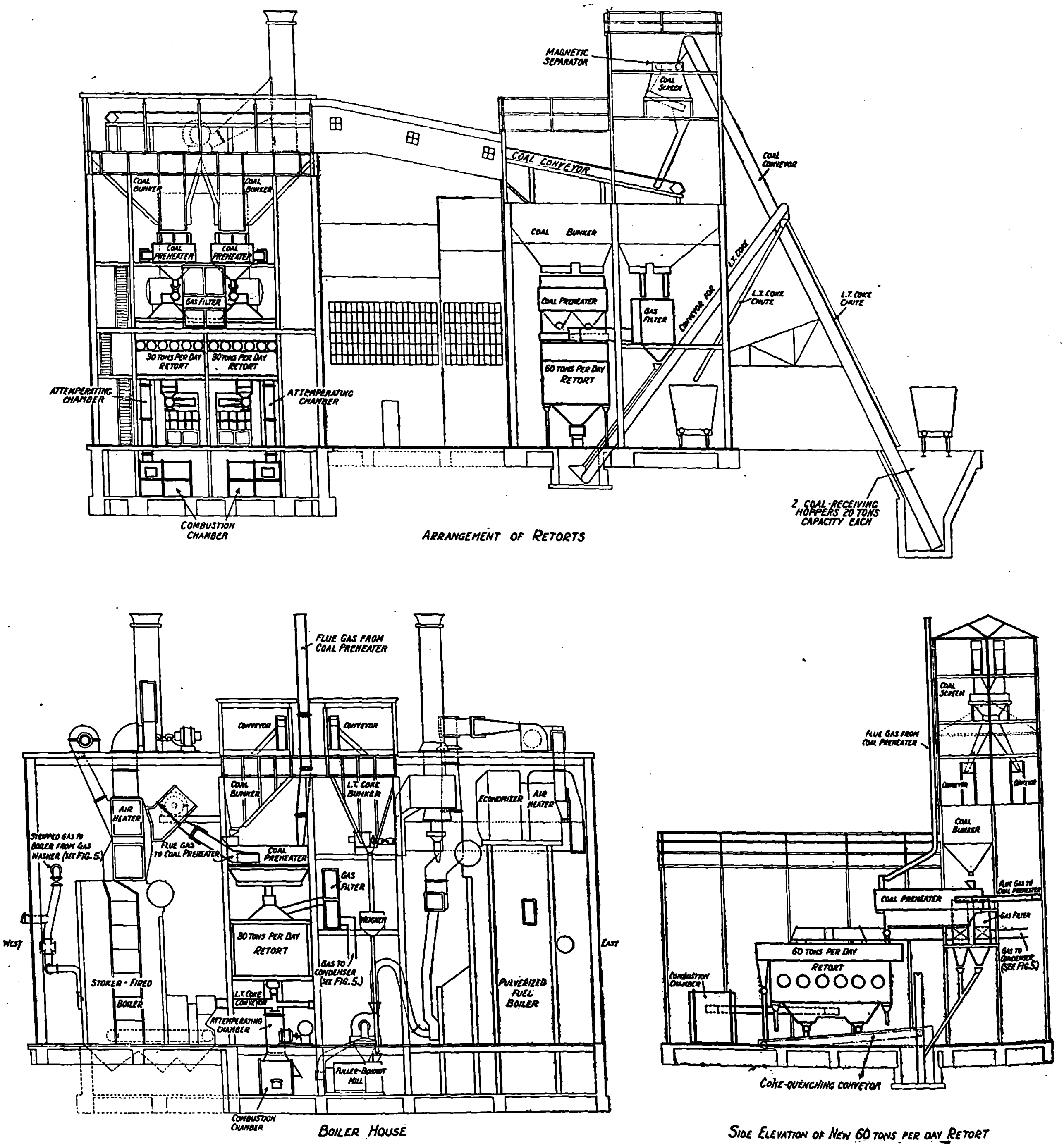
MAGNETIC SEPARATOR
COAL SCREEN
COAL CONVEYOR
COAL CONVEYOR
COAL BUNKER
COAL BUNKER
COAL PREHEATER
COAL PREHEATER
GAS FILTER
30 TONS PER DAY RETORT
30 TONS PER DAY RETORT
ATTEMPERATING CHAMBER
ATTEMPERATING CHAMBER
COMBUSTION CHAMBER
COAL BUNKER
COAL PREHEATER
GAS FILTER
60 TONS PER DAY RETORT
CONVEYOR FOR L.T. COKE
L.T. COKE CHUTE
L.T. COKE CHUTE
2 COAL-RECEIVING HOPPERS 20 TONS CAPACITY EACH
ARRANGEMENT OF RETORTS
FLUE GAS FROM COAL PREHEATER
CONVEYOR
CONVEYOR
COAL BUNKER
L.T. COKE BUNKER
AIR HEATER
STRIPPED GAS TO BOILER FROM GAS WASHER (SEE FIG. 5)
FLUE GAS TO COAL PREHEATER
COAL PREHEATER
GAS FILTER
WEIGHER
30 TONS PER DAY RETORT
GAS TO CONDENSER (SEE FIG. 5.)
L.T. COKE CONVEYOR
ATTEMPERATING CHAMBER
WEST
STOKER-FIRED BOILER
ECONOMIZER
AIR HEATER
PULVERIZED FUEL BOILER
EAST
RAYMOND-BONNOT MILL
COMBUSTION CHAMBER
BOILER HOUSE
COAL SCREEN
FLUE GAS FROM COAL PREHEATER
CONVEYOR
CONVEYOR
COAL BUNKER
FLUE GAS TO COAL PREHEATER
COAL PREHEATER
GAS FILTER
GAS TO CONDENSER (SEE FIG. 5)
60 TONS PER DAY RETORT
COMBUSTION CHAMBER
COKE-QUENCHING CONVEYOR
SIDE ELEVATION OF NEW 60 TONS PER DAY RETORT

FIG. 2.—General arrangement of low-temperature distillation plant at Dunston power station.

The use of flue gases in the first stage of the process in the manner described not only prevents undesirable condensation of oil vapours on the coal entering the retorts, but also effects an economy in the heat required to distil the coal, as the heating gases used in the preheater are practically waste gases from the boiler plant. The preheated fuel falls over the discharge end of the preheater grate into a hopper containing screw conveyors which feed the coal into a rotary coal-feeding valve which prevents leakage of gas between the preheater and the retort.

Each retort consists of a casing constructed of mild-steel boiler plate lined with brickwork where necessary. The upper part of the retort contains a device for feeding the coal on to the fuel bed and automatically spreading and levelling the incoming fuel by means of rotating scrapers which revolve at a speed of 1 r.p.m. The fuel bed is approximately 3 ft. deep and is supported on six slowly rotating rollers which fulfil the functions of a supporting grate and coke extractor. These extractor rollers consist of 6-in. square mild-steel shafts on which are fitted toothed wheels of non-growing cast iron, the teeth of which are spaced so that small spaces are left between the teeth of the adjacent wheels for the passage of the heating gases upwards through the coal. The rollers are operated by ratchets which are moved backwards and forwards by hydraulic cylinders. The lower portion of the retort forms a chamber for the reception of the heating gases and serves as a hopper into which the coke is continuously extracted prior to being fed to the stoker hoppers on the boiler.

Since the coke is used on stokers it is essential that large pieces of coke should be crushed down to a convenient size, and for this purpose a 2-roll crusher is provided in the bottom of the coke hopper. The crushed coke then passes through a rotary sealing valve into a screw conveyor which delivers it to the stoker hoppers. The screw conveyor traverses from side to side in the same manner as the well-known Babcock and Wilcox coal-distributing gear used on coal-fired stokers, and thus an even distribution of the larger and smaller pieces of coke is obtained in the stoker hopper. The screw conveyors are totally enclosed and are provided with water sprays which partially quench the coke before it reaches the stoker hoppers. The steam thus produced at the expense of the sensible heat of the coke is utilized in the manner described in the following paragraph.

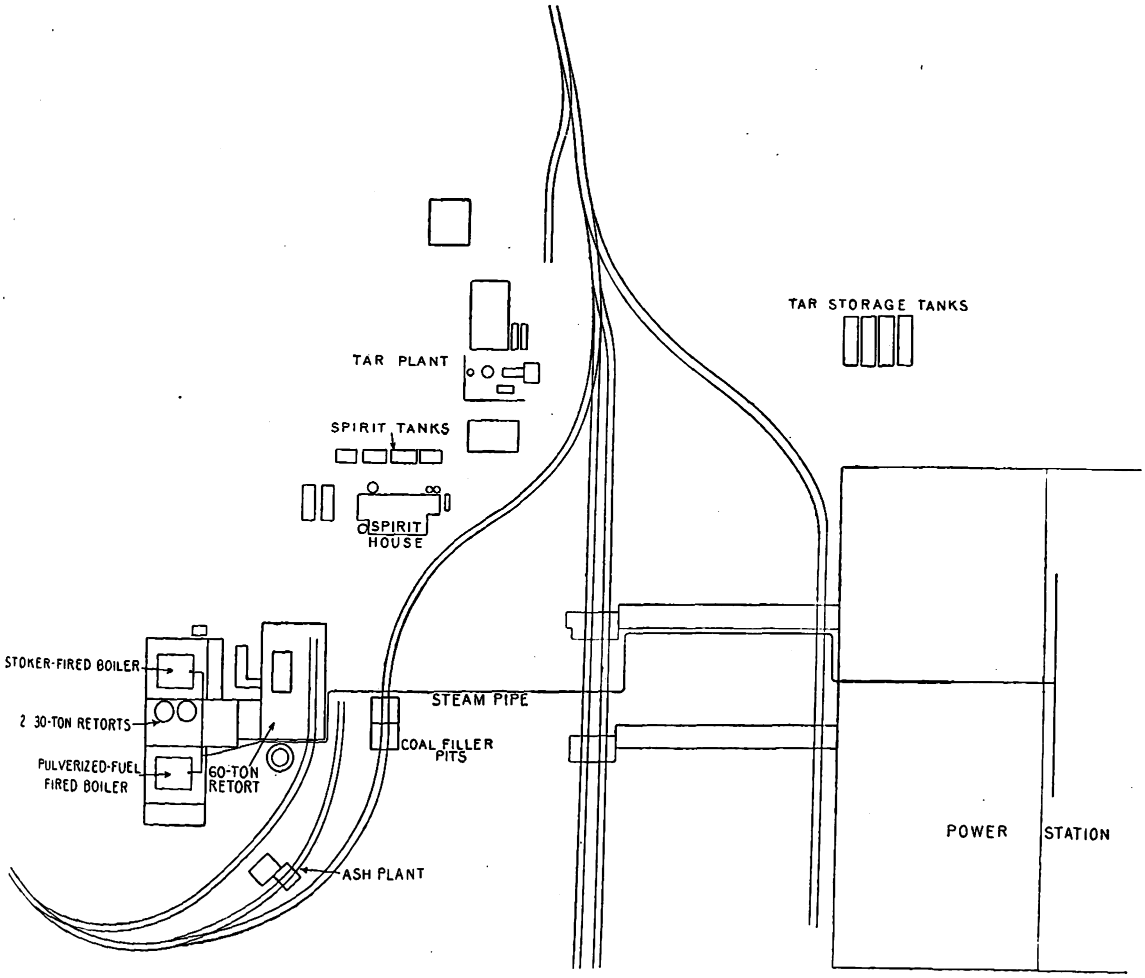

FIG. 3.—Site plan.

The distillation of the coal in the retorts is effected by passing a mixture of superheated steam at atmospheric pressure and combustion products at a temperature of between 600 and 700° C. into the lower hoppers of the retort and upwards through the fuel bed. No external heating of the retort is used which might be likely to cause overheating and consequent cracking of the oils evolved from the coal. The use of internal heating in the manner described ensures that the volatile constituents of the fuel are distilled and are carried off by the flow of gases at or below their temperature of evolution, and no volatile product is subjected to a higher temperature than that at which it was evolved.

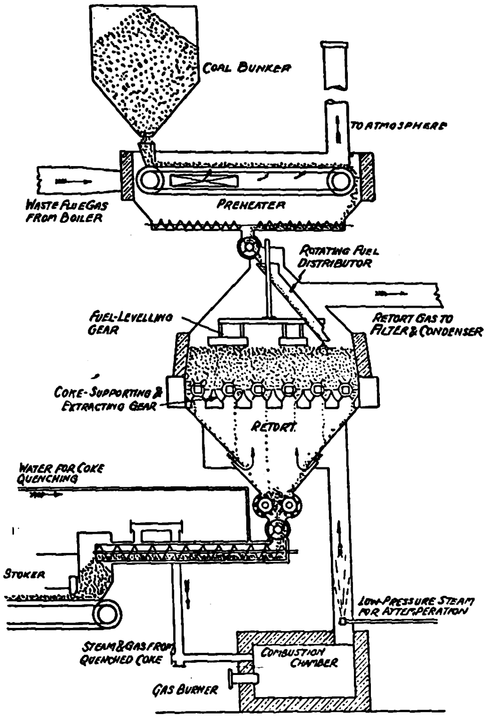
COAL BUNKER
TO ATMOSPHERE
WASTE FLUE GAS FROM BOILER
PREHEATER
ROTATING FUEL DISTRIBUTOR
FUEL-LEVELLING GEAR
RETORT GAS TO FILTER & CONDENSER
COKE-SUPPORTING & EXTRACTING GEAR
RETORT
WATER FOR COKE QUENCHING
STOKER
LOW-PRESSURE STEAM FOR ATTEMPERATION
STEAM & GAS FROM QUENCHED COKE
COMBUSTION CHAMBER
GAS BURNER

FIG. 4.—Diagram of retort plant.

The maximum temperature of the fuel in the retort does not exceed 550° C., which represents true low-temperature distillation conditions.

The distilling medium is obtained by first burning a suitable fuel in a small combustion chamber located below each retort, and, when combustion is complete, sufficient steam at atmospheric pressure is added to produce distilling gases of the required composition and temperature. Reference has already been made to the quenching of the hot coke leaving the retorts by spraying water into the enclosed coke screw-conveyors, whereby steam is generated. Part of the steam required for the production of the distilling gases is obtained from the quenching of the coke in the manner already described, and the additional amount necessary may be obtained by bleeding the turbine casings at a point where the steam may be obtained at substantially atmospheric pressure. The hot products of combustion may be obtained by any one of the following methods, all of which are available at Dunston.

(1) Combustion of powdered fuel.
(2) Combustion of producer gas.
(3) Combustion of coke-oven gas.

A small amount of gas is given off by the coke in the coke-quenching screw-conveyors and this is utilized in the combustion chamber for assisting in the production of the distilling medium. In order that the steam and combustion products may be thoroughly mixed before entering the retort, they pass through a relatively long brick-lined duct which serves as an attemperating chamber. The time taken for each particle of coal to pass through the retort is approximately 3 hours, and the rich retort gas and oil vapours from the coal mixed with the distilling medium are drawn off from the upper part of the retort and passed through gas filters which clean the gas of dust before condensation and further treatment. The gas filter consists of chambers in each of which there is a bed of small coke through which the gas is filtered. Arrangements are made for the withdrawal of dust and coke from the bottom of the filter, and the admission of fresh coke to the top. The

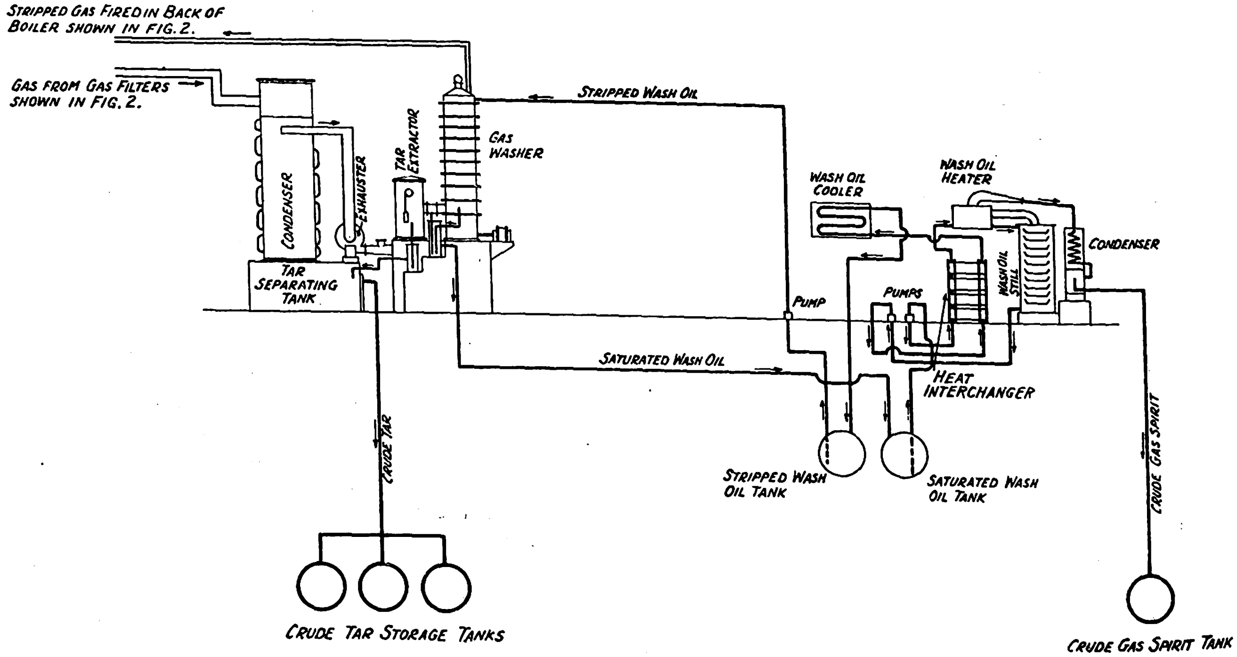
STRIPPED GAS FIRED IN BACK OF BOILER SHOWN IN FIG. 2.
GAS FROM GAS FILTERS SHOWN IN FIG. 2.
CONDENSER
EXHAUSTER
TAR EXTRACTOR
GAS WASHER
STRIPPED WASH OIL
TAR SEPARATING TANK
WASH OIL COOLER
WASH OIL HEATER
CONDENSER
WASH OIL STILL
PUMP
PUMPS
SATURATED WASH OIL
HEAT INTERCHANGER
CRUDE TAR
STRIPPED WASH OIL TANK
SATURATED WASH OIL TANK
CRUDE GAS SPIRIT
CRUDE TAR STORAGE TANKS
CRUDE GAS SPIRIT TANK

FIG. 5.—Diagram of gas-condensing and gas-washing plant.

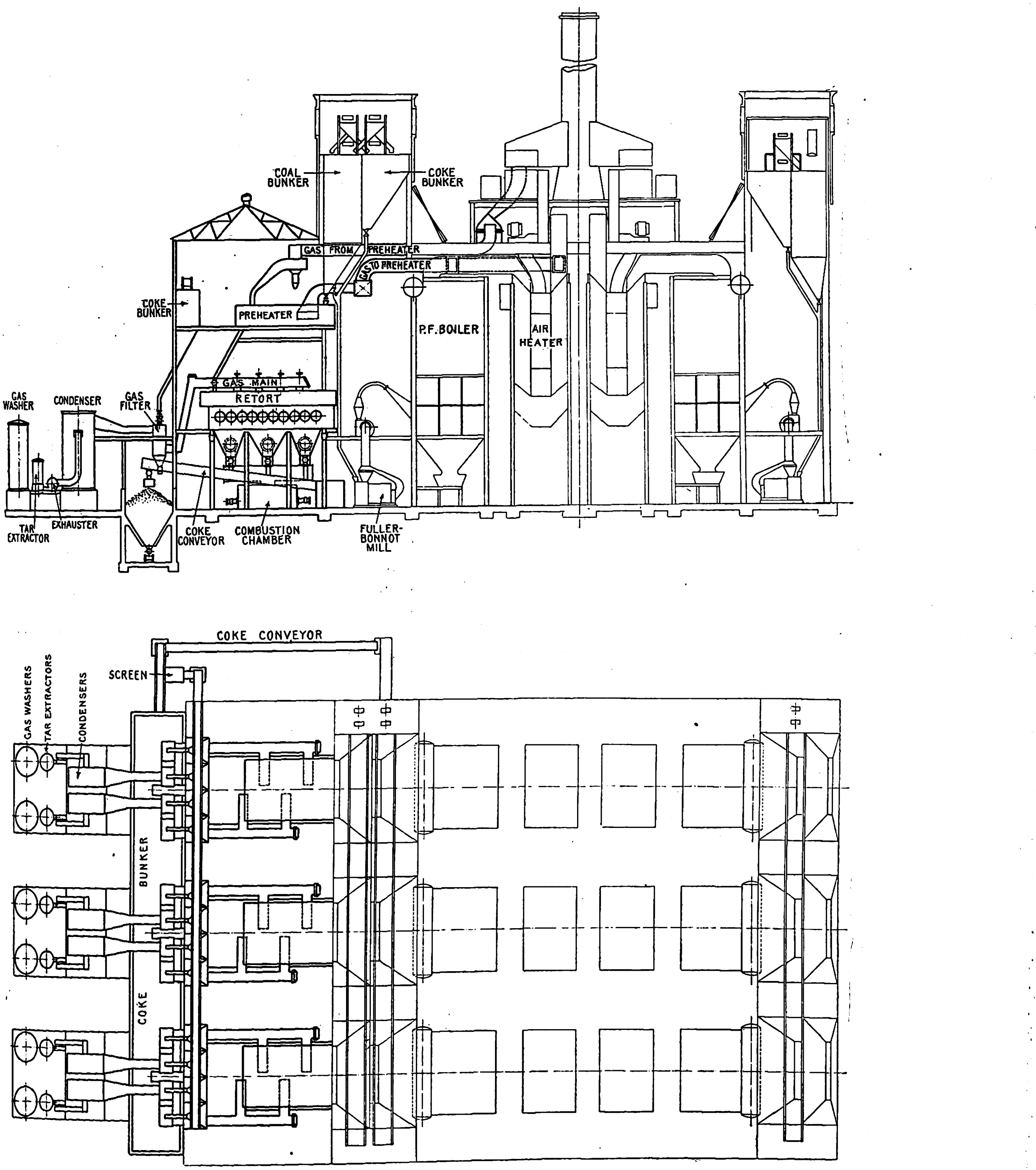
COAL BUNKER
COKE BUNKER
COKE BUNKER
GAS FROM PREHEATER
GAS TO PREHEATER
PREHEATER
P.F. BOILER
AIR HEATER
GAS MAIN
RETORT
GAS WASHER
CONDENSER
GAS FILTER
TAR EXTRACTOR
EXHAUSTER
COKE CONVEYOR
COMBUSTION CHAMBER
FULLER-BONNOT MILL
COKE CONVEYOR
SCREEN
GAS WASHERS
TAR EXTRACTORS
CONDENSERS
BUNKER
COKE

Fig. 6.—Typical arrangement of modern boiler house equipped with three 160-ton-per-day retorts. Scale 1 in. = 44 ft.

dust-free gas is then passed to a water-tube condenser in which the gas is cooled and the tar vapours are condensed, the resultant crude tar being collected in a separating tank and then pumped to storage tanks for sale or further treatment.

A rotary gas exhauster shown near the condenser in Fig. 5 draws the gases from the retorts through the condenser and forces them through a tar extractor to remove the final traces of tar, and finally to a rotary gas washer where the gas is brought into intimate contact with wash oil which absorbs the spirit from the gas. The oil used in the gas washer may conveniently be a light creosote oil produced by refining the tar made in the process. After passing through the gas washer the gas, which has a calorific value of about 80 B.Th.U. per cubic ft., is piped to burners fitted to the combustion chambers of the boilers and burnt to assist the coke in the generation of steam.

The plant for recovering the crude light spirit from the wash oil is shown at the right-hand side of Fig. 5. The design of this part of the plant is generally similar to that which has been used for many years in gas works and coke-oven plants for the recovery of benzol, and presents no feature of special importance. The following is the sequence of operation:—Stripped oil is pumped continuously through the gas washer to absorb the spirit from the gas, and returns in a saturated state to the storage tank, while the saturated wash oil is also pumped continuously to the stripping plant in which the crude spirit is recovered for sale or further treatment. The plant for refining the crude tar and crude spirit from the gas for the production of the finished by-products, shown in Fig. 1, also follows the usual gas and tar works practice. The preparation of the finished by-products is preferably carried out in a separate plant located at some convenient distance from the power station, so that crude tar and crude spirit can be easily pumped over to the storage tanks which form part of the refining plant. The present plant has proved entirely satisfactory over a long period of working, but it is evident that to meet present-day conditions where power plants are increasing in size and it is the practice to install boilers of large evaporative capacity, retort units of very much larger capacity than 30 tons of coal per 24 hours are required for commercial operation. With this in view, designs have been prepared for single-retort units capable of dealing with 160 tons of coal per 24 hours, which it is considered would be a convenient size for use in conjunction with the size of boiler unit now coming into general use. In order to manufacture retorts of large size it has been found necessary to adopt certain modifications in the design, e.g. the cross-section of the retort is now of rectangular instead of circular section, with the result that the retort units can be more conveniently disposed in or alongside the boiler house and the cost of construction per ton of coal distilled is very much less. The cost of labour required to operate large units is also very much lower than with relatively small units. The method adopted for distilling the coal contained in the new 60-ton retort, as well as those now designed for even larger capacity is, however, identical with that already described, as practice has shown this method to be entirely satisfactory owing to its simplicity and the ease with which it can be controlled.

[The discussion on this paper will be found on page 229.]

DISCUSSION ON

"LOW-TEMPERATURE CARBONIZATION OF FUEL, WITH SPECIAL REFERENCE TO ITS COMBINATION WITH THE PRODUCTION OF ELECTRICITY."*

JOINT MEETING OF THE INSTITUTION AND THE INSTITUTE OF FUEL, 21ST NOVEMBER, 1929.

Mr. W. M. Selvey: A joint meeting such as this would at one time have been termed unique; and whilst it is unique from the sense of priority as regards these two important institutions, meetings of this kind are becoming increasingly necessary. On this occasion we have in active association the older high-temperature carbonization industry known as the gas industry, bringing with it the new low-temperature carbonization industry, and the electrical power industry. The fostering of the low-temperature industry by the high-temperature industry has only just begun, and in a tentative measure, and its fostering by the electrical industry is shown, in the papers presented this evening, to be coming about only in three places: at Wölfersheim, in Germany; at Milwaukee, in the United States; and at Dunston-on-Tyne, in the North of England. The fact that Dunston is in Durham is of very material interest, because Northumberland coal, and not Durham coal, is being used there. Dr. Rosin has covered admirably what may be called the philosophical side of the question. Are we to visualize a system which is (*a*) a dual co-operation of electrical supply with the chemical industry (distillation, etc.); (*b*) a triplex co-operation of electrical supply, the gas industry (rich gas) and the chemical industry; or (*c*) a quadruplex co-operation of electrical supply, the gas industry, the chemical industry, and the domestic fuel industry (the product of which latter is commonly referred to in the United States as "artificial anthracite")? Under heading (*a*), consider the paper by Messrs. Smythe and Weeks. Obviously this is the simplest type of co-operation to bring about, considering our rigid national type of organization; for instance, the chemical industry has received statutory protection against overlapping with the gas industry. It has long been known that the real profits in this co-operation are all in the direction of the working up of the by-products; for instance, in connection with the introduction of German coke ovens in England in the early days. In some cases, in Yorkshire, coke ovens were installed free of cost in exchange for 10 years' production of by-products. Hence, the dual co-operation is a proposition to cheapen electrical power by (i) bringing into the balance sheet a profit from success in a collateral activity; (ii) producing the raw material for the collateral activity from a cheaper form of raw fuel than had hitherto been possible (i.e. steam slack, as against gas-making and coking slacks). It might broadly be claimed that (ii), even alone, justified (i), should statutory restraint ever be sought by misguided persons to smother this scheme. Consider, also, the scheme at Wölfersheim, which fits the above particularly well, in that brown coal is the cheaper form of raw material. Here, then, is a possible explanation of our having been shown two such processes in actual practical operation. They have "graded up" a raw product. With regard to the triplex co-operation, Mr. McEwen states, in effect, that he must add to the simple system of power and chemicals a graded-up gas product, and immediately he has to balance the parallel requirements of gas and power. He will probably succeed, but here he has to his hand financial interests which own and operate, at the same time, gas and power undertakings. In this connection the far-sighted have already acquired chemical interests, so that here is, probably, the only real way of bringing such a scheme about—a common financial umbrella. It is obvious that such a scheme presents no real difficulties in a country such as the United States, with its comparatively unfettered private enterprise, but in this country, with its statutory companies operating power and gas, and chemical companies with Parliamentary protection, it cannot be expected, unless a new spirit comes about and legislation is conceived for furthering industry instead of being solely for the protection of the individual consumer or the preservation of the *status quo*. This would indeed be a revolution. When we consider a scheme of the nature of (*c*), in which domestic fuel is sold according to a variable market, when gas is sold to a gas company when and as it can take it, and the balance of unsaleable fuel, whether breeze or surplus gas, or gas of low calorific value, is used for power, to say nothing of working up the by-products, one is appalled by the change which would be necessary in the national habits before such a system could become general. It certainly could not be of much or primary interest to the power concern, and therefore whatever successful schemes may eventuate, which are in part of this type, are not likely to fall within the scope of this consideration. This does not mean that such schemes may not be successful in other directions. I believe that the authors would be generally in agreement with me in that respect. Dr. Rosin states that in Germany they are already moving from the dual to the triplex. Yet one constantly sees simple-looking economic balance sheets which assume that much of this could be effectively brought about.

Dr. A. T. de Mouilpied: I agree with Mr. McEwen and Dr. Rosin as to the necessity, on economic grounds, for a working alliance between the coal-treatment plant, the power station and the gas distributors. Dr. Rosin has called it, very aptly, a triple coupling; but he states that in the near future gas will be looked upon as of greater importance than oil. I cannot agree with this statement, because I think that the hydrogenation of the primary coal oils will ultimately be found to be the most profitable by-product outlet, at least in this country. Fundamentally, however, the important product is the semi-coke. The authors of all three papers adopt the basis of the equivalence of heat units in the raw coal and in the semi-coke. As Mr. McEwen expresses it, there is no appreciation in the value of the solid residue. It is true that the calorific value of the semi-coke is of the same order as that of the original coal; it is sometimes a little higher for the semi-coke, depending upon the amount of moisture in the coal, and also upon whether one is comparing " gross " or " net " calorific values, but, broadly speaking, the calorific values are much the same. The figures given in the paper by Messrs. Smythe and Weeks show that quite well. There has been evidence for a considerable time, however, that the semi-coke, when burning, gives off a good deal more radiant heat than the coal, and a comparative test has been made, under industrial conditions, of a parent coal and its semi-coke. So far as I know, this had not been done before. A coal was selected and treated in the Salermo retort, the basic principle of which is the external and progressive heating of small particles kept in continuous motion in a system of troughs and revolving paddles. This system produces a very homogeneous semi-coke, made at a low temperature (500–550° C.), in such a way that there is no overheating of the charge and no cracking of the vapours, which are at once removed with the gas. The normal volatile content is from 13 to 14 per cent, so that the coke has the desired ignitability and combustibility. The semi-coke does not suffer from the presence of graphite, which has been referred to in the paper by Messrs. Smythe and Weeks as characteristic of semi-coke made in some externally-heated retorts. Mr. Shaw, city electrical engineer at Worcester, gave facilities for a test to be carried out there this summer. The boiler used was a Stirling water-tube boiler, with a heating surface of 8 989 sq. ft., this being the main boiler at the station. The test lasted for 8 hours in each case, and the fuel was burned in the pulverized form. The coal used was Birch Coppice screenings, containing 10·9 per cent of moisture, 19·1 per cent of ash and 29·3 per cent of volatile matter, with a calorific value of 9 830 B.Th.U. per lb. gross and 9 375 B.Th.U. per lb. net. The semi-coke was made from it at Fulham, and this semi-coke, as burned, contained 1·72 per cent of moisture (for it had picked up some moisture when travelling from London), 26·4 per cent ash, and 14·1 per cent volatile matter. Its calorific value was 10 055 B.Th.U. per lb. gross and 9 790 B.Th.U. per lb. net. During the 8-hour coal test, 46 276 lb. of coal were burned and 296 251 lb. of water evaporated; of semi-coke, in the same time, there were burned 41 882 lb., and 309 246 lb. of water were evaporated. The weight of water evaporated per lb. of fuel from and at 212° F. was 7·796 lb. for the coal and 8·926 lb. for the semi-coke. This showed an increase in equivalent evaporation per lb., using semi-coke, of 14·5 per cent. Making the necessary correction for the higher calorific value of the semi-coke, in that particular test the latter was worth, therefore, for steam-raising purposes 12·2 per cent more per gross heat unit than the original coal, and 10·1 per cent more per net heat unit—which latter I consider to be the more desirable basis to adopt. Some explanation of the difference in the results with the coal and the semi-coke is to be found in the fact that the furnace temperature is 378 deg. F. higher for the semi-coke, while the boiler exit temperature was 33 deg. F. lower. There must have been more radiant heat liberated, and in the absence of smoke it was effectively used. This was, of course, an isolated test, and it is extremely desirable that this direct comparison should be repeated using, for the semi-coke, pulverizers and, particularly, burners adapted to its combustion. I offer these results as evidence to support the view that semi-coke has a higher value than that based on heat units only. If this were definitely established, it would have an important bearing on the economic aspect of the problem. The absence of deposit on the boiler tubes when using semi-coke must increase efficiency and save the cost of cleaning. With regard to the effect of distillation on the sulphur content of the fuel, the coal used at Worcester contained 2·27 per cent of sulphur, while the semi-coke contained 1·09 per cent, or less than half that contained in the coal. This reduction of 50 per cent, leading to a similar reduction in the amount of sulphur acid fumes emitted from a station, has a very direct bearing on a problem which is being much discussed. Can Dr. Rosin give some indication of his method of removing phenols from waste liquors?

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* Introductory papers by Mr. McEwen (page 205), Dr. Rosin (page 212), and Messrs. E. H. Smythe and E. G. Weeks (page 219).

Dr. C. H. Lander: In comparing low-temperature carbonization as applied prior to steam generation for, say, electric power production, with low-temperature carbonization applied for the purpose of producing a totally different type of solid fuel, one finds the problem eased considerably in one direction (on the side of electric power), but in another direction made more difficult. The easing of the problem arises from the fact that it is possible to design machinery capable of very large " through-puts," which machinery should be cheap in capital cost and labour cost. On the other hand, there is no increase in the commodity value of some of the carbonization products, i.e. one heat unit in the product has only the cash value of one heat unit in the raw coal. For instance, to take an extreme case, supposing one installed a low-temperature carbonization plant at an electricity works, and burned the coke, gas and tar under the boilers, the result would be the expenditure of capital and labour to lose the heat units used in the process, with no compensating advantage. The next step, perhaps, is to install a plant on the lines of that referred to in the paper by Messrs. Smythe and Weeks, in which case there is little or no increase in the commodity value of the solid fuel produced by low-temperature carbonization as compared with the fuel with which one started. Therm for therm, it is substantially the same; there might be an increase of 5 or 10 per cent in thermal value, but the increased value is not nearly equivalent to 20s. per ton, as might be the case with solid fuel produced from cheap coal for domestic use. Again, the gas is burned under the boiler, and there is no increase of commodity value there. The engineers of generating stations which have been burning coke-oven gas say, quite definitely, that the gas is worth to them exactly its thermal value. Hence in this particular case one's activities are narrowed down to the stepping-up of the commodity value of the tar. If one obtains finished products from the tar, one obtains a greater commodity value, but it costs money to obtain the finished products. Mr. McEwen has pointed out the advantage of selling the gas, and the commodity value of the gas is raised if one can get gasworks prices for it. Trouble has been experienced in connection with the specific gravity of the gas. It is not recognized as widely as it should be that for gasworks purposes the specific gravity is almost equal in importance to the calorific value; if changes of specific gravity occur, the effect of the constancy of calorific value is upset, and modifications of burners become necessary. Mr. McEwen's paper shows that many difficulties have been overcome, but other difficulties, of a minor nature, have appeared as the work has progressed. Tests have recently been carried out on the plant at Dunston-on-Tyne; the report has not yet been published, but the figures obtained confirm absolutely the figures given in the paper by Messrs. Smythe and Weeks. I feel that there is a tendency, in connection with this subject, to accept any explanation as axiomatic simply by virtue of its constant repetition. Is it actually Mr. Smythe's experience that coke made in an externally-heated retort is more difficult to burn than coke made in an internally-heated retort? I have experienced no difficulty in burning in a pulverized form coke made in an externally-heated retort. In any case I doubt the validity of the explanation put forward. Certainly some cokes are more reactive, more easily burned, than others, and it has become customary to attribute this to the presence of graphite in the less reactive high-temperature cokes. Some years ago Sir William Bragg made some X-ray experiments on four types of coke—a metallurgical coke, a vertical-retort coke, an externally-heated low-temperature retort coke, and an internally-heated (superheated steam and gas) low-temperature retort coke. The tests were carried out most carefully, and the haloes which are characteristic of graphite were discovered in all four samples. Of course, the tests did not show whether the graphite was present in different quantities, but it is quite possible that the graphite had nothing to do with the results. However, by the ionization-chamber method, a measure can be obtained of the size of the graphite particles, and as the tests proceeded from the less reactive to the more reactive cokes, it was found that the size of the particles diminished. This might or might not be the correct explanation; there is as yet insufficient reliable evidence available to settle the point. It is particularly interesting to have confirmation by Dr. Rosin that the brown-coal problem is the one which is of the greatest interest to Germany in connection with low-temperature carbonization. Brown coal contains so much moisture that its commodity value as a boiler fuel is very low. It has to be dried: its commodity value is increased by the extraction of the moisture, and it is perfectly natural, when dealing with an absolutely non-coking coal, to go a step further and carbonize it.

Mr. H. Nielsen: With regard to the process described by Mr. McEwen, it seems to be wrong to grind the raw coal first and carbonize it afterwards, as this involves grinding from 30 to 35 per cent more material. After all, the quantity of heat generated in the boiler, weight for weight, by powdered raw coal and powdered residue was, for all practical purposes, the same. It has been found by experience over a considerable period, on quite large-scale working, that the grinding of the residue, i.e. a residue with no graphitic carbon deposit, shows a saving in power sometimes as great as 30 per cent over that expended in grinding the corresponding raw coal. Taking this into consideration, for a given amount of heat set free in a boiler one can effect a saving in overall power consumption in grinding of about 45 to 50 per cent. Therefore, it seems more satisfactory to carbonize the raw coal in its original condition, and then to cool and quench the residual fuel if so desired, since a residual fuel of some size can always be dealt with much more easily than a very finely ground, highly reactive powder. With regard to the paper by Dr. Rosin, I have been told that considerable difficulty has been experienced with the Geissen retort owing to the growth of the cast iron, and that in one or two cases the passage through the retort of the material to be carbonized had been almost stopped, owing to the growth of the metal having resulted in the closing up of the corrugations.

Mr. E. W. L. Nicol (*communicated*): The statement on page 206 of Mr. McEwen's paper regarding American practice and preference is no doubt correct, but it would be unfortunate if it were misconstrued as applying equally to this country. Business relations have, in fact, been established between several of the principal London electric and gas supply authorities for the purchase and supply of high-temperature coke as fuel. This business "alliance' is one result of the development of the sandwich system of firing coke, and the coke-burning mechanical stoker, and it has been maintained amicably to the mutual advantage of the parties, upon a fairly large scale, during the past 10 years. This fact tends to support the view that the development of combined gas-manufacturing and electric-generating stations is unnecessary in this country. The coal through-put of the Greater London gas supply authorities already exceeds 5·6 million tons a year; and quite a considerable proportion of the resultant 2·5 million tons of high-temperature coke is utilized by public electric and other power stations by means of mechanical stokers, either alone or blended with low-grade coal of a description that otherwise is often considered to be unsuitable for use with chain grates. Low-temperature coke is obviously more amenable to the pulverized-fuel system of firing steam boilers; but the question of facilitating or retarding the development of this system is no complete criterion for judging the respective merits of the high-temperature process of coal carbonization and those of the low-temperature process.

Mr. N. Prentice: (*communicated*): Can Messrs. Smythe and Weeks give the composition of the heating gases before the latter enter the retort? Only about one-half the volatile content of the coal is extracted, and the reason given for leaving the remaining 12 to 14 per cent is to ensure better use in the steam-boiler firing. Could not this large percentage be made use of for by-products if the resultant gas and coke were used in a Humphrey-type gas pump and Diesel-type pulverized-fuel pump and a water turbine, instead of a boiler and steam turbine? No credit is taken for sulphur or ammonia and the resultant sulphate of ammonia, which would increase the value of the by-products, and which are not available with straight boiler-firing.

THE AUTHORS' REPLIES TO THE DISCUSSION AT THE JOINT MEETING.

Mr. S. McEwen (*in reply*): Mr. Selvey's classification showing possible co-operators with a low-temperature carbonization industry prompts him to conclude that in the extended stage of his classification, namely, the quadruple co-operation of the electrical industry, the chemical industry, the gas industry and the domestic-fuel industry, an electric power company would not be materially interested. It may be said, however, that while such co-operation embraces a wide field three industries of the group fall within the sphere of public service, the power company being by no means the least important. This surely is sufficient justification for the power station engineer to occupy a prominent place in the development of means for the more rational utilization of our national fuel resources. Although Mr. Selvey seems impressed by the apparent impossibility of any working alliance between industries now entrenched and protected against each other, I would submit that the situation could be met by the establishment of coal "refineries" wherein the raw coal would be classified, cleaned, graded and carbonized, the products being supplied to meet the requirements of the four industries of Mr. Selvey's quadruple group. The adoption of the scheme for the provision of a gas "grid," now being considered, would remove the only barrier to the practicability of the suggested coal-refinery system.

The use of carbonized fuel, whether in lump or powdered form, for power generation, as one of the principal products of the "refinery," demands the interest and co-operation of the power engineer, and in this connection the claims made by Dr. de Mouilpied, as to greater value of a heat unit in the form of semi-coke as compared with a heat unit in the form of coal, are of interest. It would be of the greatest help to the commercial development of an industry for carbonizing coals at low temperatures, for the production of fuel for power generation, if a higher price per B.Th.U. could be established for semi-coke as compared with coal. I have said that there is no appreciation in the value of the solid residue, and there is certainly none comparable with the appreciation in value which results from the carbonization of coal to form a smokeless domestic fuel, and, while unhesitatingly admitting the accuracy of Dr. de Mouilpied's comparative trials, the results obtained do not directly yield data enabling me to appraise in monetary terms the benefit to be derived from the use of semi-coke. The power engineer, if asked to pay more per B.Th.U. for a ton of semi-coke than he pays for coal, will consider alternative methods of securing a similar benefit to that derived from the use of semi-coke. The comparative trials referred to by Dr. de Mouilpied show that with semi-coke as a fuel an efficiency, based on the net calorific value of the fuel, of 88·47 per cent was obtained while the boiler was operated at a capacity of 5·2 lb. of water from and at 212° F. per sq. foot of heating surface. Now it is known to the power station engineer that by a redistribution of heating surface presenting the maximum area to radiant heat, and by preheating the air required for combustion, it is possible to evaporate over 20 lb. of water from and at 212° F. per square foot and to obtain an evaporative efficiency of 90 per cent. With the development of steam-boiler practice a greater scope for improvement in results is offered than can possibly accrue from the substitution of semi-coke for coal. In the end the combustion of semi-coke will give better results than can be obtained from coal from the same boiler equipment, but the measure of the improvement can be stated in terms of the heating surface necessary for a given performance, and the increase in value of semi-coke to the power engineer over that of coal of an equal B.Th.U. content will not be greater than is represented by the annual charges for capital to be expended on additional heating surface, calculated in relation to the annual coal consumption. It will be found that such charges will not exceed 2 or 3 per cent of the value of the coal. In my opinion it is therefore desirable in preparing a prospective balance sheet for a low-temperature carbonization scheme for a power station to appraise the semi-coke at a value, per B.Th.U., equal to that of raw coal, and to rely on the distinct advantages which will result from its use to secure its ready adoption by power station engineers when the fuel becomes available.

Mr. Nielsen, in advocating the carbonization of raw coal in its original condition and the subsequent pulverization of the semi-coke for the preparation of powdered smokeless fuel, presents only one of the economic factors involved, namely, the relative costs of pulverization. There is, however, another factor which on balance is of much greater importance, namely, the cost of carbonization. For years the development work in low-temperature carbonization was confronted with the difficulty of securing a sufficiently high rate of heat transmission with the very low heat head it was possible to employ. For this reason operating and capital costs attained a very high figure, the capacity of low-temperature retorts being relatively low. By the method of carbonizing pulverized coal in suspension, an enormous heat-absorbing surface is exposed to the source of heat, and thus one of the factors for a high rate of heat transmission is at its maximum. In practice it has been proved that the carbonization of powdered coal in suspension is effected in a period of a few seconds, whereas the carbonization of lump coal requires several hours. Such a high rate of heat transmission made it possible to overcome the handicap of low temperature head and secure a high capacity from a single retort with the attendant low charges for operation and capital. The extra cost of pulverizing involved in the process described is only a fraction of the saving obtained as compared with the cost of carbonizing raw coal in its original form.

Mr. Nicol expresses the fear that my statement that coke produced by high-temperature processes is not favoured by power station engineers in America might be assumed to apply to power station engineers in this country, and in my opinion, while my paper dealt specifically with American conditions, the application of my statement is not limited geographically but is substantially true for all countries. The use of coke breeze, a waste product from high-temperature carbonization plants, is adopted for power generation in any country where its price is sufficiently lower than that of raw coal to compensate for the limitations which such fuel imposes on a steam-generating plant. Although, as Mr. Nicol states, the consumption of coke, presumably in the form of breeze, by power stations is considerable from the gas manufacturer's point of view it is inconsiderable when compared with the quantity of raw coal consumed for power generation. Power station engineers would not purchase high-temperature coke in any form if raw coal of a similar calorific value were available at the same price per ton. This being the case, it follows that high-temperature coke is not favoured by power engineers. Low-temperature coke can make reasonable claims to the favour of power engineers.

Dr. P. Rosin (*in reply*): The method adopted for treating carbonization liquor applies especially to the removal from brown coal effluent-water of phenols and fatty acids, which are somewhat different from the bituminous-coal phenols. The method consists in thoroughly pre-drying the coal, then destroying the sulphuretted hydrogen (H_2S) by sulphur dioxide (SO_2) and extracting the concentrated phenols and acids by a multiple-effect scheme. This extraction follows the example given by the Emscher Genossenschaft for removing phenols from coke-oven liquors, except that a percentage of certain insoluble tar bases is added to the extracting benzol. I would emphasize the great importance of pre-drying the carbonization coal, in order not only to diminish the effluent-water nuisance but also to increase the throughput of the carbonization furnaces.

As to Mr. Nielsen's question, the difficulties due to the growth of the cast-iron rings in the Geissen furnace have been overcome by thoroughly controlling the temperature. Moreover, special steels, such as nichrotherm, a heat-resistant steel containing nickel and chrome, have shown advantages as compared with cast iron.

Messrs. E. H. Smythe and **E. G. Weeks** (*in reply*): In reply to Dr. Lander's criticism of our remarks concerning the semi-coke produced by externally heated retorts, this was the only matter referred to in the paper of which we had not actual experience, and the statement was based on a series of experiments conducted in Germany and reported to us. We should be only too pleased, however, to compare notes with Dr. Lander, and are quite ready to be convinced by him of our mistake.

With regard to Mr. Selvey's remarks in connection with the use of Northumberland coal, the Dunston carbonization plant was designed primarily to operate with the type of coal used in power stations for steam generation, and although it is situated in the county of Durham it is at the extreme north of that county and is thus close to the South Northumberland coalfield, which produces steam coals of the class normally used in power stations. For this reason the Dunston plant is normally operated with Northumberland non-coking steam coals, and the results given in the paper are based on experience gained with that class of coal. The coal produced in the county of Durham is, as is well known, the finest coking coal in the world and, as such, is in great demand for the high-temperature carbonization industries and usually commands a higher price than non-coking steam coal, with the result that coking coals are not in general use in power stations and are not, therefore, of immediate interest for low-temperature carbonization in combination with the production of electricity.

In connection with Dr. de Mouilpied's statement as to the increased evaporation obtained in a steam boiler when fired with low-temperature coke, compared with the results obtained for similar tests made with the parent coal, we would say that our experience with boilers fired with chain grates and burning low-temperature coke has shown no appreciable increase in evaporative efficiency. It was interesting to hear a similar statement by Mr. McEwen, who has used pulverized low-temperature coke for firing boilers. In view of the fact that boilers burning coal now attain efficiencies of 90 per cent and over, it can hardly be conceived that an additional 9 or 10 per cent efficiency would be obtained by converting the fuel from coal to low-temperature coke. Dr. de Mouilpied also refers to the percentage of sulphur contained in the low-temperature coke as being half that in the parent coal. Our experience shows that no hard-and-fast rule can be laid down for the reduction in sulphur content, as it varies widely with different coals. In certain instances the reduction in the percentage of combustible sulphur in the coke approaches the figure mentioned by Dr. de Mouilpied, whilst in others there is no appreciable decrease. It is important that any figures given for sulphur content of coal or coke should clearly show whether the laboratory determination has been made for " total sulphur " or " combustible sulphur," as any confusion in this respect may lead to entirely erroneous conclusions.

With regard to Mr. Prentice's inquiry as to the composition of the heating gases before the latter enter the retort, these gases are a mixture of low-pressure steam and combustion products at a temperature of about 650° C. The average composition by volume of the heating gases entering the retort is approximately as follows: steam 46 per cent, carbon dioxide 3·2 per cent, oxygen 4·8 per cent, nitrogen 46 per cent. Mr. Prentice suggests that the large percentage of volatile matter left in the low-temperature coke might be made available as by-products, presumably by completely distilling the coal at a high temperature in order to reduce the volatile to a very low figure. If our understanding is correct, Mr. Prentice's suggestion is equivalent to ordinary high-temperature carbonization and in this connection it might be noted that the yields of by-products from high-temperature carbonization are not higher than from low-temperature carbonization, except that there is an increased yield of gas and sulphate of ammonia. High-temperature carbonization is not remunerative unless a price is obtained for the gas in excess of that which a power supply undertaking could afford to pay for gaseous fuel, and in view of the recent developments in the manufacture of synthetic ammonia the recovery of sulphate of ammonia from coal is far from attractive. With regard to the use of Humphrey pumps and Diesel engines plus water turbines, we submit that while these might produce power at high thermal efficiency they are not at present available in sufficiently large units to meet the requirements of the modern electric power station.

EAST MIDLAND SUB-CENTRE, AT NOTTINGHAM, 26TH NOVEMBER, 1929.*

Mr. L. M. Jockel: On page 220, in Messrs. Smythe and Weeks's paper, reference is made to the lack of utilization in the boiler furnace of the "higher value heat units" in the coal from the volatiles; but this cannot always be assumed, and depends to some extent upon the constituents of the volatile matter. Fuel technologists are now agreed, I think, that two coals of similar ultimate analysis, when heated to the same temperature, may behave differently in practice both as regards the yield of volatile matter and the nature of the coke formed. Although the subject has not been fully investigated, it would seem that the yield of volatile matter is dependent on the presence of certain constituents which are rich in oxygen. In regard to the gas firing of boilers, the efficiency is naturally affected to some extent by such considerations, and from experience I can say that gas firing is not always a very efficient proposition. On the same page, the higher and lower heating values of coal and coke are referred to, and very exact calorific values are given. I should like to ask the authors what is meant by the expressions "higher" and "lower" heating values, as, of recent years, the Institution of Civil Engineers has definitely laid down standard expressions for calorific value and thus ruled out any ambiguity in regard to the old methods of stating heating values on a higher or lower basis. Calorific values should be stated to the nearest ten, as the accuracy of the Mahler bomb is only about ± 0·5 per cent in practice. It is a particularly interesting fact that the calorific value of the semi-coke, quoted on page 220, is almost as good as that of the raw coal treated. Is the sulphur content always higher after low-temperature coking than the content in the raw coal? I gather that ammonium sulphate recovery is not worth while at low temperatures. Unfortunately no costs are given in the paper, but it is difficult to see, at present, how the cheapening of a unit of electricity can be effected by low-temperature carbonization plant with fairly cheap coal, although, of course, fuel prices will undoubtedly increase during the next few years. Can Messrs. Smythe and Weeks give us particulars of space required by the Dunston plant, expressed, say, as weight of water evaporated per hour per sq. ft. of floor area?

Mr. F. Nicholls: Undoubtedly we shall eventually have to carbonize our coal instead of using it in the present way. From an electrical engineer's point of view the plant appears to be very simple, and from an operator's point of view it is not very difficult to operate, so that the power station engineer need not be afraid of such a plant. The price which can be obtained for the oil will be a determining factor as to whether it is worth while working such a plant to produce oil. It would be interesting if Messrs. Smythe and Weeks would give us some information on this point; i.e. regarding capital charges, and maintenance costs per ton of coal used. They have pointed out that they have had no trouble with the preheaters; it occurs to me that they would be troubled with fires from waste gases, and might also suffer from temperature variations. What is the volatile content in the coke fed to the boilers at Dunston, and why is it proposed to use pulverized coke in the newer plant, and not coke, as at present?

Mr. W. Pearson: The desirability of recovering the valuable constituents of the coal used in generating stations is admitted; but, with industry controlled as at present, the determining factor is overall cost. I would ask Messrs. Smythe and Weeks whether the margin at present available for return on the capital expended on the additional plant is great enough to afford a reasonable prospect of financial success when a large proportion of the coal used in generating stations is treated in this way, with consequent reduction of the prices obtainable for the by-products.

Mr. F. Dransfield: One sees in this paper the beginning of the end for power station engineers. Electricity will be generated in the future from the waste products of other industries, and one can visualize public or private concerns supplying the requirements of a community for electric power, gas, steam, smokeless fuels and liquid fuels from one co-ordinated plant. People with vision are attacking the various phases of the problem, and, although at the present moment one does not expect these experimental plants to pay on a commercial basis, it is interesting to find that the Dunston plant in its developed state is yielding a profit on its working costs. I am pleased to see that the plant is simple and easy to operate; but, speaking as an operating engineer, one could wish for a neater lay-out for the sake of general cleanliness and ease of maintenance. Why is it proposed to change over to pulverized-coke firing instead of stoker firing in the newer plant? Is it purely for the sake of experience, or have difficulties arisen with the coke-fired stoker? The coal in the coalfields of this district has a high ash and moisture content, approximating up to 20 per cent in each case, and, by virtue of the nature of the ash, would present difficulties in cleaning. Would coal of this nature lend itself to treatment in the authors' plant or in the plant where the carbonization takes place in the pulverized form?

Mr. C. A. Brearley: Can the system described by Messrs. Smythe and Weeks be extended to the production of semi-coke for domestic fuel? In general, modern power stations already burn their fuel with a high degree of efficiency, and the cost of carbonization, in comparison with the value of the residual fuel, is much higher for industrial than for domestic coal. If, therefore, the process can be made advantageous for power-producing fuel, there would appear to be a much wider margin for its exploitation in the domestic fuel market. The claim, on page 220, that the combustion of semi-coke instead of raw coal will diminish the smoke nuisance, seems scarcely justified—at least in reference to efficient power stations—since the analyses quoted show an increase of the order of 25 per cent in both ash and sulphur content.

Mr. C. D. Wilkinson: I should like to point out that the most valuable of the by-products are the spirits, and also to know whether there is a satisfactory cracking process.

Mr. W. Wyness: Has the coal to be graded, or can it be put into the retort in any size? Also, can the plant be graded or reduced as regards intake or output?

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* The paper by Messrs. Smythe and Weeks (see page 219) was the only introductory paper read at this meeting.

Mr. R. C. Woods: I notice that the plant is arranged to supply only that quantity of fuel that is required for the steam generators, and yet Messrs. Smythe and Weeks claim smoke abatement. I do not think that there are many generating plants which produce much smoke. Is it proposed to sell the fuel? The by-products seem to be very much less valuable than claimed by the Press. Are they very different? Would income from the sale of the by-products pay for the treatment?

Messrs. E. H. Smythe and **E. G. Weeks** (*in reply to the Nottingham discussion*): As regards the remarks of Mr. Jockel, the term "higher value heat units" refers to that portion of the coal which in the form of oils has a higher market value per B.Th.U. than the raw coal. If these oils are burnt in the boiler furnace they are not being used to the best advantage. It is agreed that two coals of very similar ultimate analysis may behave differently under low-temperature distillation conditions, but it is not a difficult matter to determine by laboratory assay the suitability of each coal for treatment and to estimate the yields of oils and other products which may be obtained in practice. The low-grade gas made at Dunston is fired under the boiler because this is the most convenient method of utilizing it in that plant. In other installations it might be found advantageous to utilize this gas for generating combustion products for preheating the coal, and/or heating the retorts. The best method of using the gas must be determined for each individual case. The calorific values of the coal and coke are determined in the usual manner adopted in the carbonization industries, and are not calculated in accordance with the special methods recommended by the Institution of Civil Engineers. The calorific values are the result of a rather too accurate conversion from the "calories" in which they were determined, to British thermal units. We agree that they should have been stated to the nearest ten. The sulphur content of the coke compared with that in the parent coal varies with different coals. In some cases the percentage of sulphur in the coke is equal to, or greater than, that in the coal, whilst in others the percentage of sulphur in the coke may be as low as half that in the coal. This wide variation is to some extent due to the chemical composition of the sulphur. Under low-temperature distillation, the recovery of ammonia in the form of ammonium sulphate is not worth while, as the yield does not warrant the installation of the relatively expensive apparatus required. The floor space occupied by the low-temperature retort plant is approximately the same as that required for the boiler which it serves.

In reply to Mr. Nicholls, there has been no trouble at Dunston with fires in the preheaters which are heated with waste flue-gases from the boiler. It will be appreciated that in normal operation the oxygen content of the waste boiler flue-gases is small and that therefore the danger of firing the coal is very remote. The control of the preheating temperature is easily effected, as the temperature of the waste boiler-gases remains constant within reasonable limits. There is no possibility of the combustible retort-gases finding their way into the preheaters, owing to a simple sealing device in the form of a rotary valve which isolates the preheater from the retort. The average volatile contents of the semi-coke fed to the boilers is 14 per cent, as mentioned on page 220 of the paper, and experience has shown that this percentage gives the best results in practice.

As regards the financial aspect of the process referred to by Mr. Nicholls and Mr. Pearson, it is agreed that this is dependent on the cost of installing and operating the process and on the market value of the by-products. The cost of installation and the operating costs are to a considerable extent dependent on the size of the plant and the quantity of coal handled by each unit, and it is therefore impossible to give a definite figure which would apply under all circumstances. It may, however, be assumed that if the semi-coke is used as a boiler fuel and is credited at the same price as the coal, it would be uneconomical to treat any smaller quantity than 100 tons per day, whereas the cost per ton of installing and operating a plant capable of treating 300 to 400 tons per day would be very much lower. On the other hand, if the fuel produced were intended for domestic use, it might be worth while to install smaller units. Assuming, however, the case of a plant capable of treating, say, 400 tons a day of coal costing 11s. to 12s. per ton, then, on the basis of the value of the by-products given in the paper and now obtainable in this country, there would be a reasonable margin of profit after due allowance is made for first cost, maintenance and depreciation. The reasons for the use of pulverized coke in the newer plant are given below, in our reply to Mr. Dransfield's remarks.

Mr. Pearson assumes that large-scale operation will necessarily result in a reduction of the price obtainable for the by-products, but experience in other directions has shown that this is not inevitably the case; also, it is not unreasonable to assume that further uses will be found for these by-products as they become available in commercial quantities. In any case the demand for fuel oil for steam-raising purposes and for use in internal-combustion engines increases yearly, and it has been shown that the primary tar oils produced by low-temperature distillation can conveniently be treated to meet this ever-present demand.

Mr. Dransfield's comments on the lay-out of the plant are doubtless based on the impression given by the photographs of the circular retort at Dunston. As mentioned in the paper, this design is being superseded by a retort of rectangular construction, with the result that a very much neater and cheaper lay-out will be possible, as was shown by the lantern slide of the model of the 160-ton-per-day retort working in conjunction with a pulverized-fuel boiler. The reason why pulverized-fuel firing has been adopted in connection with the new retort at Dunston is that, having already demonstrated the suitability of semi-coke for stoker firing, it has been thought advisable also to demonstrate its suitability as a pulverized fuel. No difficulties have been experienced in burning semi-coke from the older retorts on chain-grate stokers, and no difficulty is anticipated either in pulverizing the semi-coke or in maintaining efficient combustion in the furnace of the pulverized-fuel boiler. Regarding the coal in the

Nottingham district, unless the moisture content is altogether abnormal, which we understand is not the case, the preheater will be capable of drying the coal to a sufficient extent to permit of its being treated satisfactorily in the retort. In cases where an exceptional amount of moisture is present it may be necessary to increase either the size of the preheater or the temperature of the preheating gases. The question of whether any coal would be worth while treating is mainly dependent on the yield of oils obtainable under low-temperature distillation conditions. If the ash content of the coal is not too high to make it unsuitable as a boiler fuel when fired in the raw state, it may be assumed that the coke produced will be at least equally suitable as a boiler fuel.

In answer to Mr. Brearley's remarks, the Babcock process is well adapted to the production of semi-coke for domestic purposes. Tests made in stoves and open fire-places have proved that, provided the semi-coke is made from reasonably clean coal, the fuel gives excellent results, as it is easy to ignite and burns freely. It is very well suited for use in stoves and it is possible to maintain a more steady rate of combustion than when high-temperature coke is used. For this purpose it is, in fact, an excellent anthracite substitute. Dunston semi-coke has now been used for some time in open fire-places at Babcock House, and owing to its cleanliness is preferred to coal. We agree that the value of this fuel is greater for domestic than for industrial purposes, but that fact should not absolve us from endeavouring to get the best out of the coal used for industrial purposes. It should be quite possible to install low-temperature distillation plant at large coal-consuming centres such as electrical generating stations, and to arrange matters so that the larger size of semi-coke produced by the retort would be sold as a domestic fuel and the smaller size used either on chain grates or in pulverized form for steam-generating purposes. The process is quite well suited for this dual purpose. It is agreed that the combustion of coal in modern power stations is now carried out under conditions which reduce the emission of smoke to a minimum, but in a large number of coal-consuming undertakings this is not the case, and in such instances the use of semi-coke would undoubtedly be of considerable benefit to the health of the community.

In reply to Mr. Wilkinson, the cracking of the primary tars produced by low-temperature distillation has not yet been undertaken on a commercial scale, but tests have been made which show that these tar oils are amenable to treatment by recognized cracking processes and will produce from 30 to 40 per cent of high-grade motor spirit possessing excellent anti-knocking properties.

In reply to Mr. Wyness, the process has been designed to deal with coal of the grading normally used in power stations; an example of this grading is given on page 220 of the paper. In actual practice it is preferred to treat coals having less than 20 per cent of fines below a $\frac{1}{8}$-in. sieve. As regards the input and output of the plant, it is preferable from an economic point of view to work the retorts at the full rate of through-put for which they are designed, although it is quite possible to reduce this rate if required to meet the load requirements of the boiler plant.

The points raised by Mr. Woods have already been referred to in the preceding part of the discussion.

NAVAL WIRELESS TELEGRAPH COMMUNICATIONS.

By G. SHEARING, B.Sc., and Captain J. W. S. DORLING, R.N., Members.

(*Paper first received 5th July, and in final form 14th October,* 1929; *read before the* WIRELESS SECTION *4th December, and before the* HAMPSHIRE SUB-CENTRE *19th December,* 1929.)

SUMMARY.

The paper gives a short account of the development of wireless telegraph apparatus for naval purposes. The historical development is referred to, the wireless telegraph lines required for naval ships are outlined, and the essential requirements and chief features of some of the apparatus used under sea-going conditions are briefly described. The organization for giving effect to the policy of H.M. Board of Admiralty is also indicated.

Part (1). HISTORICAL.

The first experiments in wireless telegraphy in the Navy were commenced by Captain H. B. Jackson, R.N. (now Admiral of the Fleet Sir Henry Jackson) in H.M.S. "Defiance" in 1896. Trials were carried out in 1897 between "Defiance" and the gunboat H.M.S. "Scourge," when ranges up to 3½ miles were obtained. The transmitting apparatus consisted of a Hertzian oscillator energized by an induction coil worked either from the electric light mains through a resistance or from a 12-volt battery. The arrangement is shown in Fig. 1. A diagram of the receiving circuit is shown in Fig. 2, the detector being of the coherer type, a glass or ivory tube containing two metal plugs being employed. It will be seen from the diagram that arrangements were made for the automatic recording of signals.

As a result of these early experiments, attempts were made to develop greater power with a view to getting longer ranges, and in 1898 this development work was in hand, but trouble was experienced owing to the failure of the induction-coil insulation under damp conditions. This difficulty was eventually overcome by coating the coil with paraffin wax, and, in 1899, sets were fitted in H.M. Ships "Europa," "Juno" and "Alexandra," Mr. G. Marconi (now Marchese Marconi) being in charge of the trials, which were carried out during the peace manœuvres. Effective ranges of 50 miles were obtained during these trials. The collaboration between scientist and naval officer, started at this early stage, persists to the present day with equally fruitful results.

In 1900 further progress was made and by the end of the year 43 ships and 8 shore stations either had been, or were being, fitted with wireless telegraph apparatus. Thirty-two of the sets employed were supplied by the Marconi Co., the remainder being constructed in H.M.S. "Vernon" and H.M.S. "Defiance" to Captain Jackson's specifications. The speed of signalling was about 10 words per minute and reception was automatic.

During 1903, Muirhead's automatic transmitting apparatus was installed for trial. Only two waves were in use at this time, these being known as "A" tune and "B" tune, "A" tune being of 395 ft. and "B" of 1 150 ft. A variable-wave set known as "C" tune was developed at a later date. The magnetic detector was tried and introduced at this period.

In 1905 a naval wireless telegraph establishment was organized in "Vernon" and work was commenced on an experimental 5-kW set for erection at Horsea Island in Portsmouth Harbour. In this year the well-known rejector circuit for reception was introduced by Mr. H. A. Madge, who had recently been appointed as civilian wireless expert in "Vernon."

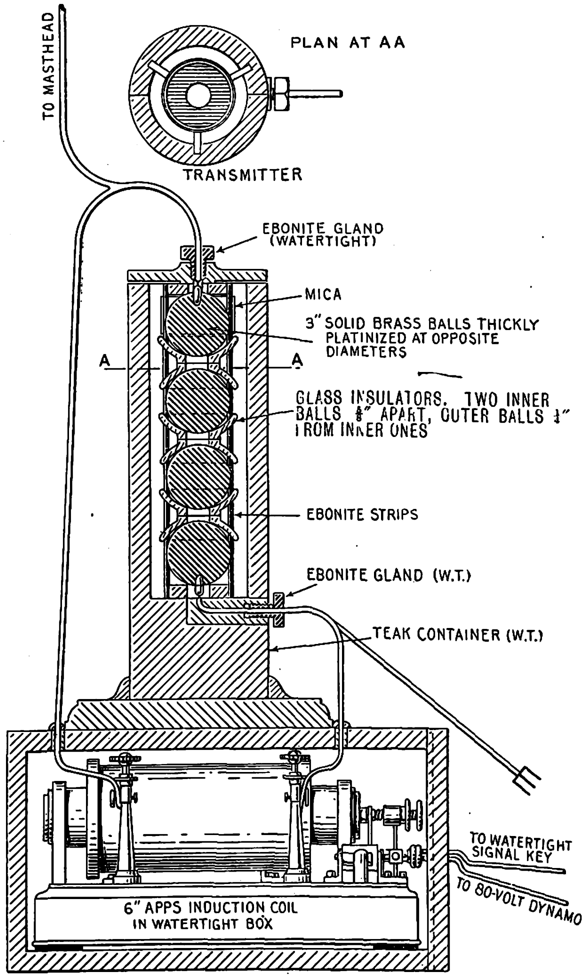
TO MASTHEAD
PLAN AT AA
TRANSMITTER
EBONITE GLAND (WATERTIGHT)
MICA
3" SOLID BRASS BALLS THICKLY PLATINIZED AT OPPOSITE DIAMETERS
A
A
GLASS INSULATORS. TWO INNER BALLS ⅛" APART, OUTER BALLS ¼" FROM INNER ONES
EBONITE STRIPS
EBONITE GLAND (W.T.)
TEAK CONTAINER (W.T.)
TO WATERTIGHT SIGNAL KEY
TO 80-VOLT DYNAMO
6" APPS INDUCTION COIL IN WATERTIGHT BOX

FIG. 1.

At the end of 1905, naval interest in wireless telegraphy was somewhat on the wane owing to the very large number of failures which had occurred during trials at sea. At the beginning of 1906, however, a series of competitive exercises was carried out in the various fleets, with more satisfactory results. Up to this time, the development of wireless telegraphy had been under the control of the Torpedo Branch of the Navy, but signalmen had been used for operational purposes.

In 1906 it was decided to commence a new branch, the Wireless Telegraph Branch, in which men could specialize. This had very marked beneficial results, as would be expected since the candidates for the new branch were all compelled to undergo a special course of training in wireless telegraphy. Operators rapidly became more efficient and the number of failures during manœuvres consequently decreased.

During 1906, experiments were carried out on a number of new wavelengths. Towards the end of the year, range trials were carried out between "Vernon" at Portsmouth and H.M.S. "Furious" on passage to the Mediterranean. Ranges of 600 miles were obtained regularly by day and up to 1 200 miles by night. The wavelength known as "R" tune, 2 500 ft., was found to be the most satisfactory. A long wave of 7 000 ft. was not found satisfactory. During this year, with more operators available, telephone reception became the normal procedure and the silent cabinet for reception was introduced in ships.

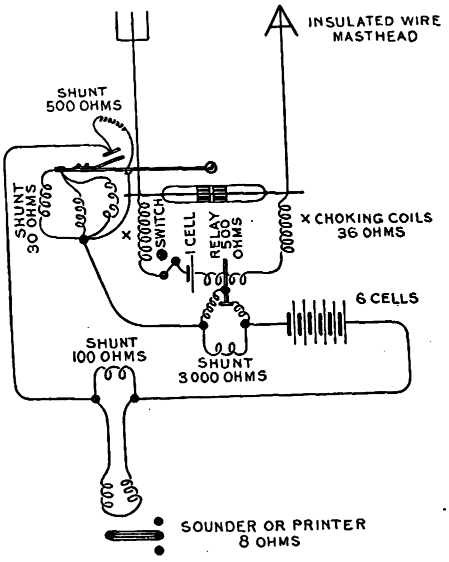

FIG. 2.

In 1907 the service Mark II set, later known as Type 1 spark, of the order of 12-kW H.T. output, was introduced for heavy ships, and, in 1908, experiments were commenced with the Poulsen arc in "Vernon" and "Furious." Preliminary experiments with wireless telephony and various forms of crystal and electrolytic detectors were also commenced in this year.

In 1909 the crystal detector was first used. High-power shore sets employing spark telegraphy were put into operation at Horsea, Cleethorpes and Gibraltar, and medium-power sets at Pembroke, Aberdeen and Ipswich. In 1910, a quenched-spark set was built for the naval airship. In this year also a wireless telegraphy course for officers qualifying for the Signal rank of Lieutenant (S) was approved.

During the years 1911–1912 a very considerable amount of experimental work was done, using the Poulsen arc, but there was no standardization of the apparatus at this period. The question of the development of methods of accurately measuring wavelengths also received considerable attention. During these years, also, the development of spark telegraphy sets continued and by 1913 the following were the main ship sets then in use:—

Type 1 (old Mark II main-power set).
Type 2 (old Mark I original low-power set).
Type 3, battleship auxiliary set.
Type 4, destroyer set.
Types 5 and 6, portable and harbour defence sets.
Type 9, cruiser auxiliary set.
Type 10, submarine sets.

Of these sets, Type 1 utilized a d.c. power supply of 20 kW, the remainder 3 kW or less.

During 1913 a 100-kW Poulsen arc was installed at Horsea Island, and three 440-ft. wooden lattice masts were erected, this work being carried out by Mr. C. F. Elwell. Also during this year the use of heterodyne reception for continuous waves was commenced.

During 1914, immediately prior to the commencement of the War, experiments were in hand on valve reception and arrangements were being made for complete arc sets to be supplied to ships at sea. The commencement of the War gave a great impetus to the development of wireless telegraphy, and the development of the thermionic valve is mainly associated with the war period from 1914 to 1919, first as a method of reception and later as a transmitter. In 1917 the wireless telegraphy established in "Vernon" was transferred ashore to H.M. Signal School, Portsmouth.

Whilst spark and arc systems of wireless telegraphy were mainly employed by ships at sea during the war period, the experimental development of the valve during the same time indicated that there was a probability that both these systems would ultimately be superseded by the thermionic valve system. In January, 1919, aerial currents of 50 amperes were obtained using a shore station valve transmitter.

The post-war developments which have occurred since 1919 have confirmed this view, and at the present time, except for special emergency purposes, spark transmitters are becoming obsolete and arc transmitters have been almost entirely replaced by valve transmitters in all types of ships. At the conclusion of the War, sets employing valves for power transmissions utilized valves of the order of 400 watts anode rating, but since this period the development of power valves has been rapid, until now single valves are in use with sets at sea which are capable of dissipating 8–10 kW at their anodes under oscillatory conditions.

The high-power sets developed up to 1923 were long-wave transmitters for long-range working, but during this year long-range experiments at sea in connection with the higher frequencies above 3 000 kilocycles per sec. (100 m) were commenced. During cruises in 1924 and 1925 of H.M.S. "Yarmouth" to the Canary Isles and to the Mediterranean, it was found possible to maintain short-wave communication with ships at Portsmouth during certain periods of the day, and in 1925 these experiments were continued with good results at greater distances to the Far East. The world cruise of H.M.S. "Renown" during January to June 1927, provided another opportunity for testing the capabilities of short-wave working on long ranges, and except for three days in a period of six months it was found possible to maintain communication during a part of each day of the cruise between Whitehall and "Renown," Whitehall controlling a short-wave transmitter at Horsea Island.

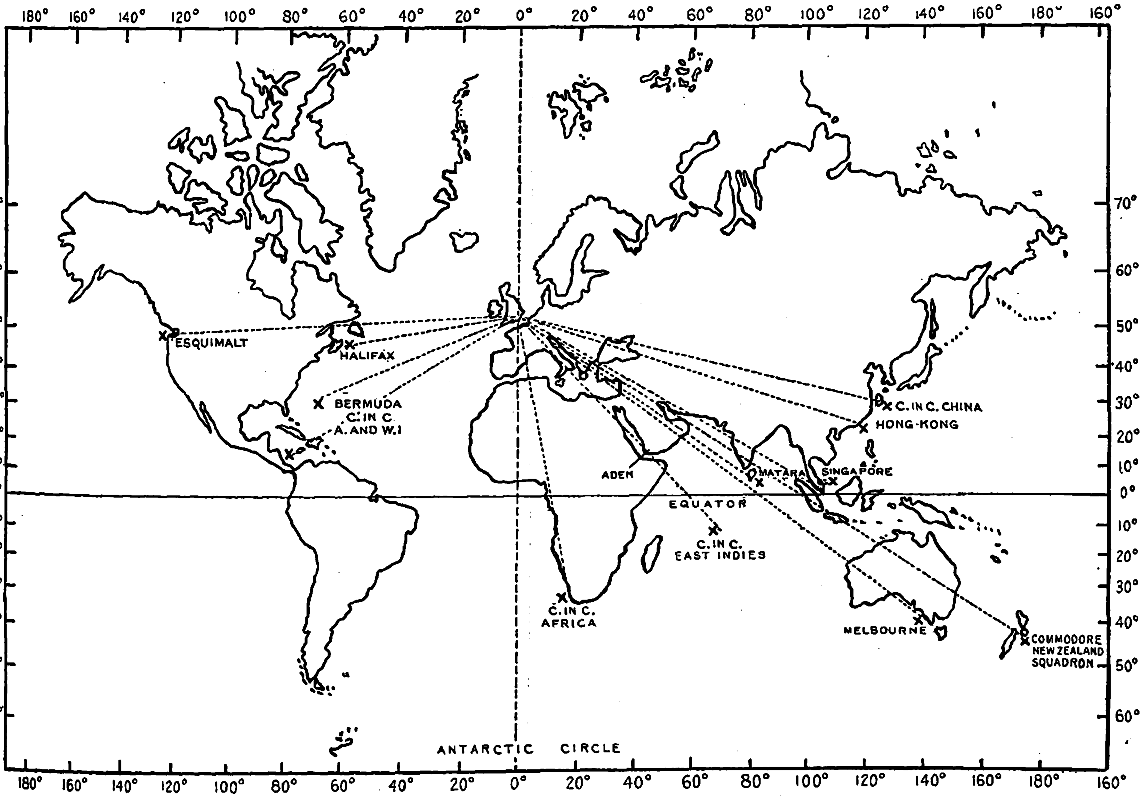

FIG. 3.

Regular service routines employing short waves between England and naval ships and shore stations overseas have now been in operation since 1926.

Apart from the direct application of wireless telegraphy to communications, the apparatus developed by H.M. Signal School for distant control, by the use of wireless signals, of target ships, such as H.M.S. "Agamemnon" and H.M.S. "Centurion," is well known and has been referred to in the Press.

Part (2). REQUIREMENTS TO BE FILLED BY A NAVAL WIRELESS TELEGRAPH SYSTEM.

It is a truism that trade follows the flag. The reverse that wherever trade flows there must the flag be also, is equally true.

The trade of this country is world-wide, and hence British men-of-war are to be found in all parts of the world. These ships are divided up into squadrons and are normally stationed in certain areas, for example China, East Indies, Africa, America and West Indies. Each squadron is under the orders of its Naval Commander-in-Chief.

A system of communication, to be effective, must link up the ships of these far-flung squadrons with their own Commander-in-Chief and with the Admiralty. The backbone of the system consists of a series of naval shore wireless stations situated in various British possessions throughout the world and in most cases forming a continuous chain of communication as indicated in Fig. 3 (Horsea and Mediterranean stations are not shown).

NAVAL SHORE WIRELESS STATIONS.

In the United Kingdom there are therefore wireless stations designed to communicate with ships in adjacent waters, and others for really long-distance communication with the stations abroad. Each naval area or station abroad has, depending on its size and position, one or more wireless stations, which act as terminal points for the traffic to and from the Admiralty and other commands, and as distributing and collecting centres for ships in the vicinity. Where commercial wireless stations are not available the naval stations are used also for communicating with merchantmen.

The wireless telegraph apparatus of these shore stations has therefore to be capable of communication with:—

(*a*) The Admiralty, either direct or through links.
(*b*) The Commander-in-Chief of the station and the ships on his station.
(*c*) Any merchant ships in the area.
(*d*) Adjacent naval commands.

To fulfil these requirements a medium-power long-wave valve transmitter of about 25-kW H.T. input is usually fitted for local working within a radius of, say, 1 500 to 2 000 miles. For the longer distances short-wave transmitters of various types are used. These range from 2- to 10-kW H.T. input. Recently it has been the practice to put all the receiving apparatus in a separate building at some distance from the transmitters.

Arrangements are made whenever possible for the wireless stations to be linked up with the cable and land-line system.

Cruisers and Other Ships on Foreign Stations.

These ships must be able to communicate with:—

(*a*) The Commander-in-Chief of their station and other ships on the station.
(*b*) The shore wireless station in the area.
(*c*) Adjacent commands.
(*d*) Merchant ships and aircraft in their vicinity.

The advent of the short-wave system has made it possible for ships in any part of the world to communicate direct with each other and with the Admiralty at certain times of the day. This facility is made use of to supplement the normal lines of communication and to avoid delays to especially important messages.

To fulfil the requirements stated above, the wireless telegraph equipment in H.M. ships of cruiser class and above has the following characteristics:—

(1) Range (long wave)—1 000–2 000 miles.
(2) Power (long wave)—12-kW H.T. input to transmitter.
(3) Power (short wave)—8-kW H.T. input.
(4) Valve transmitters are used in all cases.
(5) Receiving apparatus (long- and short-wave). Two or three sets are fitted.
(6) Direction-finding apparatus on the Bellini-Tosi system is fitted in most cruisers.
(7) Fire-control wireless sets are fitted for use when cruisers are concentrated in squadrons.

Apart from its actual technical performance, the apparatus must have certain very definite characteristics to fit it for use in a ship at sea. For example, it must be robust, simple to handle, reliable under all climatic conditions, proof against vibration and the shocks of gunfire, and capable of being maintained in full efficiency for months at a time by the ship's wireless staff.

The Main Fleet.

So far we have only considered the shore wireless stations and the cruising ships on foreign stations. Behind the cruisers and the ultimate source from which they obtain their liberty of action is the main battle fleet—the Grand Fleet of the Great War.

A self-contained battle fleet consists of battleships and battle cruisers which provide the main fighting power, together with cruisers for scouting, aircraft carriers, destroyers and submarines.

The whole force is under the command of its Commander-in-Chief, who must be able to transmit his orders to any unit of the force. The scouting units of the fleet must be able to transmit the information they obtain to the Commander-in-Chief and the other senior officers of the fleet. The Commander-in-Chief must also be in touch with the Admiralty and other authorities.

All these lines of communication should be able to work simultaneously without interference. This is usually done by multiple reception in the flagship, all transmissions being made by wireless guardships specially allocated for each wave. The apparatus used for these purposes is similar to that fitted in cruisers, already outlined.

Short-distance apparatus is also fitted in special offices in the battleships and cruisers to permit of inter-communication within the fleet without interfering with the long-distance lines. This short-distance apparatus is used for manœuvring the battle fleet and also provides an essential link between the wireless guardships and the flagship.

The striking feature of a fleet action is the speed at which everything happens. The two fleets may be approaching one another at 40 to 50 miles an hour, and even with aircraft reconnaissance the time between first sighting the enemy and joining action may be only an hour or two. During this limited time the scouts of the fleet have to observe that part of the enemy fleet which may be in sight, determine their position, composition, course and speed, and then signal this information to the Commander-in-Chief. From all these reports he has to determine what the enemy as a whole are doing and then manœuvre his force into the best position. The volume of signalling during this critical hour or so is very great, especially in the fleet flagship, and special means are necessary to ensure that no signal is delayed. The wireless apparatus is designed for the rapid handling of messages and so that the guardships can readily control the traffic on their particular wave-lengths. In all ships the messages are received and transmitted, not in the wireless offices between decks, but in a remote-control office near the Admiral's or Captain's bridge, thus reducing to a minimum the intermediate stages between the issue of an order or report and its receipt by the person for whom it is intended. Pneumatic tube and buzzer systems are fitted for the rapid transmission of messages in case of a breakdown of the remote-control system.

The direction-finding sets fitted in some ships often prove their value during this stage of the action. Direction-finding bearings may be obtained of the enemy, or, should, for example, some of the scouting vessels or aircraft be uncertain of their positions relative to the battle fleet, a wireless bearing may be a useful check.

Wireless communication is also largely used after the action has started. Reports of the movements of the enemy forces continue to be made, and the fleet is manœuvred by a combination of wireless and flag signalling

All ships, down to destroyers, also use special low-power sets for fire control. The essential feature of this line of communication is that it should be free from interference from any other line and absolutely reliable even under action conditions.

For obvious reasons it is not possible to elaborate the above outline, but it will be sufficient to show that the requirements of a naval wireless system are many and varied, and that the overall efficiency of the Navy must depend largely on the efficiency of its wireless communications.

Part (3). Offices and Apparatus.

Typical Office Arrangements.—The initial lay-out of a modern warship involves an immense amount of preliminary work and trouble in the process of subdividing the available space for the various requirements. The fact that the ship is to be capable of fighting in action is a primary factor, and when provision has been made for the essential armament, propulsion machinery and living quarters for the crew, the space available for any other given requirement is very limited.

The ideal communication requirements are, of course, known, and a preliminary estimate of the space necessary is usually worked out in advance by the technical staff for the information of the Board of Admiralty. The actual space available is almost invariably found to be less than this estimate and it then becomes a matter of compromise as regards how far the ideal requirements may be met in the space which can be allocated. In this manner the wireless telegraph office is evolved of definite dimensions into which the main portion of the apparatus, apart from aerials, is to be placed. The general arrangements for the wireless telegraph offices and aerial systems of a battleship are indicated in the simplified diagram, Fig. 4.

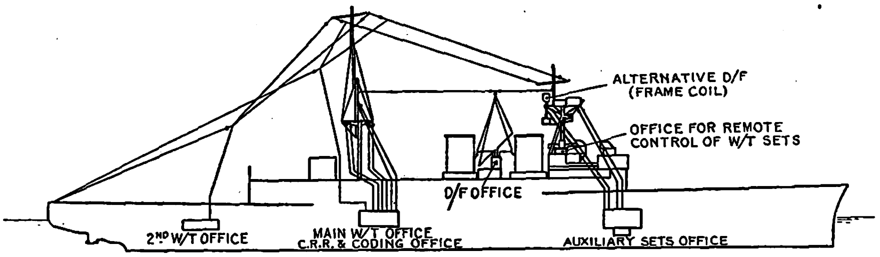
ALTERNATIVE D/F (FRAME COIL)
OFFICE FOR REMOTE CONTROL OF W/T SETS
D/F OFFICE
2ND W/T OFFICE
MAIN W/T OFFICE C.R.R. & CODING OFFICE
AUXILIARY SETS OFFICE

Fig. 4.

The main and auxiliary offices for heavy ships are situated below the main armoured deck, and the space has to include the following:—

(*a*) A silent cabinet for the accommodation of the receiving gear from which small trunks or cables go to the various receiving aerials.

(*b*) A cage protected by safety gate switches in which are contained the high-tension power supply and auxiliary apparatus for the transmitters. These have to supply oscillatory power to the aerial by means of a conductor fitted in a trunk which goes to the deck insulator to which the aerial system is connected.

(*c*) Low-tension power control apparatus for the wireless-telegraph motor-generators.

(*d*) Suitable gangways for ready access to all controls and for visual inspection of instruments.

(*e*) Coding office.

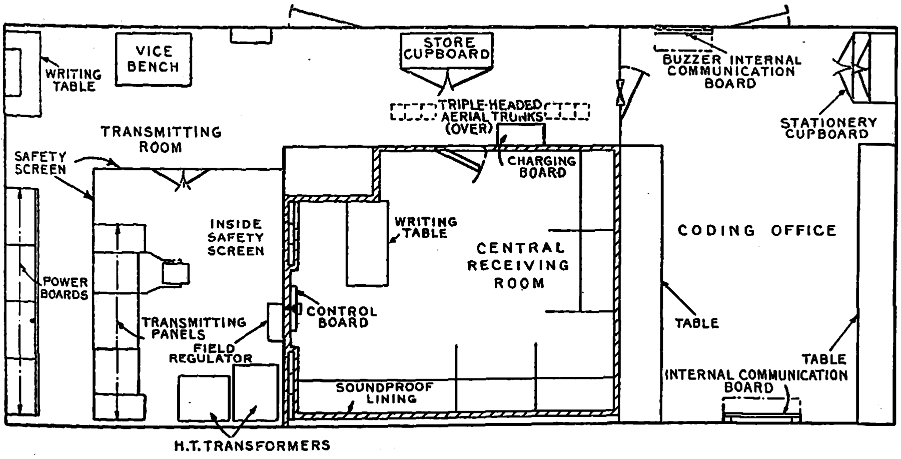
WRITING TABLE
VICE BENCH
STORE CUPBOARD
BUZZER INTERNAL COMMUNICATION BOARD
TRIPLE-HEADED AERIAL TRUNKS (OVER)
STATIONERY CUPBOARD
TRANSMITTING ROOM
SAFETY SCREEN
CHARGING BOARD
INSIDE SAFETY SCREEN
WRITING TABLE
CENTRAL RECEIVING ROOM
CODING OFFICE
POWER BOARDS
CONTROL BOARD
TRANSMITTING PANELS
FIELD REGULATOR
TABLE
TABLE
INTERNAL COMMUNICATION BOARD
SOUNDPROOF LINING
H.T. TRANSFORMERS

Fig. 5.—Typical lay-out of wireless telegraph offices in heavy ships.

Primary Requirements.—The main conditions to which the wireless telegraph apparatus should conform are:—

(*a*) Space and weight limitations.
(*b*) Reliability of operation.
(*c*) Mechanical strength to resist shocks arising from gunfire and sea-going conditions.
(*d*) Ability to withstand extremes of temperature and weather.
(*e*) Efficient operation in offices below the main armoured deck, connected to the aerials via trunks or conductors of length which may exceed 100 ft.
(*f*) Minimum possible time of starting up for transmissions, with listening-through arrangements.
(*g*) Safety for operators. Controls readily accessible for quick operation.
(*h*) Rapid tuning arrangements covering a wide band of waves.
(*k*) Simple and easy to operate.

Design and Development.—The problem of designing oscillatory apparatus to fit into a given space which invariably is very much less than that available for the same power in shore stations imposes limitations on the technical design. The circuits and adjustments for wave-change have to be reduced to the minimum possible, the arrangements for replacement of gear have to be easy and rapid and the indicating instruments have to be capable of being viewed from widely varying positions.

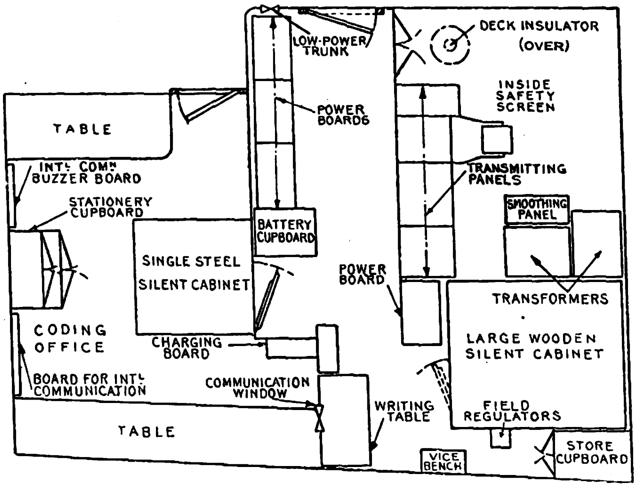
LOW-POWER TRUNK
DECK INSULATOR (OVER)
INSIDE SAFETY SCREEN
POWER BOARDS
TABLE
INTL COMN BUZZER BOARD
STATIONERY CUPBOARD
TRANSMITTING PANELS
SMOOTHING PANEL
BATTERY CUPBOARD
SINGLE STEEL SILENT CABINET
POWER BOARD
TRANSFORMERS
CODING OFFICE
CHARGING BOARD
LARGE WOODEN SILENT CABINET
BOARD FOR INTL COMMUNICATION
COMMUNICATION WINDOW
WRITING TABLE
FIELD REGULATORS
TABLE
VICE BENCH
STORE CUPBOARD

Fig. 6.—Lay-out of wireless telegraph office for light cruisers.

The procedure usually adopted is to develop experimentally the apparatus first in a wooden model of the office space. From this the proposals and specifications for fitting the set in ships are prepared. Lay-outs for typical wireless telegraph offices of various sets for battleships, cruisers and destroyers are shown in the plans, Figs. 5, 6 and 7.

Installation and Trials.—The installation of the sets is carried out by the contractor or dockyard under the supervision of H.M. Signal School, Portsmouth, the completion of the wiring and final tuning of the high-frequency apparatus being carried out by the co-operation of the Signal School and the ship's staff. This installation work includes the following:—

(*a*) Fitting lined receiving rooms (silent cabinets).
(*b*) Fitting safety screen and all apparatus components.
(*c*) Fixing ventilation fans, air supply and exhaust trunks.
(*d*) Construction of aerial trunk, deck insulators and aerial conductor system.
(*e*) Fixing of all moving machinery, which is fitted outside the office.
(*f*) Wiring work as specified, covering low-tension lead-cased or bare high-tension wiring.

Upon the completion of the installation, the ship's staff has to carry out the following duties:—

(i) Test all the running machinery.
(ii) Complete the high-tension and high-frequency wiring for the transmitters and receivers not shown in the specification.

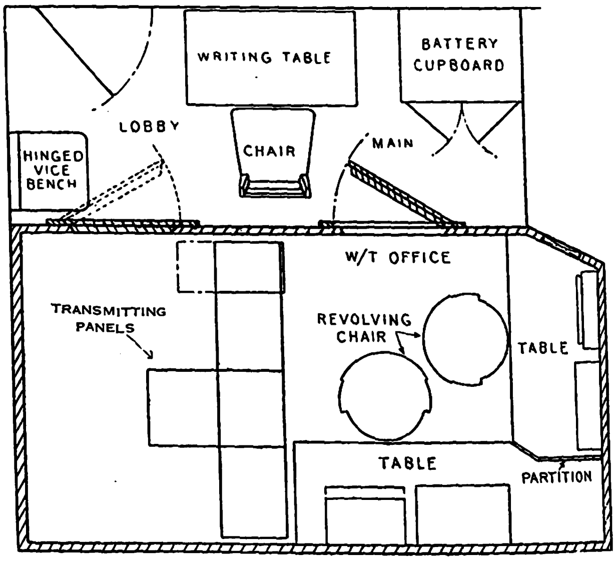
WRITING TABLE
BATTERY CUPBOARD
LOBBY
HINGED VICE BENCH
CHAIR
MAIN
W/T OFFICE
TRANSMITTING PANELS
REVOLVING CHAIR
TABLE
TABLE
PARTITION

Fig. 7.—Typical lay-out of wireless telegraph office for destroyers.

(iii) Fill the oil-insulated apparatus such as transformers and condensers with oil which has been carefully dried.
(iv) Erect the aerial system.

The sets are then ready for tuning and external communication trials, which are carried out by Signal School Officers in conjunction with the ship's staff.

Apparatus.

(A.) *Power Supplies for Main Wireless Telegraph Transmitters.*—The power supply for both thermionic valve or spark wireless telegraph transmitters is mainly high-tension low-frequency alternating current, and the earlier post-war development of valve transmitting sets was facilitated by the fact that existing power plant which was installed initially for spark transmitters could be used also for valve transmitters. The frequency value for the alternators has been determined mainly by

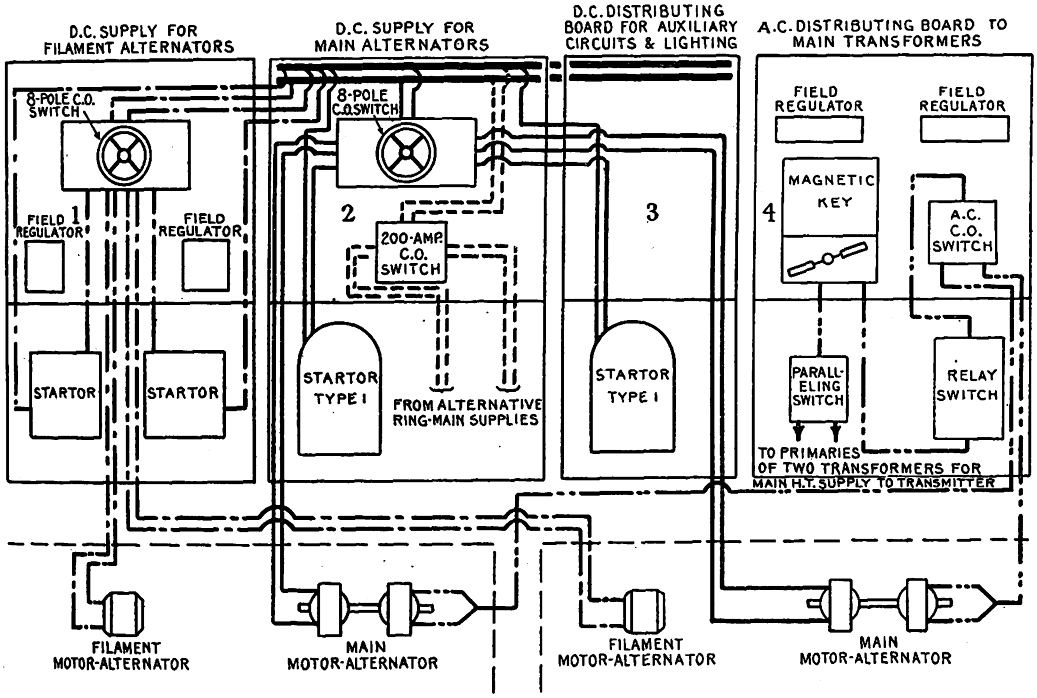
D.C. SUPPLY FOR FILAMENT ALTERNATORS
D.C. SUPPLY FOR MAIN ALTERNATORS
D.C. DISTRIBUTING BOARD FOR AUXILIARY CIRCUITS & LIGHTING
A.C. DISTRIBUTING BOARD TO MAIN TRANSFORMERS
8-POLE C.O. SWITCH
8-POLE C.O. SWITCH
1
2
3
4
FIELD REGULATOR
FIELD REGULATOR
FIELD REGULATOR
FIELD REGULATOR
200-AMP. C.O. SWITCH
MAGNETIC KEY
A.C. C.O. SWITCH
STARTOR
STARTOR
STARTOR TYPE I
STARTOR TYPE I
FROM ALTERNATIVE RING-MAIN SUPPLIES
PARALLELING SWITCH
RELAY SWITCH
TO PRIMARIES OF TWO TRANSFORMERS FOR MAIN H.T. SUPPLY TO TRANSMITTER
FILAMENT MOTOR-ALTERNATOR
MAIN MOTOR-ALTERNATOR
FILAMENT MOTOR-ALTERNATOR
MAIN MOTOR-ALTERNATOR

FIG. 8.—Diagram of power boards and power arrangements.

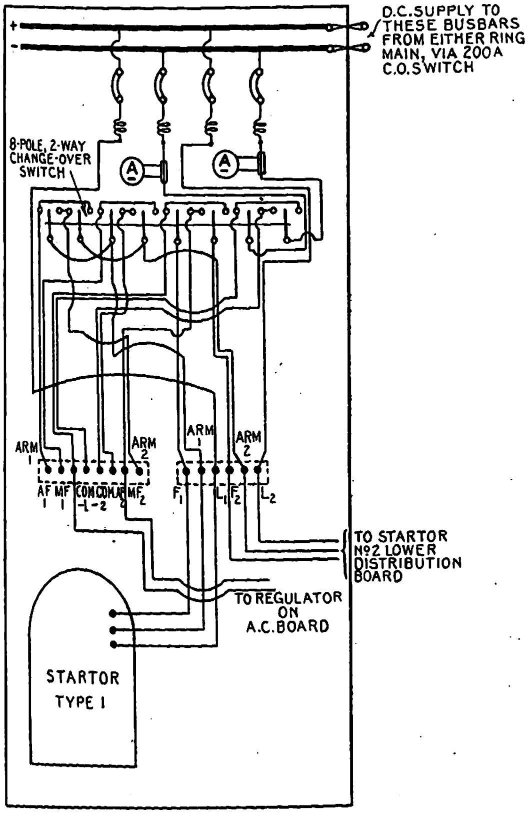
D.C. SUPPLY TO THESE BUSBARS FROM EITHER RING MAIN, VIA 200A C.O. SWITCH
+
-
8-POLE, 2-WAY CHANGE-OVER SWITCH
A
A
ARM 1
ARM 2
ARM 1
ARM 2
AF 1
MF 1
COM -1
COM -2
AF 2
MF 2
F1
L1
F2
L2
TO STARTOR No2 LOWER DISTRIBUTION BOARD
TO REGULATOR ON A.C. BOARD
STARTOR TYPE I

FIG. 9.—D.C. supply boards for main motor-alternators. Wiring diagram showing supply to main alternators.

Note.—Com. −1, Com. −2 denote common negatives 1 and 2.

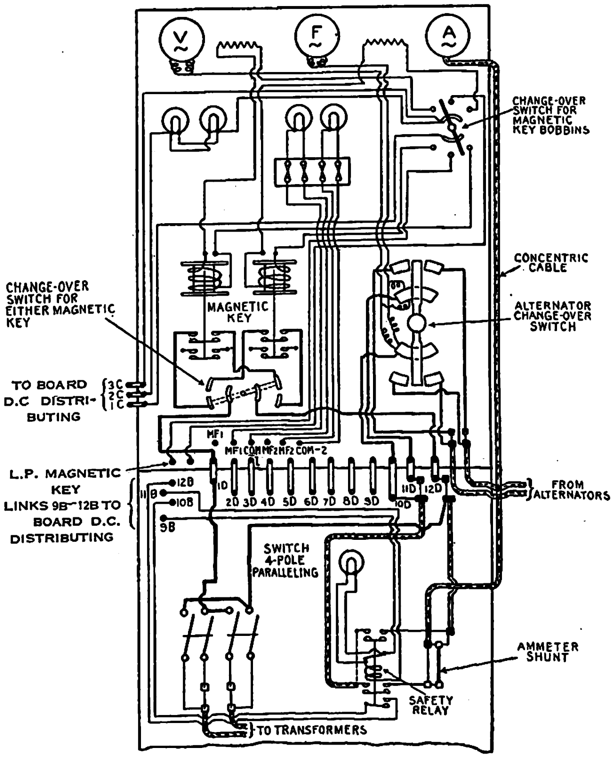
V
F
A
CHANGE-OVER SWITCH FOR MAGNETIC KEY BOBBINS
CONCENTRIC CABLE
ALTERNATOR CHANGE-OVER SWITCH
CHANGE-OVER SWITCH FOR EITHER MAGNETIC KEY
MAGNETIC KEY
TO BOARD D.C DISTRIBUTING
3C
2C
1C
MF1
MF1 COM MF2 MF2 COM-2
L.P. MAGNETIC KEY
LINKS 9B-12B TO BOARD D.C. DISTRIBUTING
12B
11B
10B
9B
1D
2D 3D 4D 5D 6D 7D 8D 9D
10D
11D
12D
FROM ALTERNATORS
SWITCH 4-POLE PARALLELING
AMMETER SHUNT
SAFETY RELAY
TO TRANSFORMERS

FIG. 10.—A.C. supply boards for main motor-alternator.

the note frequency which can be read easily through other wireless telegraph interference and is not tiring to the operator when listened to for long, continued periods. For spark transmitters the frequency adopted was 350 cycles per sec., giving a note frequency of 700, but for the valve transmitters this has been changed to 500 and 1 000 cycles respectively.

The power supply for the motor-generators is taken from d.c. busbars on power boards in the wireless office supplied from the ring mains of the ship. This supply is at either 220 or 100 volts, depending on the ship. The ring-main power supply is in duplicate and these supplies are via branch circuit-breakers fitted in separate watertight compartments outside the wireless telegraph office which are controlled by "on" and "off" pushes from inside the office. The machines are usually installed below the water line of the ship, with their axes arranged fore and aft. It is usual to mount one pair of machines, e.g. main and filament motor-alternators, in one watertight compartment separate from the other pair. The earlier machines were of three-bearing type, but these have now been superseded by four-bearing machines, the motor and alternator being separate machines with flanged coupling, due to overheating of bearings with the earlier type and the greater ease of passing the four-bearing machines, when separated, through the hatchways.

Duplication of the machines and power panels is adopted, each motor-generator being installed complete with its own d.c. and a.c. control gear. In addition, arrangements are also made whereby either machine can be operated from either startor. For certain cases automatic control gear is installed to give a constant value of generated voltage.

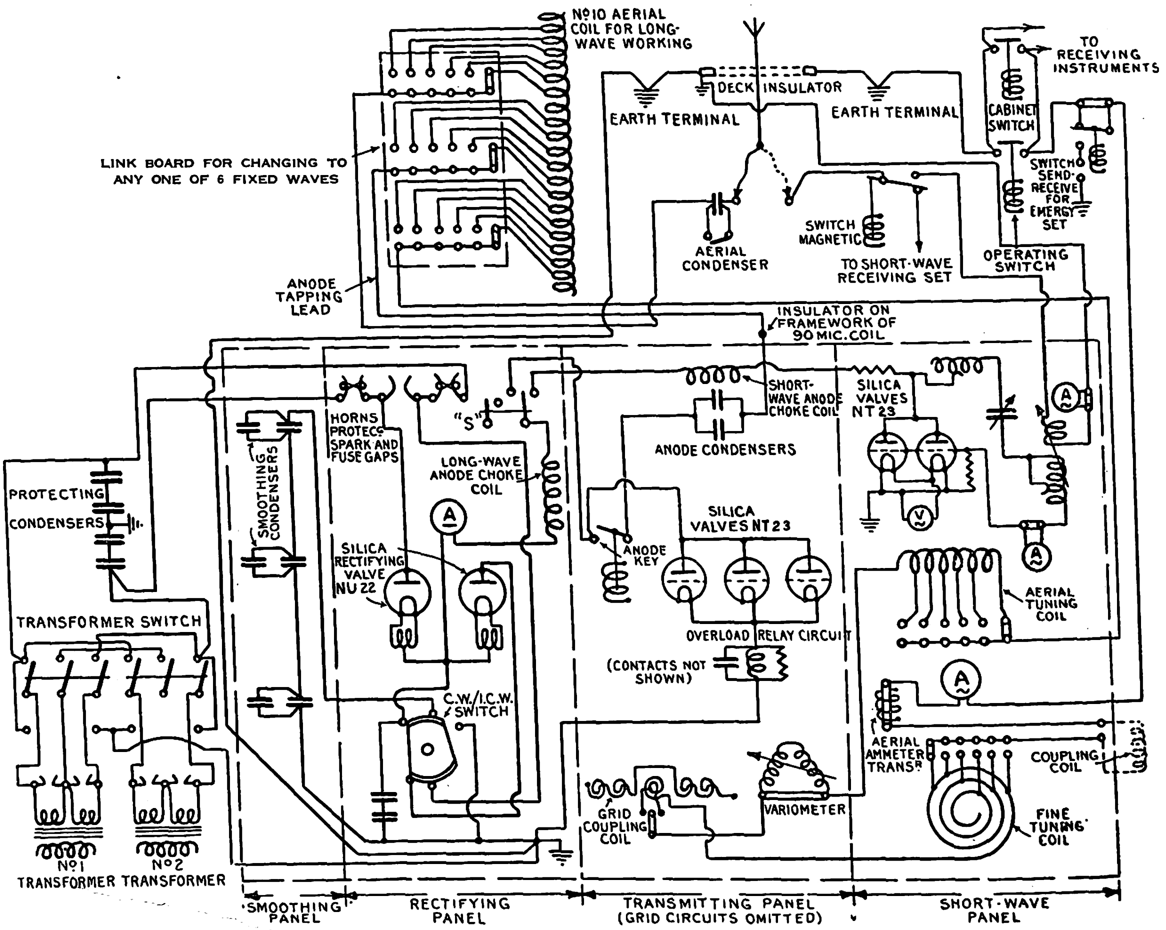
No 10 AERIAL COIL FOR LONG-WAVE WORKING
LINK BOARD FOR CHANGING TO ANY ONE OF 6 FIXED WAVES
ANODE TAPPING LEAD
DECK INSULATOR
EARTH TERMINAL
EARTH TERMINAL
TO RECEIVING INSTRUMENTS
CABINET SWITCH
SWITCH SEND-RECEIVE FOR EMERGY SET
AERIAL CONDENSER
SWITCH MAGNETIC
TO SHORT-WAVE RECEIVING SET
OPERATING SWITCH
INSULATOR ON FRAMEWORK OF 90 MIC. COIL
SHORT-WAVE ANODE CHOKE COIL
SILICA VALVES NT 23
ANODE CONDENSERS
PROTECTING CONDENSERS
SMOOTHING CONDENSERS
HORNS PROTECG SPARK AND FUSE GAPS
"S"
LONG-WAVE ANODE CHOKE COIL
A
SILICA RECTIFYING VALVE NU 22
SILICA VALVES NT 23
ANODE KEY
A
V
A
AERIAL TUNING COIL
TRANSFORMER SWITCH
OVERLOAD RELAY CIRCUIT
(CONTACTS NOT SHOWN)
C.W./I.C.W. SWITCH
A
AERIAL AMMETER TRANSR
COUPLING COIL
GRID COUPLING COIL
VARIOMETER
FINE TUNING COIL
No 1 TRANSFORMER
No 2 TRANSFORMER
SMOOTHING PANEL
RECTIFYING PANEL
TRANSMITTING PANEL (GRID CIRCUITS OMITTED)
SHORT-WAVE PANEL

FIG. 11.—Diagram of H.T. and oscillatory circuits. "S" = change-over switch for long- or short-wave transmitter.
(Low-power panel not shown.)

The power panels themselves are of metal framework structure and follow general electrical engineering practice for marine purposes. Each of the panels is contained in an angle-iron frame so arranged that any of the individual units can be readily removed.

Subdivision is carried to a greater degree than otherwise would be the case, to enable each part to pass through the hatches.

The power supply is so arranged that both machines may be running simultaneously, but if one is on load then the other must be running light. The power panels are comprised in four main parts which subdivide into two parts. These parts serve the following functions:—

(i) D.C. supply and a.c. output board for the filament motor-alternators.

(ii) D.C. supply board for main alternators, with busbars for supplying No. 1 board.
(iii) Distribution board for lighting and all auxiliary circuits, including operating and control circuits, fans and motors charging battery circuits.
(iv) A.C. distribution board for main alternator.

A schematic diagram showing the general arrangements and functions of these parts is shown in Fig. 8.

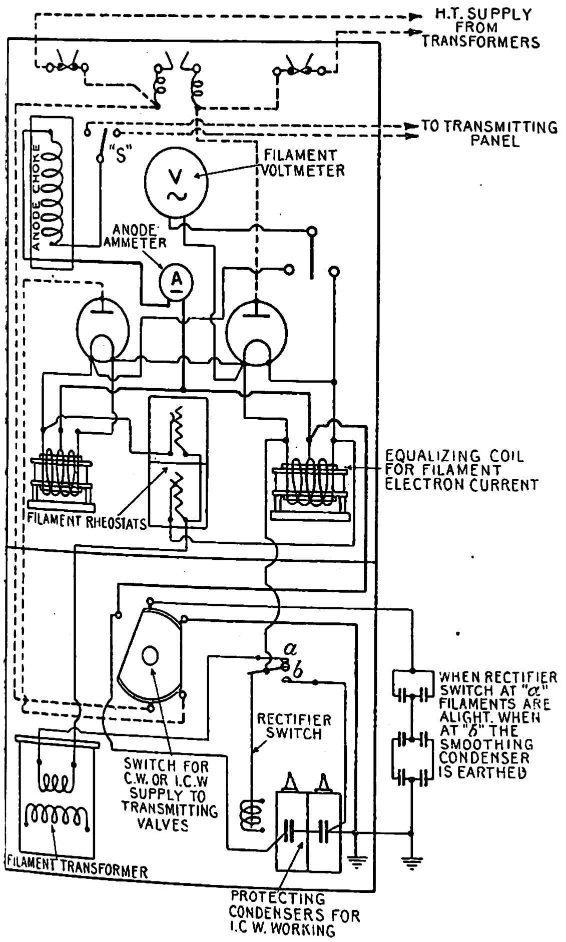
H.T. SUPPLY FROM TRANSFORMERS
TO TRANSMITTING PANEL
ANODE CHOKE
"S"
FILAMENT VOLTMETER
V
ANODE AMMETER
A
EQUALIZING COIL FOR FILAMENT ELECTRON CURRENT
FILAMENT RHEOSTATS
a
b
WHEN RECTIFIER SWITCH AT "a" FILAMENTS ARE ALIGHT. WHEN AT "b" THE SMOOTHING CONDENSER IS EARTHED
RECTIFIER SWITCH
SWITCH FOR C.W. OR I.C.W SUPPLY TO TRANSMITTING VALVES
FILAMENT TRANSFORMER
PROTECTING CONDENSERS FOR I.C.W. WORKING

Fig. 12.—Rectifying panel.

The earlier hand-starting has been replaced by autostartor controls and these have proved much more satisfactory than the hand startor. Tests have shown that the auto-startors fitted do not throw off under the normal vibrations of the ship or shock from gunfire. As typical circuit illustrations for the power boards, wiring diagrams for the d.c. and a.c. supply boards for the main motor-alternator are shown in Figs. 9 and 10. With regard to the d.c. board, duplicate supplies are taken from the busbars through pairs of circuit breakers. The positive supply leads go from each circuit breaker to one of the two startors for the motor-alternators. The negative lead goes to an 8-pole, 2-way change-over switch which serves the dual function of d.c. change-over for alternators and for startors, enabling either startor to be used with either motor.

The a.c. board supplies the primary of the main h.t. transformer. This supply is via a safety relay switch and magnetic key. Two magnetic keys are fitted and switching arrangements provided whereby either key can be brought into use for signalling with either alternator. The magnetic key is operated for signalling by solenoid control from the morse key.

The distribution boards also include indicating lamps and safety devices as follows:—

(*a*) Indicating lamps for main and filament d.c. motors.
(*b*) Indicating lamps for main alternators.

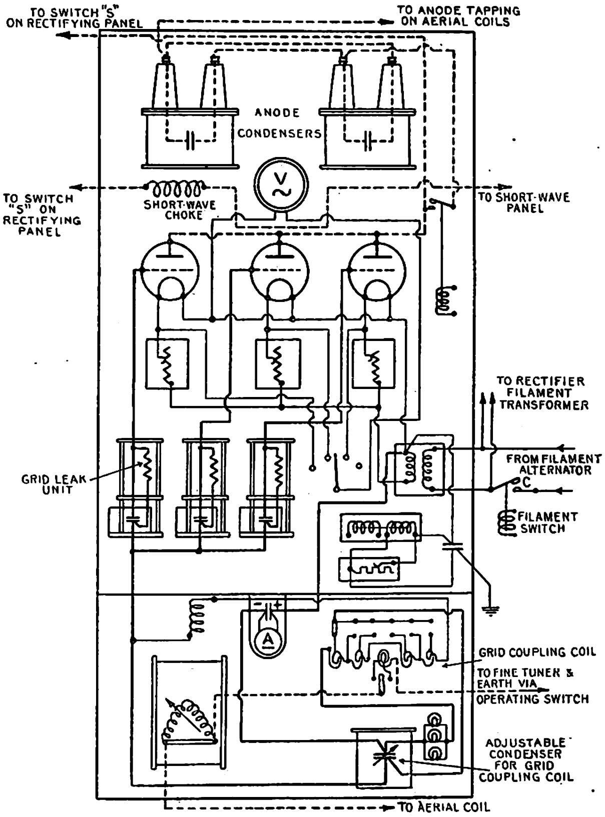
TO SWITCH "S" ON RECTIFYING PANEL
TO ANODE TAPPING ON AERIAL COILS
ANODE CONDENSERS
V
TO SWITCH "S" ON RECTIFYING PANEL
SHORT-WAVE CHOKE
TO SHORT-WAVE PANEL
TO RECTIFIER FILAMENT TRANSFORMER
FROM FILAMENT ALTERNATOR
C
GRID LEAK UNIT
FILAMENT SWITCH
A
GRID COUPLING COIL
TO FINE TUNER & EARTH VIA OPERATING SWITCH
ADJUSTABLE CONDENSER FOR GRID COUPLING COIL
TO AERIAL COIL

Fig. 13.—Transmitting panel.

(*c*) Internal signalling lamps between receiving office and power-boards, with bell and push on the board.
(*d*) Operating lamps.
(*e*) Locking-device for ring-main change-over switch.

(B.) *Design of Valve Transmitters for Long and Short Waves.*—It is not intended here to discuss the types of wireless telegraph circuits which are employed. The earlier post-war valve transmitters * were either directly connected to the aerial circuits or coupled via an intermediate or primary oscillatory circuit, these transmitters being used on what are usually known as long or medium waves, i.e. frequencies between 60 and 3 000 kilocycles per sec. (5 000 and 100 m). The later designs employ master-oscillator types of generator circuits, the frequencies in certain cases (for the shorter waves) being stabilized by quartz crystal control. The introduction of short waves has modified the requirements very considerably. Their advantages for long-range working at distances from a few hundred miles up to world-wide ranges during certain portions of the 24 hours of each day are well known, and it has been necessary to arrange for the fitting of attachments to existing longer-wave sets capable of transmitting on a band of waves covering 4 300 to 21 500 kilocycles per sec. (70 to 14 m).

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* See G. Shearing: "Naval Wireless Telegraph Transmitters Employing Rectified Alternating Current," *Journal I.E.E.*, 1925, vol. 63, p. 309.

The general arrangement of the oscillatory circuits for one of the earlier main valve long-wave transmitters with short-wave attachment is indicated in Fig. 11. The rectifying and oscillatory circuits, with the exception of the aerial coils, are arranged in panels of light steel or aluminium alloy framework with the front and outer ends protected by expanded-metal screens. These panels are supplied with the internal wiring completed as far as practicable. The arrangement of typical rectifying and long-wave transmitting panels is shown in Figs. 12 and 13.

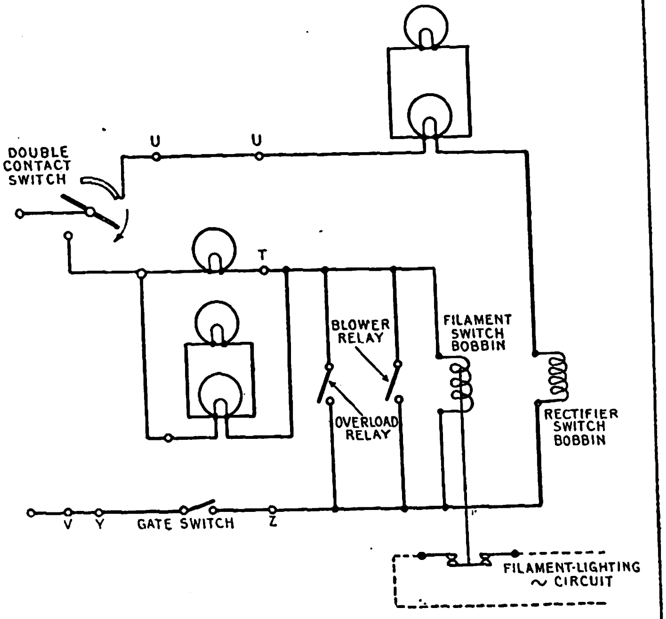

DOUBLE CONTACT SWITCH
U
U
T
BLOWER RELAY
FILAMENT SWITCH BOBBIN
OVERLOAD RELAY
RECTIFIER SWITCH BOBBIN
V
Y
GATE SWITCH
Z
FILAMENT-LIGHTING ~ CIRCUIT

FIG. 14.—Simplified diagram of d.c. control and relay circuits for transmitting and rectifying valves.

(C). *Operating Controls for Valve Transmitters.*—For a valve transmitter as shown in Fig. 11, the following d.c. circuits are provided:—

(i) Signalling and remote-control circuits for operating all the switches working in unison with the morse key, e.g. magnetic key for main power to valve set, anode key for isolating the valve anode circuit from the aerial circuit, operating and cabinet switches which are closed for earthing the receivers during marking and opened for listening-through during spacing. The circuits of the remote-control bobbin and repeater to the bridge are also included. The morse key is fitted with a bobbin attachment for operation from the bridge and other remote positions.

(ii) Blowers for valve cooling and main safety circuits. The main power-supply relay is in series with the blower circuit when the gate of the cage is closed, so that it cannot be "made" until one of the blowers is switched on.

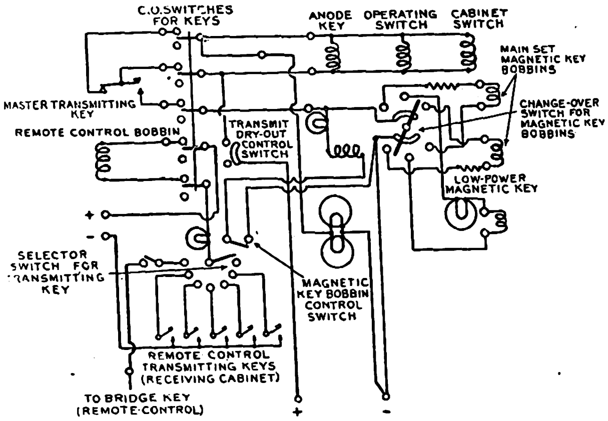

C.O.SWITCHES FOR KEYS
ANODE KEY
OPERATING SWITCH
CABINET SWITCH
MAIN SET MAGNETIC KEY BOBBINS
MASTER TRANSMITTING KEY
REMOTE CONTROL BOBBIN
TRANSMIT DRY-OUT CONTROL SWITCH
CHANGE-OVER SWITCH FOR MAGNETIC KEY BOBBINS
LOW-POWER MAGNETIC KEY
+
-
SELECTOR SWITCH FOR TRANSMITTING KEY
MAGNETIC KEY BOBBIN CONTROL SWITCH
REMOTE CONTROL TRANSMITTING KEYS (RECEIVING CABINET)
TO BRIDGE KEY (REMOTE-CONTROL)
+
-

FIG. 15.—Diagram of signal and remote-control circuits.

(iii) Alarm circuit. This warns the auxiliary offices when the main set is about to transmit. Indicating lamps are also fitted in the receiving cabinet, telling the operator of the main set when these auxiliary aerials have been earthed.

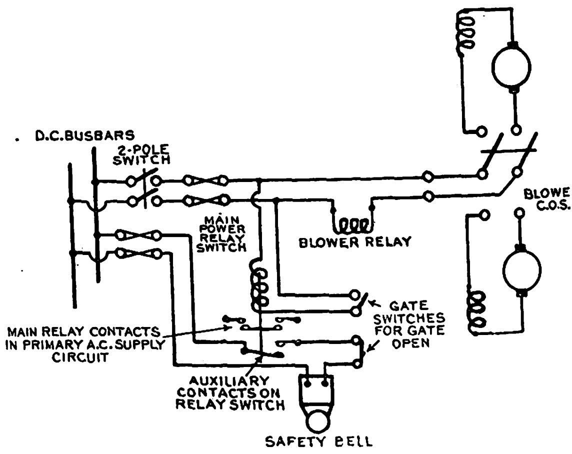
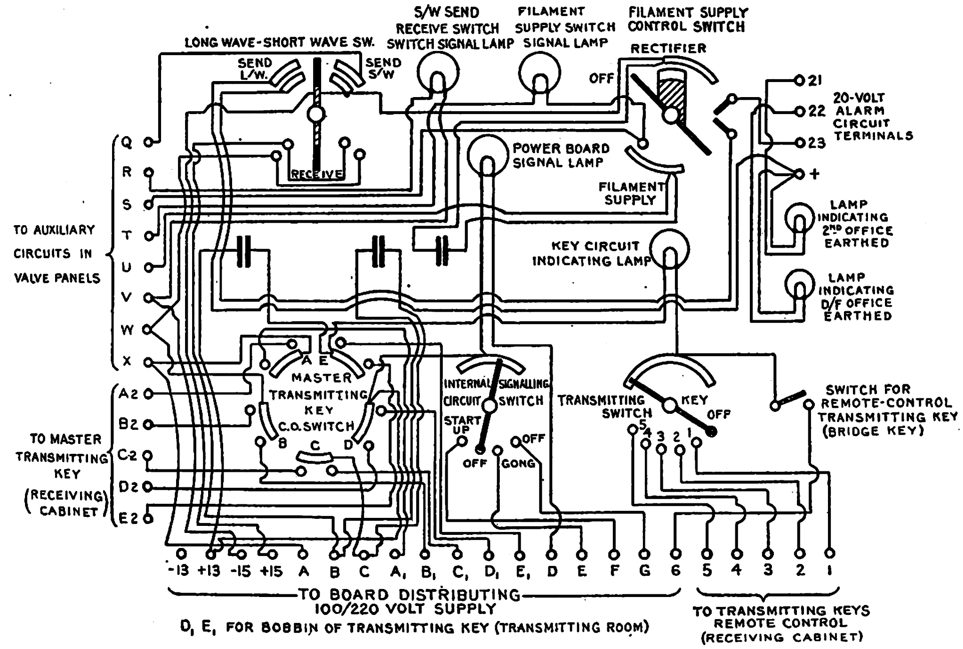

D.C.BUSBARS
2-POLE SWITCH
BLOWER C.O.S.
MAIN POWER RELAY SWITCH
BLOWER RELAY
GATE SWITCHES FOR GATE OPEN
MAIN RELAY CONTACTS IN PRIMARY A.C. SUPPLY CIRCUIT
AUXILIARY CONTACTS ON RELAY SWITCH
SAFETY BELL

FIG. 16.—Diagram of blower and main safety circuits.

(iv) Internal signalling circuit. Lamps and bell with pushes for enabling the operator in the cabinet to convey his requirements to the operator at the power boards.

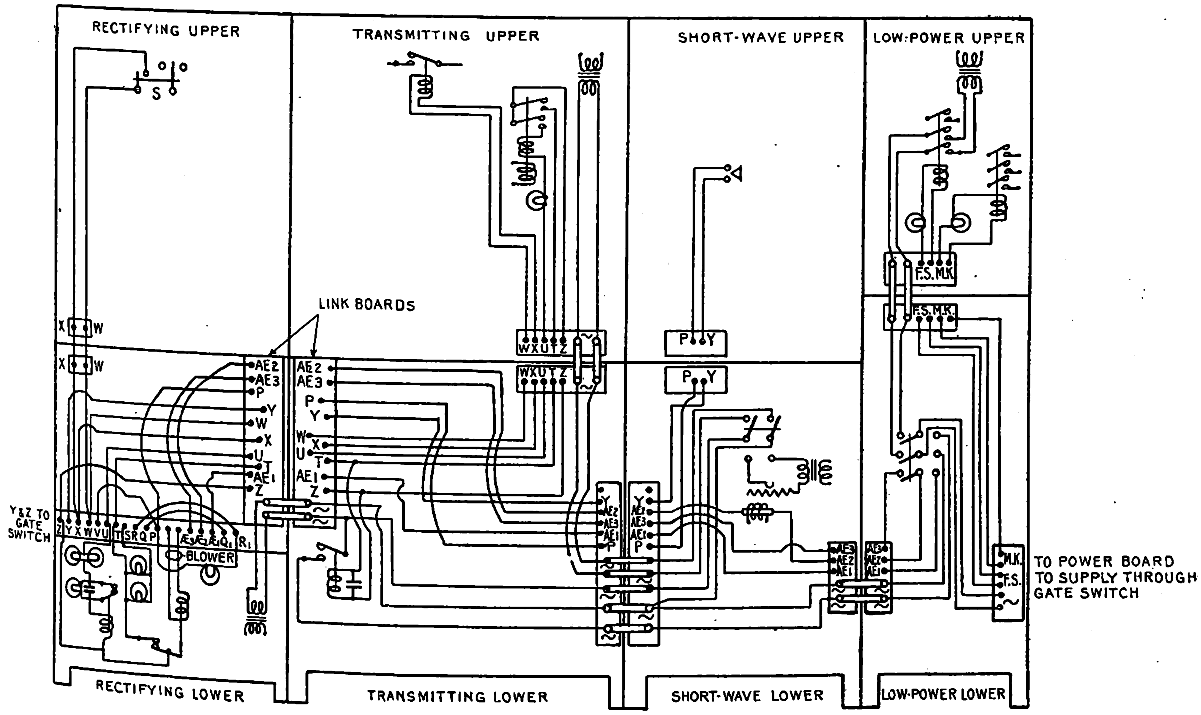
A simplified diagram of the valve filament and rectifier switch circuits is given in Fig. 14. The double-contact switch ensures that the rectifier switch contact "a" (see Fig. 12) makes before and breaks after the filament switch contact " c ", which is in the filament alternator supply lead to the primaries of all filament transformers (see Fig. 13). Thus no filament current is flowing when the rectifier switch is broken. If this were not done the contacts might fuse and prevent the switch from short-circuiting the smoothing condenser when the set is shut down after a transmission.

In addition, it will be seen in Fig. 14 that the contacts of the overload and blower relays are placed across the filament-switch magnetizing bobbin, so that unless they are open the filament switch is also open and the valves are switched off. The overload relay contacts close and switch off the valve filaments if for any reason whatever the valves carry excessive current. Similarly, the



S/W SEND RECEIVE SWITCH SWITCH SIGNAL LAMP
FILAMENT SUPPLY SWITCH SIGNAL LAMP
FILAMENT SUPPLY CONTROL SWITCH
LONG WAVE-SHORT WAVE SW.
RECTIFIER
SEND L/W.
SEND S/W
OFF
RECEIVE
POWER BOARD SIGNAL LAMP
FILAMENT SUPPLY
21
22
23
20-VOLT ALARM CIRCUIT TERMINALS
+
LAMP INDICATING 2ND OFFICE EARTHED
LAMP INDICATING D/F OFFICE EARTHED
KEY CIRCUIT INDICATING LAMP
Q
R
S
T
U
V
W
X
TO AUXILIARY CIRCUITS IN VALVE PANELS
A E
MASTER TRANSMITTING KEY C.O. SWITCH
B C D
INTERNAL CIRCUIT
SIGNALLING SWITCH
START UP
OFF
GONG
OFF
TRANSMITTING SWITCH
KEY
OFF
5 4 3 2 1
SWITCH FOR REMOTE-CONTROL TRANSMITTING KEY (BRIDGE KEY)
A2
B2
C2
D2
E2
TO MASTER TRANSMITTING KEY (RECEIVING CABINET)
-13 +13 -15 +15 A B C A1 B1 C1 D1 E1 D E F G 6 5 4 3 2 1
TO BOARD DISTRIBUTING 100/220 VOLT SUPPLY
D1 E1 FOR BOBBIN OF TRANSMITTING KEY (TRANSMITTING ROOM)
TO TRANSMITTING KEYS REMOTE CONTROL (RECEIVING CABINET)

FIG. 17.—Transmitter control board.



RECTIFYING UPPER
TRANSMITTING UPPER
SHORT-WAVE UPPER
LOW-POWER UPPER
S
X W
X W
LINK BOARDS
AE2
AE3
P
Y
W
X
U
T
AE1
Z
W X U T Z
P Y
F.S. M.K.
Y&Z TO GATE SWITCH
Z Y X W V U T S R Q P
AE3 AE2 AE1 R1
BLOWER
M.K.
F.S.
TO POWER BOARD TO SUPPLY THROUGH GATE SWITCH
RECTIFYING LOWER
TRANSMITTING LOWER
SHORT-WAVE LOWER
LOW-POWER LOWER

FIG. 18.—Auxiliary circuits in valve panels.

blower relay-contacts close if the blower motor supplying cooling air to the valves is not running.

Signalling control of the main sets is usually provided for by alternative morse keys, one of which is installed in the central receiving room adjacent to the operator, and the other on the d.c. distribution panel adjacent to the set for testing purposes. A schematic diagram of this circuit is given in Fig. 15, in which are shown:—

(*a*) The keying circuits for operating the magnetic key used for signalling.

(*b*) Circuits for closing the anode key in the transmitter circuit, the operating switch in the aerial earth lead and the cabinet switches for earthing receivers during marking.

(*c*) The bobbin attachment for the morse key when the set is operated from the remote-control positions.

Fig. 16 illustrates the safety circuits, which are supplied from a 2-pole switch from the distribution panel. From this it will be seen that the main power relay is opened whenever the safety gates are opened. As a protection against signalling when a man is aloft, an indicator plate with the words " man aloft " is hinged to the power board in such a manner that when bolted down it fouls the switch handles of the 2-pole switch and so prevents it from being closed.

The alarm circuit for other wireless telegraph offices utilizes a separate d.c. 20-volt supply. In each office is provided a buzzer and lamp. With the closing of the main safety gates the buzzer sounds and the lamp glows. With the earthing of the office aerial the buzzer ceases to sound but the lamp continues to glow so long as the main set is in operation. A diagram of the operator's control board installed in the central receiving room is shown in Fig. 17. The method of arranging the panel d.c. circuits which are connected to the control board is shown in Fig. 18. Each separate panel can be transported with its control circuits completely wired, and links complete the circuits between panels.

(D.) *Valve Transmitters having High Constancy of Frequency.*—The more recent designs of combined long-wave and short-wave transmitters employ master oscillator control for both the long-wave and short-wave circuits. One of these circuit arrangements for a ship transmitter is shown in Fig. 19, in which the control stages are designed for operation on either long or short waves, and the main stage for short-wave operation comprises a high-frequency double-acting system of two valves which are neutralized to avoid retroaction. For long-wave working the valves are used in parallel. Signalling is obtained by grid-potential control. The general arrangements of auxiliary circuits are similar to those described in detail above for an earlier design. Switching arrangements are provided whereby the change from long-wave to short-wave working can be effected.

For shore station short-wave transmitters used for point-to-point working, quartz-crystal controlled transmitters are employed for frequencies of the order of 7 500 to 10 000 kilocycles per sec. (40 to 30 m). In certain cases, frequency-doubler circuits are employed for transmissions on the corresponding band of 15 000 to 20 000 kilocycles per sec. (20 to 15 m), so that one crystal controls transmissions on the two waves. A general diagrammatic circuit of such a transmitter is shown in Fig. 20, in which the amplifier circuits are of high-frequency double-acting design, the third harmonic of the crystal frequency being selected and amplified. Automatic signalling is provided for by grid-potential control of one of the lower power stages, using a Creed relay as indicated in the diagram. Fig. 21 shows circuit arrangements for doubling the frequency, i.e. to the sixth harmonic of the crystal frequency.

In the case of all naval ship transmitters, the circuit design is such that no spacing wave is transmitted and arrangements are provided for listening-through.

(E.) *Assembly of Transmitter Components.*—The main requirements to which the wireless telegraph apparatus should conform have already been enumerated on page 243, from which it will be seen that the assembly and design of the components are a compromise between electrical and mechanical requirements. It is especially important to ensure that the relatively weaker links in the apparatus must all be easy of access for removal for repair and replacement. In assembling the components the distribution of the electric and magnetic fields has to be borne in mind, and undesirable magnetic and electrostatic coupling between coils must be reduced to a minimum. Any long metal parts near high-voltage coils are so mounted that their axes lie as nearly as possible in an equipotential plane.

(F.) *Panel Frameworks.*—The shock of gunfire causes the decks and bulkheads of the wireless telegraph offices in some ships to whip by as much as ½ inch. A framework must therefore be bolted either to the deck or to a bulkhead, but not to both. Fixing to the deck is the best solution. Heavy parts such as transformers and oil-filled condensers are, for this reason, fixed to the framework base to minimize bending-moment stresses due to shock. The question of angle iron, non-ferrous metal or wooden frames for the panels is determined by the space available. If the space is very cramped, voltage considerations may compel the use of wood; if more space is available, then angle aluminium alloys have the advantage of lightness; also, being non-magnetic and of low ohmic resistance, they do not cause appreciable losses. Angle iron has strength but it must be lined with thin copper to reduce its losses where parts cross an intense high-frequency magnetic field from a coil.

(G.) *Transmitter Oscillatory Coils.*—The oscillatory coils used may be very briefly dealt with under the headings of coils used for (i) long-wave, and (ii) short-wave transmitters.

(i) *Coils for long-wave transmitters.*—The materials mainly employed for insulation are ebonite, paxolin, porcelain and pyrex glass. The trend of later design has been to build American whitewood frameworks to support combs of ebonite which carry the coil windings. Porcelain parts have also been used for the combs, these being made from plastic clay which is vitrified by firing, but they were found not to lend themselves to accurate manufacture as regards dimensions. Those made by the dust process have the disadvantage that they are non-homogeneous and are porous before glazing. Paxolin and similar products are only used for parts requiring mechanical strength and not subjected to very high voltages at high frequencies. As regards American whitewood, whilst this is an excellent insulator when kept dry, it is not so satisfactory when subjected to the humid atmosphere in ships. The moisture absorbed by the surface of the wood increases its surface permittivity to such an extent as to cause brushing under the very high voltage gradients which exist for the coil designs due to space limitations. Treating the surface of the wood

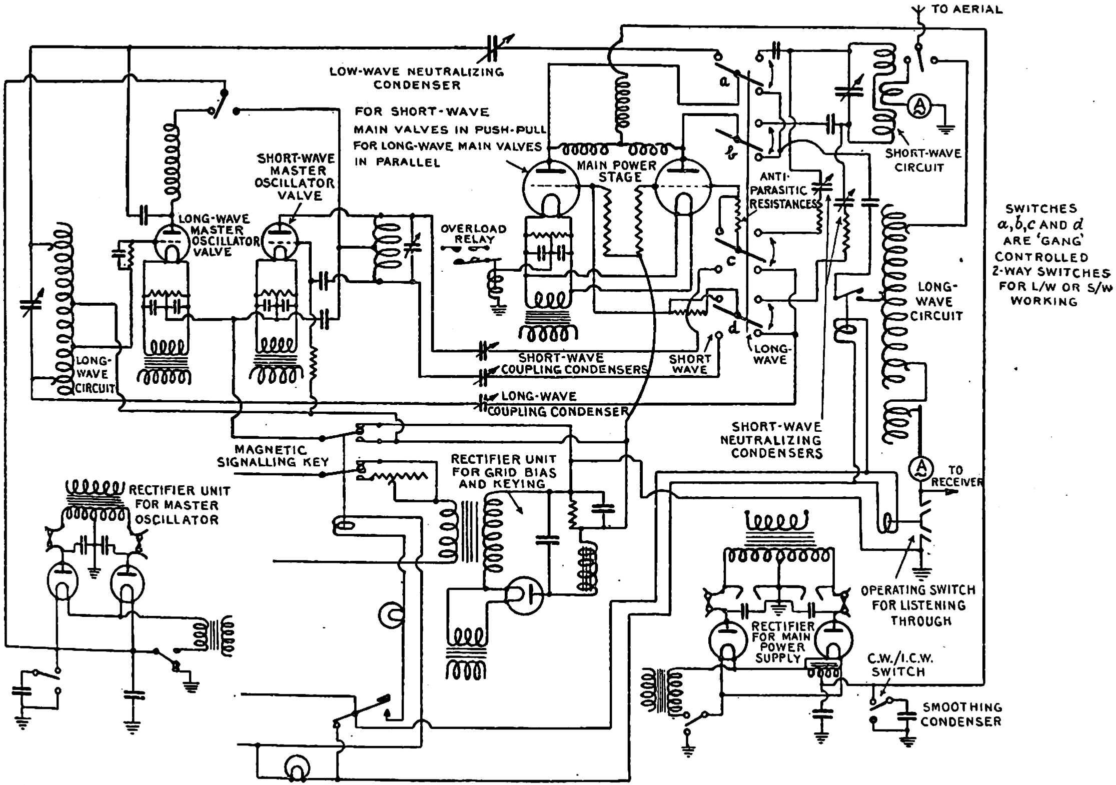

TO AERIAL
LOW-WAVE NEUTRALIZING CONDENSER
FOR SHORT-WAVE MAIN VALVES IN PUSH-PULL FOR LONG-WAVE MAIN VALVES IN PARALLEL
SHORT-WAVE MASTER OSCILLATOR VALVE
LONG-WAVE MASTER OSCILLATOR VALVE
MAIN POWER STAGE
a
b
c
d
ANTI-PARASITIC RESISTANCES
A
SHORT-WAVE CIRCUIT
SWITCHES a, b, c AND d ARE 'GANG' CONTROLLED 2-WAY SWITCHES FOR L/W OR S/W WORKING
OVERLOAD RELAY
LONG-WAVE CIRCUIT
LONG-WAVE CIRCUIT
SHORT-WAVE COUPLING CONDENSERS
SHORT WAVE
LONG-WAVE
LONG-WAVE COUPLING CONDENSER
SHORT-WAVE NEUTRALIZING CONDENSERS
MAGNETIC SIGNALLING KEY
RECTIFIER UNIT FOR GRID BIAS AND KEYING
RECTIFIER UNIT FOR MASTER OSCILLATOR
A
TO RECEIVER
OPERATING SWITCH FOR LISTENING THROUGH
RECTIFIER FOR MAIN POWER SUPPLY
C.W./I.C.W. SWITCH
SMOOTHING CONDENSER

FIG. 19.—Naval type combined long-wave and short-wave master-controlled transmitter. Self-oscillating and low-power connections not shown.

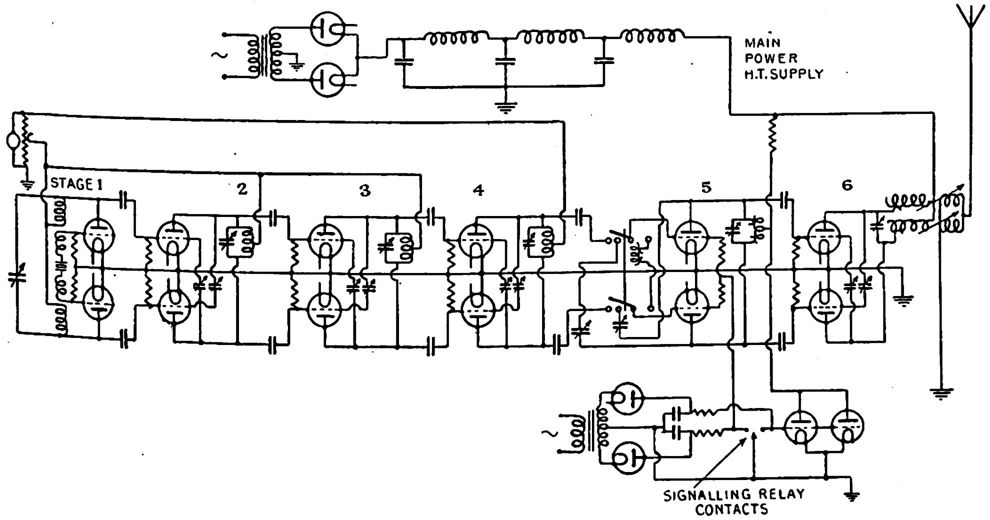

MAIN POWER H.T. SUPPLY
STAGE 1
2
3
4
5
6
SIGNALLING RELAY CONTACTS

FIG. 20.—Simplified circuit diagram of quartz-crystal controlled short-wave transmitter.

with a heavy coat of varnish largely destroys its high insulating properties, and the use of a very thin layer of varnish has been found to be not entirely satisfactory. As regards dimensions, a ratio of 3 : 1 in diameter to length gives the most efficient design of coil so far as copper losses and the length of wire for a given inductance are concerned. To obtain the required number of tapping points over a large range of frequency and to utilize the space within the framework to the best advantage, it is, however, usually necessary to reduce this ratio to 1: 1. In ship sets the long-wave coils are nearly always wound multi-layer because of space limitations. Stranded wire, each strand being insulated, is largely used and the windings are carried in slots. These slots are so designed that the voltage stress across a tooth does not exceed 5 000 volts per inch under the worst conditions. It is necessary to guard against the assumption that the greater the number of strands of the standard size (No. 38 S.W.G.) used in the wire, the less will be the resistance of the coil. For a given conductor there is a best spacing of the strands in the conductor and a best spacing of the conductors forming the coil. It is also desirable to keep the number of terminals down to a minimum. If a coil of N turns be tapped to form sections each having $\sqrt{N}$ turns, and if the last section is tapped at every turn, then the coil inductance can be tapped in steps of one turn throughout and the number of tapping points will be a minimum.

(ii) *Short-wave coils.*—For the larger ship sets these are wound with copper tube which carries a tapping clip for adjustment of wavelength. These coils are almost self-supporting but the end turns and a middle turn are usually clamped to porcelain insulators mounted on a wooden base, and in all designs the maximum permissible rigidity is necessary to secure constancy of wavelength. The electrical considerations tend to weaken the mechanical design, e.g. the turns have to be spaced sufficiently far apart to prevent the tapping clip from short-circuiting to the adjacent turns, and the coil has to be long compared with its diameter to enable single-turn tappings to be made having sufficiently fine adjustment of inductance in addition to the insulated clamping supports which are fitted to secure rigidity. The coils are also cooled by air blast to reduce the variation of frequency which otherwise occurs with change of temperature.

(H.) *Transmitting Condensers.*—The development of fixed condensers for specified wireless telegraph transmitting requirements is left to the makers of such apparatus. The usual type consists of copper-foil plates and ruby-mica dielectrics built up in sections connected in series or series-parallel as necessary to meet the specified conditions. Great care is taken to exclude any air bubbles between the plates and dielectric. The best procedure for assembly is to arrange for the sections to be placed in a vacuum in order to withdraw any air present within the condenser unit, and afterwards to dip them in paraffin wax for sealing. The procedure of placing the sections simply in boiling paraffin wax to drive out the air by heat is not satisfactory, for a proportion of the air may become sealed in spaces between the plates and dielectric at less than atmospheric pressure, and ionization losses may then occur.

The long-wave transmitting condensers usually have their units assembled in metal cases which are filled with either oil or wax and to which one of the condenser terminals is connected. The type of design which is favoured is that in which the case is suitably insulated from earth by porcelain pillars or blocks, by reason of the saving in space and cost for the container. It is of special importance to give the manufacturers full information as to the type of load and working conditions. The losses in a condenser are less when it is used in a spark or interrupted-continuous-wave circuit than for the case when the same circuit is used for continuous waves and passing the same effective current. The peak voltage values for the former are, however, much higher. The power factor of a good mica condenser is of the order of 0·2 of 1 per cent, but if the condenser is poorly constructed this power factor may easily increase to give double the power loss.

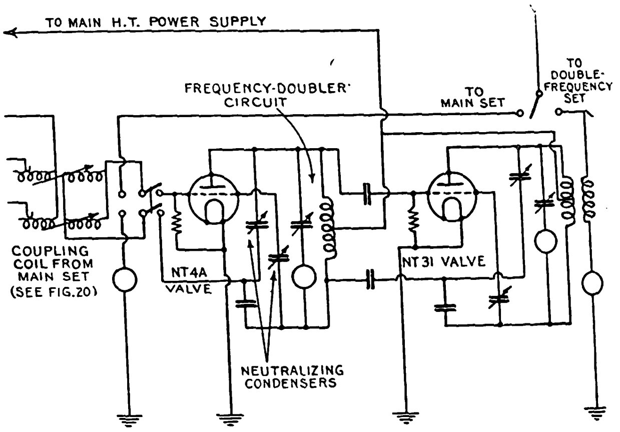

TO MAIN H.T. POWER SUPPLY
FREQUENCY-DOUBLER CIRCUIT
TO MAIN SET
TO DOUBLE-FREQUENCY SET
COUPLING COIL FROM MAIN SET (SEE FIG.20)
NT4A VALVE
NT31 VALVE
NEUTRALIZING CONDENSERS

FIG. 21.—Frequency-doubling circuits for short-wave transmitter.

In connection with the losses in a condenser, the arrangement of the condenser plates is of great importance, for if the sections are so arranged that the bottom plates are connected to a low-potential terminal and the top plates to the high-tension terminal, the high potential gradient around the edges of the top plate may then cause heavy losses in the top clamping plate of insulation. Cases have been experienced where ebonite clamping plates have melted locally, adjacent to the edge of the top plate. Designs in which the condenser is arranged in two sets of units connected in parallel so that the h.t. plates face one another at the centre are much better in this respect; also, metal clamping plates may then be used. In certain cases fixed condensers are employed in short-wave transmitting circuits and it is then essential to keep the current path through the terminals, leads and condenser elements as short as possible, otherwise the inductance of this path may become serious.

The adjustable tuning condensers used either are oil-filled for long-wave high-voltage transmitters or employ air dielectric for short-wave transmitters. The oil-filled condensers for small transmitting sets are usually more troublesome than the larger units, owing to the fact that any fibres in the oil are drawn between the plates by electrostatic attraction, with a tendency to bridge the plates. The condensers for short-wave transmitters are of low capacity, and to get a reasonable variation it is essential to keep their minimum capacity as small as possible. The chief difficulty experienced with the short-wave condensers is that a small roughness on one plate may start a brush discharge and cause arcing-over at a comparatively low voltage. In the case of transmitting sets employing neutralizing condensers, there is also the difficulty of maintaining the capacity-to-earth ratio of each set of plates constant to secure the symmetry which is essential for satisfactory operation throughout the tuning range.

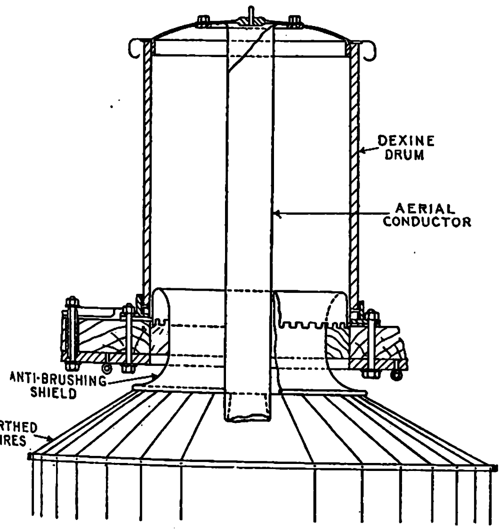


FIG. 22.—Deck insulator.

(J.) *Main Aerial Trunk and Deck Insulators.*—The fact that the main wireless telegraph office is usually situated below the main armoured deck has necessitated the fitting of special trunks whereby the high-frequency energy may be delivered to the main aerial with minimum loss and without danger to personnel. The trunk itself is of steel, and to prevent loss of power due to eddy currents it was formerly usual to fit a cylindrical system of earth wires which were soldered to the copper lining of the deck insulators. These deck insulators were fitted on the upper deck and at the exit for the aerial conductor from the wireless telegraph office. In addition, a similar deck insulator was fitted at intermediate decks if these were armoured or formed part of the watertight sub-division of the ship. More recently the use of the earth wires has been abandoned. In some cases, however, the trunk is copper-lined. One design of deck insulator system is shown in Fig. 22.

The insulating material used in this particular arrangement is dexine, which has the disadvantage that if it becomes encrusted with salt, owing to exposure to spray, a burn-out is liable to occur. If, however, the burn-out is not too deep, so that the charred material can be removed by scraping, and the surfaces are then varnished with shellac, the insulator can be used again. More recently a porcelain bowl-shaped insulator has been used with suitable fittings for securing it to the lower deck casting as shown in Fig. 23. The upper casting and the central cylindrical conductor are at the aerial high-frequency potential, the copper lining being an anti-brushing shield of spun copper fitted through the hole in the deck. The aerial feeder inside the trunk is a copper tube of about 2 in. diameter. For the deck-insulator design of Fig. 22 the joints between the insulating drum and the castings are made by means of a bitumen compound to ensure the arrangement being watertight; dermatine rings are used for the design of Fig. 23. It is important to note that the insulator itself is not of sufficient strength to withstand a considerable pressure in an upright direction, and for this reason the steel trunk itself is designed to be a watertight structure with all doors and manholes into it fitted as watertight doors.

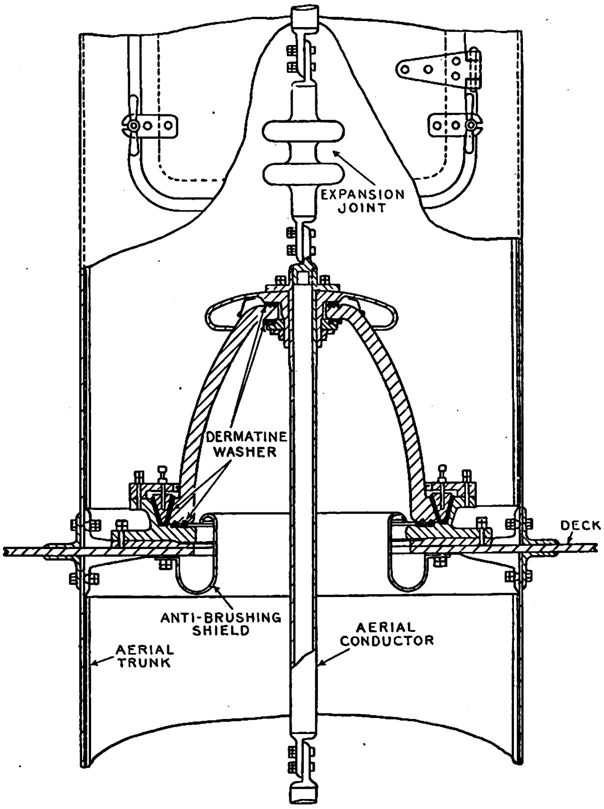


FIG. 23.—Deck insulator.

(K.) *Main Aerial Systems and Insulators.*—Two types of aerials have been employed in main aerial systems, these being either:—

(i) Sausage aerials having two or more legs each comprising 10 wires on circular spreaders at about 1 ft. diameter, or

(ii) Flat roof aerials of about 6–8 single wires in parallel, arranged along yards of 30 to 40 ft. in length.

Experience with these two types indicates that for a given range and capacity there is very little difference in the communication, and the mechanical considerations of handling, rigging and maintaining the aerial in position are the main deciding factors as regards which type of aerial is employed. The chief advantages of the flat roof over the circular-spreader type of aerial are the reduction of strain on the masts for a given aerial sag and windage, the greater ease of handling and the reduction in cost. The wooden yards used for supporting the aerials are painted with an aluminium paint, thereby forming a metal sheath over the wood and preventing charring around the points of metal bolts or screws, which may otherwise be caused by brush discharges from the high-frequency field.

The run of the aerial feeders is of very great importance for efficient working. They must be set well clear of all obstructions and, especially, kept as far as possible from the tops of the funnels to avoid (*a*) reduction of effective height, and (*b*) the losses which otherwise may occur due to the low resistance from ionization of the gases. The upper deck insulator is provided with a spray shield formed by a light sheet-steel screen of about 5 ft. diameter around the deck insulator, and a special outhaul is necessary to ensure that the feeder is well clear of the top edge of the spray shield, unless the adjacent superstructure can provide a suitable attachment. The design of aerial systems for submarines, although they are smaller than those for main aerials of heavy ships, is in some respects more complicated, due to the fact that provision has to be made for raising and lowering the main aerial, which is only employed for surface working, so that it may be taken down and housed prior to diving. The mast is usually of telescopic design. For instantaneous working immediately after surfacing from submerging, a smaller (fixed) aerial is employed.

The strain and rigging insulators at present in use are of porcelain. This material, if properly glazed, has good electrical qualities for high-frequency working, and one of its chief advantages is the ability to withstand sea weather conditions and arcing over its surface for long periods without injury. Its mechanical strength is not so satisfactory. It is especially liable to fracture under mechanical shock, and cases are known where aerial systems have collapsed for this reason. In some cases where the porcelain insulator is cemented by the use of solder into metal end-sockets, failure has occurred due to melting of the cement from the heating of funnel gases, and special designs have been prepared to avoid this danger. In a few cases, also, a curious defect has occurred in some porcelain insulators. If the temperature is a little too high when stoving the glaze during manufacture, very minute bubbles appear in it. If some of these bubbles break and the salt from sea spray lodges in the resultant holes, a very serious reduction in the insulation resistance may be brought about. For this reason there is a tendency to use pyrex glass in place of porcelain. Tests of insulating materials are continuously in hand with a view to obtaining, if possible, a material having both good electrical and mechanical qualities.

The requirements of a good aerial strain insulator may be summarized as follows:—

Electrical.—High surface and volume resistivity. Low dielectric hysteresis loss. Preferably, low permittivity.

Mechanical.—Mechanically strong under tension. Must not be brittle. Surface must not deteriorate owing to action of funnel gases and/or immersion in sea water. Must be non-hygroscopic and the surface should be such that the settlement of moisture does not produce a continuous film. Surface must not be damaged by electrical flash-over.

(L.) *Receiver Power Supplies and Arrangements.*—The main receiving apparatus for heavy ships is installed in a silent room which forms a portion of the main wireless telegraph office. It has been laid down as a general policy that all receiving instruments shall be operated independently of the ship's mains, and the power supplies for the anodes and filaments have for this reason been taken from accumulators. Two complete sets of batteries are supplied for each office. The power for charging these batteries is taken from the 220- or 110-volt d.c. ship's mains. Motor-generators are installed for charging the low-voltage filament batteries, the anode batteries being charged directly from the mains through a suitable resistance. The control gear with fuses is mounted on a special switchboard which also contains the switches for the auxiliary 20-volt ship's supply for operating the buzzer circuits and supplying the secondary lighting circuit for the wireless telegraph office.

One common filament battery and one common anode battery are employed for all the models in a single receiving outfit. The earlier designs of models used bright-emitter valves employing 6 volts for the filament battery, but these models are being gradually converted to use a special dull-emitter valve having similar characteristics. The newer models have been designed to employ types of manufacturers' dull-emitter valves which have been found to be satisfactory, and a general review of the market led to the decision to adopt a filament battery of 4 volts. The common anode battery has been usually limited to 50 volts owing to weight and space considerations. A typical lay-out of long-wave naval receiving gear for a ship's office is indicated in Fig. 24, the plans in Figs. 5, 6 and 7 indicating the general lay-out of the receiving bays. Each bay is supplied from the common anode battery via a cushioning unit to prevent interference.

The question of adopting alternative power supply systems to the above accumulator systems has received considerable attention, and the earlier policy of adopting battery supplies entirely has undergone some revision. Experimental investigations are at present in hand with rectified alternating current and with d.c. generators as sources of supply (with or without a floating battery). If floating batteries are not used these systems must be capable of being operated from either the 220-volt d.c. or the auxiliary 20-volt ship's mains in order to provide for emergencies, but if floating batteries are used these in themselves form the emergency supply. The supply of anode voltage to receivers does not appear to present any insuperable difficulties, but the importance of good voltage regulation for a filament supply to dull-emitter valves in a central receiving room when the filament current may be changed suddenly from 5 amperes to a few milliamperes renders the problem much more difficult. It is essential to arrange for automatic voltage-control devices to be fitted in the 220-volt or 20-volt busbar supply to cover the wide variations in voltage which may occur in normal ship routine, whilst the inherent regulation of the motor-alternator or d.c. motor-generator must be very small. The best arrangement as regards regulation is probably a motor-generator system with floating battery, and in this case the floating battery is available for use alone in emergency; on the other hand the rectified a.c. system has considerable advantages, especially as regards reduction of interference.

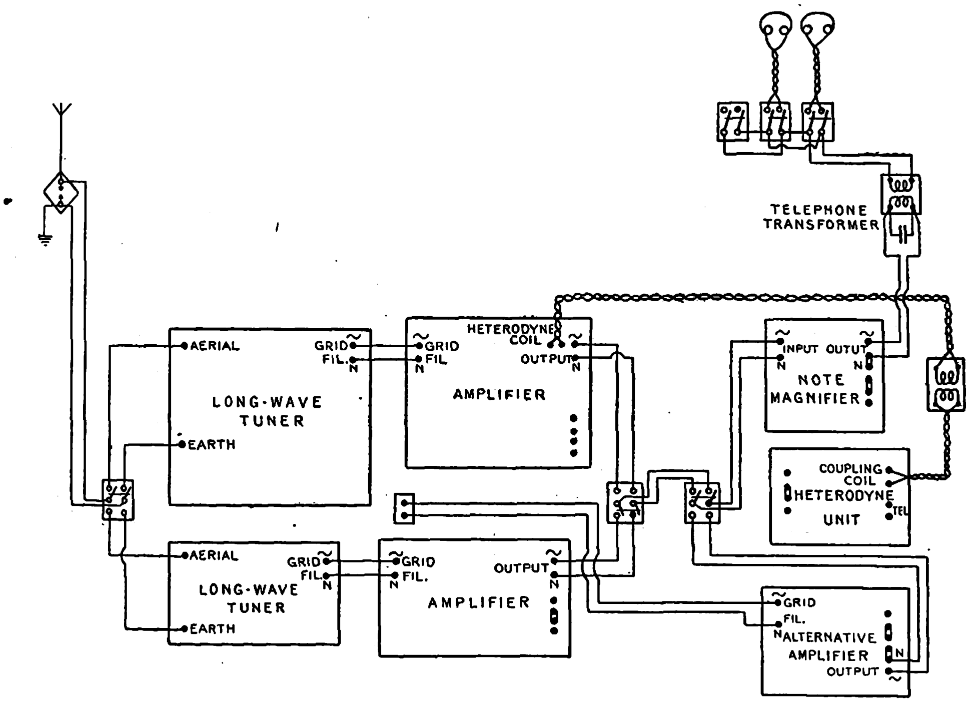


FIG. 24.—Arrangement of receiving model outfit.

The wiring and arrangements of the receivers to reduce interference has to be very carefully carried out; it may be interesting to enumerate here some of the chief interference problems which arise:—

(a) Mutual interaction from adjacent receivers, due to (i) common anode and filament supplies, (ii) local heterodynes.
(b) Morse-key clicks.
(c) Direct interference from transmitters adjacent to the receiving room.
(d) Interference between wireless telegraph offices in a ship, arising from mutual coupling between aerials.
(e) Faults such as earths or poor insulation on lighting supply leads, battery leads or fan leads introduce irregular low-frequency noises.
(f) Aerial down-hauls and stays which cross one another and rub are a serious cause of interference, especially to short-wave reception.
(g) Valve noises due to vibration, particularly in small ships.
(h) High-frequency interference from incoming cables which are connected to running machines.

The problem of interference from running machines is found to be especially troublesome, and in this connection the importance of good workmanship in the commutators and slip-rings of these machines in order to reduce sparking and ripple voltages cannot be over-emphasized. Sparking at a commutator may radiate wireless waves directly to the central receiving room. In addition, sparking or machine ripple may set up high-frequency oscillations along the cables, and, if any of these have a direct conducting path to the central receiving room, serious interference to both long- and short-wave reception may result. For the case of machines with poor brushgear design the effect of brush chatter in setting up high-frequency interference in this manner has proved especially troublesome. It has been found necessary in certain cases to fit low-pass filter units not only in the output but also in the input, i.e motor circuits of machines, to reduce this trouble.

(M.) *Receiving Aerials.*—The aerials employed for long-wave reception range from the main aerial of a ship to a short single wire. The aerial in use may be connected to the tuner in the office either by the central conductor of a long trunk or by a lead-cased cable which may have a length of the order of 150 ft. The effective capacity of the aerial receiving system may therefore vary over very wide limits, and the design of the aerial tuning circuits for a given receiver must be arranged to cover this wide variation. There is a considerable loss of receiving efficiency as the length of cable increases. More recently, cables having air and paper dielectric, and therefore much less capacity per unit length, have been employed with success in place of rubber cables.

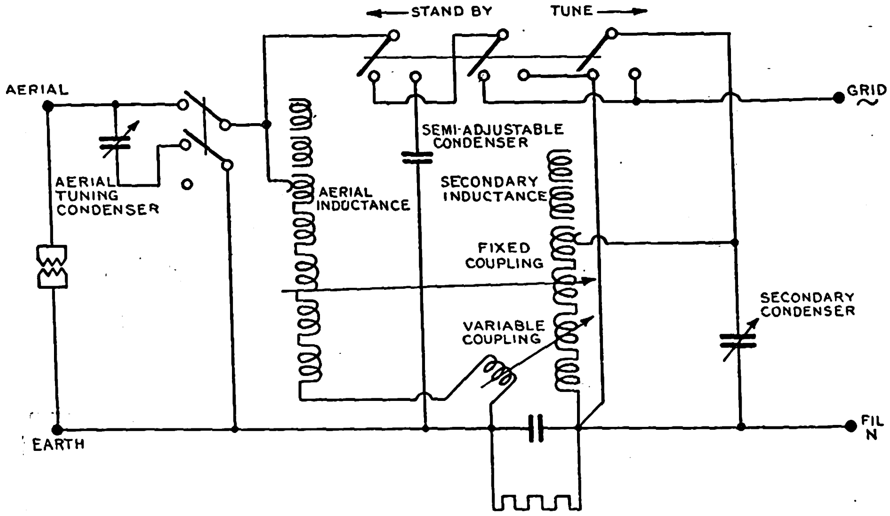


Fig. 25.—Schematic diagram of long-wave tuner.

(N.) *Receiver Design for Wide Frequency Bands.*

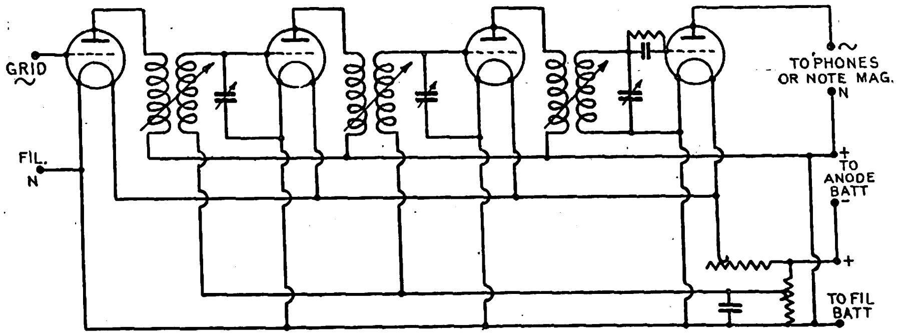


Fig. 26.—Schematic diagram of long-wave amplifier.

(i) *Long-wave receivers.*—Reception over the band of waves covering 12·5 to 6 000 kilocycles per sec. (24 000 to 50 m) has been provided by three ranges, viz. 12·5 to 600, 460 to 2 000 and 1 500 to 6 000 kilocycles per sec. (24 000 to 500, 650 to 150, and 200 to 50 m). The earlier policy was to adopt a unit form of assembly and construct a separate tuner and a high-frequency amplifier for each of these ranges. Also a standard 3-stage note-magnifier and a heterodyne to cover the range 12·5 to 2 500 kilocycles per sec. (24 000 to 120 m) was developed. Thus, any long-wave naval receiver included the appropriate tuner unit and high-frequency amplifier. The tuners are of the two-circuit magnetically-coupled type, and are fitted with a "stand-by" and "tune" switch. In the "stand-by" position the aerial circuit alone of the tuner is in use, so that quick searching is possible. In the "tune" position the closed secondary circuit is added to obtain selectivity and the inductive coupling can be loosened to any desired extent. In most cases, arrangements are made for listening-through on the wavelength being transmitted. For special purposes, such as direction-finding and submarine reception, where very high amplification combined with very quick searching is desired, special high-magnification non-selective amplifiers have been developed. Also, special tuners have been developed to allow for the high damping and high capacity to earth of loop-aerial systems when used in submarines.

Figs. 25 and 26 illustrate the circuit arrangements of one of the naval long-wave tuners and amplifiers which has had considerable application. The tuner comprises two tuned magnetically-coupled circuits and is designed for

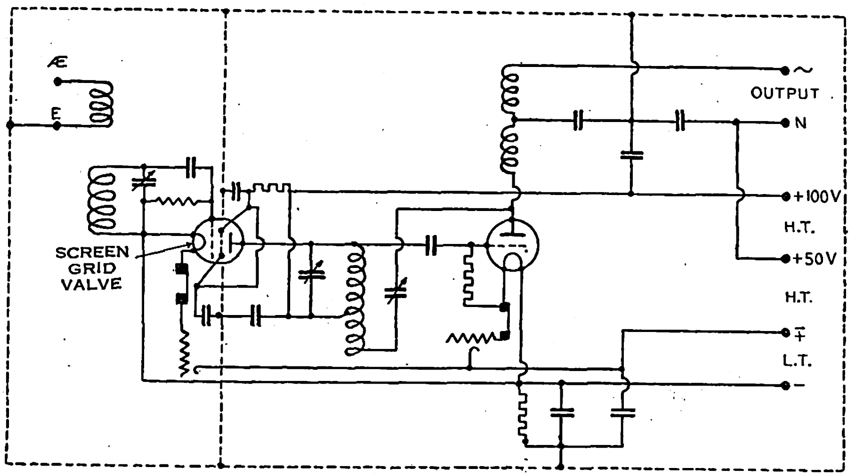
(i) tuning aerials having widely varying capacities for the entire range of 12·5 to 600 kilocycles per sec. (24 000 to 500 m), or

(ii) tuning as an acceptor circuit for the higher frequencies above 60 kilocycles per sec. (5 000 m).

A "stand-by" and "tune" switch is provided whereby the amplifier can be connected across the aerial tuning inductance when in the "stand-by" position, and across the secondary inductance when in the "tune" position. When in the "tune" position, a condenser having a capacity equal to that of the first valve of the amplifier and of the leads is connected across the primary inductance, thus obviating a change of tuning of the aerial circuit when switching over from "stand-by" to "tune." The secondary circuit is short-circuited and earthed in the "stand-by" position.

The amplifier circuits shown in Fig. 26 are designed for high amplification and selectivity. The entire range is covered by a number of range boxes which can be fitted into the amplifier. A separate heterodyne is employed which is coupled into the anode circuit of the first valve, thus to a great extent obviating radiation from the aerial.

For certain bands of waves, special provision has to be made for quick change from one wave to another, and this may be provided for either by the use of adjustable stops on the variable-condenser dial for cases where the change is small, or by change-over from one circuit to another for cases where there is a large difference between the two waves. The requirement that the majority of naval receivers must be non-radiating, necessitates an increase of circuit complications and in many cases increases the number of valves required for a given amplification.



DOTTED LINE REPRESENTS SCREENS ALL ROUND

FIG. 27.—Short-wave tuner amplifier.

More recently the general policy of the design of receiving gear has been modified, the unit construction being departed from to a considerable extent. The later designs of amplifiers now include note-magnification and separate heterodyne in one unit, and in the case of reception on longer waves of the order of 600 m and above, special provision is made for multiple reception on one aerial.

(ii) *Short-wave receivers.*—To cover the short-wave requirements, two types of special tuner-amplifiers have been developed, one a simple oscillating detector with two stages of note-magnification and no high-frequency amplification, the other an oscillatory detector preceded by a stage of high-frequency amplification to prevent oscillations from the detector from reaching the aerial and being radiated. Also, receivers have been developed employing a detector valve operating on the threshold of oscillation in conjunction with a separate quenching valve. For automatic reception at shore stations, a special circuit has been developed using the double heterodyne principle. As regards short-wave reception in ships, the fact that reception in general has to be carried out via cables or aerial trunks introduces difficulties due to the fact that for certain waves these may tune as transmission lines. The effects of this may usually be greatly reduced by the use of very loose aerial coupling, although loss of signal strength is thereby occasioned, especially for the case of interrupted-continuous-wave signals.

A typical design of non-radiating short-wave receiver for ships is shown in Fig. 27. A screen-grid valve is employed in the first stage, followed by a detector valve with reaction which is used as an autodyne for continuous-wave reception. A separate note-magnifier is used behind this model. Despite the use of the 4-electrode valve, there was found to be coupling between the tuned grid and tuned anode circuits. This coupling was reduced by introducing a very small condenser between the tuned grid circuit and the grid of the valve.

(O.) *Receiver Components and Assembly.*—The reliability in performance of receiving instruments for naval use is naturally of first importance. The apparatus has to be used in all climates, and, whilst every effort is made to reduce size and weight, instruments designed for use in H.M. ships are generally of a more substantial construction than is considered necessary for shore work.

A number of parts, components and units which lend themselves to assembly in various ways for various purposes have been developed. These are embodied in the instrument designs, with the result that certain standard practices tend to develop for naval work, with a consequent saving in cost and in the time required for production. Where the quantities required are large, mouldings, die castings and stampings are used in these parts, the necessary stock being held by the Admiralty and issued to contractors as required. In addition, commercially produced components which are standardized in the trade and suitable for the required purpose are used whenever possible.

The adaptable receiving components specially designed include an adjustable condenser with die-cast fixed and moving vane units and with moulded end plates, a series of dial switches and a series of barrel-type switches each capable of assembly for many varied purposes, filament rheostats and potentiometers, a slow-motion dial, grid leak and anode-resistance holders.

The adjustable condenser can be assembled to either 0·5, 1·0, 1·5 or 2·0 jars'* maximum capacity. It is of the twin pattern in which two sets of moving vanes, insulated from one another and mounted on opposite sides of the spindle and in the same planes, move between similarly mounted fixed vanes. Each set of moving vanes is connected to one of the sets of fixed vanes. This construction is well known and gives the maximum capacity change in a given space. The vanes are stamped from sea-resisting aluminium alloy and are held together in forms die-cast on to them. The units are assembled between end plates moulded from insulating material. These end plates carry the bushes for the spindle. The moving system is capable of adjustment endways for centring. The whole provides a strong and rigid construction capable of being assembled to a high value of maximum capacity for the space occupied, with a mechanically balanced moving system. The minimum capacity is of a fairly low order (0·02 to 0·05 jar). These condensers are not particularly suited for short-wave receiving work, and other types are being developed for this purpose.

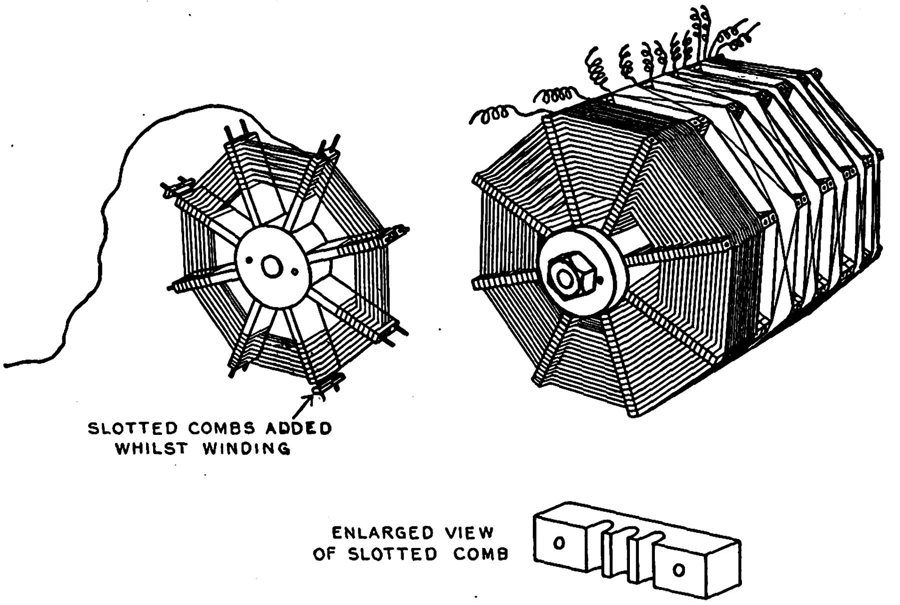

SLOTTED COMBS ADDED WHILST WINDING
ENLARGED VIEW OF SLOTTED COMB

Fig. 28.

The dial-type switches are intended for mounting directly on the faces of instruments, and the contacts and brushes are exposed. The barrel-type switches are mounted behind the instrument front. They are self-insulated and can be mounted on metal panels. They take up much less panel space than the dial type. Both types of switch can be built for many purposes.

The slow-motion dial is worm-geared with a micrometer thimble on the worm shaft. The worm is held in close mesh with the wheel by a spring, and provision is made to enable it to be immediately disengaged to permit quick setting. The design is primarily intended for wavemeters and receiving instruments requiring a high accuracy of adjustment.

A vertical and a horizontal anti-vibration 4-pin valve-holder have also been designed specially to suit service requirements. The features of these are that provision is made for locking-in the valve, damp and dust are excluded and the connections are enclosed. The valve-socket block is carried on rubber to provide an effective cushion with damping. The holders are designed to enable the rubber cushion to be replaced from the front and without disconnecting the valve-holder.

As regards the inductance coils for long-wave tuners, an endeavour is made to obtain efficient coils with a minimum of self-capacity. The theoretical maximum efficiency cannot, in general, be obtained, however, owing to limitations imposed by the permissible size of the instrument and by manufacturing conditions. In general, all coils are space-wound, one form of winding which has been adopted being shown in Fig. 28. The wire used in this case is 9/36 S.W.G., each strand being enamelled and silk-covered. The use of enamelled wire, each strand silk-covered, was found in practice to give a higher efficiency than the use of enamelled wire only due to the elimination of broken strands with the additional silk covering. Smaller coils are, in general, space-wound with 9/36 S.W.G. wire on threaded formers for ease of manufacture. When very short wavelengths are in question, losses in the former become of more importance than those in the wire. Hence solid wire is then used. For naval purposes the use of coils entirely without solid formers is impracticable, and a compromise has been reached by the use of ribbed formers, the wire being held in threads cut in the ribs. Thus, each turn of wire is supported in air and only touches the actual ebonite former by ribs on the latter. This construction has been found to give satisfaction since, in addition to reducing losses generally, it forms a means of obviating the difficulties due to the formers "sweating" in hot climates.

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* 1 jar = 1 000 cm.

Receiving instruments are mounted on bulkheads, and the space available is very limited. Consequently, controls must be on the face of the instrument, and it becomes an advantage that all parts shall come away with the instrument front. For this reason it is usual to provide a removable reversible cover which protects the front while the instrument is in transit and also serves as a bracket for securing it to the bulkhead when in use. In the later designs, the box and cover are of cast sea-resisting aluminium alloy, and the instrument front is of a similar rolled alloy.

It may be of interest to describe a small point in the design of variable inductances and condensers. Naval apparatus has hitherto been so designed that right-hand rotation gives an increased scale reading and indicates an increase of capacity or inductance and wavelength. In accordance with the decisions reached at the Washington Radio Convention the Navy has now adopted the use of kilocycles and consequently for the above apparatus a right-hand rotation corresponds to a decrease of frequency. For present and future developments of apparatus it has now been decided that right-hand rotation, corresponding to increase of scale reading, shall give increase of frequency. Consequently it has been necessary in a number of cases so to re-design the movements of condensers and inductances that right-hand or clockwise rotation gives a decrease in capacity or inductance.

(P.) *Direction-finding.*—The application of wireless telegraphy to direction-finding has great tactical importance. We may summarize the principal uses of direction-finding as:—

(1) Ascertaining the direction of enemy ships or aircraft.
(2) Checking the position of our own ships or aeroplanes making reports.
(3) Assisting aeroplanes in reconnaissances.
(4) An aid to navigation.

The type of system which is fitted in a particular ship largely depends on the structure of the ship. Just as a magnetic compass placed on board a steel ship is liable to considerable errors due to the magnetism of the ship (which errors have to be suitably corrected), so also a direction-finder is affected by the ship's structures and needs adjustment and calibration before reliable bearings can be obtained, and special correction devices have to be fitted for this purpose as with a compass.*

As a general rule it is the practice to fit the Bellini-Tosi system consisting of two loops in planes at right angles. Sometimes, however, where no suitable loops can be rigged, a rotating frame coil is fitted. Experience has shown that for a frame coil to be a success it must be placed in a position very well clear of metal work and preferably as high up as possible. In order that the coil may be conveniently rotated, the operator and instruments must be housed quite near to the coil, and sometimes this may limit very seriously the positions possible for the coil.

The Bellini-Tosi system is always fitted with one loop in the fore-and-aft line and the other loop exactly athwartships. To get the best results, regard must be paid to the positions of all large masses of metal in the vicinity of the loops, and generally the aim is so to place the loops as to secure the greatest possible symmetry with respect to the whole metal work of the ship. The loop run fore and aft is the one which invariably gives the greatest trouble in this respect.

The best position for the office, from a purely wireless point of view, is immediately beneath the aerials, but attention must be paid to other factors, such as weight distribution, vulnerability and compactness. For these reasons it is often necessary to have the instruments at a considerable distance from the aerials to which they are connected by cables. A common position for the operator and instruments is either the main or auxiliary wireless office. For the shorter waves, however, the price paid as regards accuracy for this convenience of organization and supervision is heavy, and offices immediately beneath the aerials are capable of much better accuracy.

(Q.) *Direction-finding Instrumental Design.*—The primary factors which govern the design of the receiving instruments for use in direction-finding are:—

(i) True bearings must be obtained without elaborate corrections or calculations.
(ii) Considerable amplification.
(iii) Ability to search rapidly over a band of waves so that a rough bearing may be obtained even though a transmission may last only a few seconds.

To meet these difficult requirements as far as possible, the moving element of the goniometer or frame coil is made as light as practicable to increase the speed at which a bearing can be taken, and generally the receivers have an unselective position suitable for quick search and a much more selective position for accurate work on a given band of waves.

The directional determinations are usually made by ascertaining the angle at which the search coil in a goniometer or a frame coil has to be set to give the minimum strength for the incoming signal. It is usual to find this angle by taking two readings at equal strengths, one on each side of the position of minimum strength, and to deduce the mean of these readings. To facilitate the determination of the mean value and to eliminate calculation, the naval service radiogoniometers and training units for frame coils are fitted with an automatic angle-dividing device. An additional rotatable scale is also provided which is driven by, and held in step with, the master gyro-compass. Thus, a bearing relative to the ship's head can be taken directly on the fixed scale, and true bearings are indicated directly on the rotating scale, no calculation being required for either. These two refinements, introduced into naval designs several years ago, greatly reduce both the time required to take a bearing and the error.

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* C. E. Horton: "Wireless Direction-Finding in Steel Ships," *Journal I.E.E.*, 1923, vol. 61, p. 1049.

The ordinary direction-finder does not differentiate between the true bearing and one differing from it by 180°. For tactical purposes it is essential to be able to determine the absolute direction, and "sense finders" are fitted for this purpose. In the case of the Bellini-Tosi system of loops the sense finder is a separate unit attached to the receiver and is not in use when an accurate bearing is being taken. It is subsequently switched into action to determine which of the two readings 180° apart is the correct one. Separate sense-finding aerials are not normally used but sometimes when the office is at a great distance from the Bellini-Tosi loops an auxiliary aerial of the open type is necessary; this is usually a single vertical wire. For the case of a rotating coil or a system of fixed coils it is usual to have a separate sense-finding aerial, and the sense finder is incorporated as a part of the receiver.

Part (4). ORGANIZATION AND DEVELOPMENT PROCEDURE.

The responsibility for the experimental development and adaptation of the apparatus for naval communications rests with the Captain, H.M. Signal School, Portsmouth, where a staff of naval signal and civilian officers work side by side. The naval officers are attached to the Signal School for short periods only, usually of the order of two years, and in this way there is a continuous flow of officers from ships at sea who have intimate and up-to-date knowledge of the performance of apparatus in use or under trial at sea. These officers are able to state the broad requirements to which new apparatus should conform for success under sea-going conditions, and they co-operate with the civilian officers to ensure that these requirements are fulfilled.

The Director of the Signal Department, Admiralty, is in the closest touch in all signal matters with the Captain, H.M. Signal School, and is in direct touch with the Board of Admiralty; the reports from the various Commanders-in-Chief at sea covering wireless telegraph apparatus and naval communications are considered by the Director of the Signal Department, and the policies to be adopted as a result of these reports are formulated by him, after consultation with the Captain of H.M. Signal School, for the approval of the Board of Admiralty. In this way it is ensured that the experimental work of the Signal School is in accordance with the most recent sea-going requirements.

The experimental scientific staff of the Signal School are pooled under the Director of Scientific Research for the Admiralty, whose sphere includes all matters which relate to the supply and general distribution of the scientific civilian staffs for naval experimental and research purposes.

A close liaison exists between the Signal School and the other Government and industrial organizations, such as the Radio Research Board, the National Physical Laboratory and the British Engineering Standards Association. Representatives for the Admiralty are appointed from H.M. Signal School to various committees dealing with the work covered by the above organizations. The contact with the latest experimental and research work, dealing especially with wireless, has proved of great value to the Signal School.

Apart from the relations which naturally exist between the various scientific staffs of the Admiralty which are lent by the Director of Scientific Research to various naval establishments, a close liaison with the other military services is maintained by means of the main Wireless Telegraph Board Committee and the experimental sub-committee of this Board. These committees meet at frequent intervals and discuss service experimental developments. In addition, regular visits are interchanged with the service experimental establishments and arrangements are also made whereby, as far as practicable, components are standardized for inter-service use.

As stated above, the responsibility for development and design of apparatus in accordance with Admiralty policy is vested in the Captain, H.M. Signal School. Following on the production and satisfactory tests of first experimental models, first in the Signal School laboratories and then at sea, the final designs and specifications for the components are prepared and competitive tenders invited. The apparatus delivered from firms is tested for acceptance by the Signal School, and is later installed in ships under the direction of Signal School fitting-out officers.

In preparing the final designs of apparatus, commercial methods of production and workshop practice are kept in view, and every effort is made to confine the demand to common processes. At the same time, a high standard of workmanship is invariably called for in the specifications to ensure reliability of operation under sea-going conditions. B.E.S.A. standards are always adopted whenever possible, but proprietary articles are not usually embodied in designs for Service use unless they are of sufficient outstanding merit to out-balance the disadvantages of dependence on any particular source of supply.

Finally the authors desire to emphasize the debt owed, not only to members of the Service establishments but to manufacturers of equipment, who by their cordial co-operation have contributed to the ideal which all have in mind, that is the efficiency of the British Navy.

The paper is published with the permission of the Board of Admiralty. The authors desire to thank the Captain, H.M. Signal School, Portsmouth, for assistance in the preparation of the paper and for the use of diagrams prepared for Admiralty wireless telegraph handbooks. In addition, they would express their indebtedness to the members of the Civilian and Naval Experimental Staff of H.M. Signal School who have assisted in the preparation of the paper.

DISCUSSION BEFORE THE WIRELESS SECTION, 4TH DECEMBER, 1929.

Commander J. A. Slee: As the paper suggests, wireless communication in the Navy started with what is called a "plain aerial outfit," with which it was very important to maintain the standard of insulation in the aerial, which consisted of a length of wire very heavily insulated with rubber; I think the rubber was actually put on by hand. Next we used a circuit coupled between the transmitting gear and the aerials. There were two separate transmitters and two separate receivers making two separate sets of different wavelengths, which were then called A and B "tunes." There was no official transmitting apparatus in those days; we had a complete and properly constructed receiver—of the coherer type, of course—but we had to build up our own transmitters to specifications supplied, and to arrange with the carpenters to build various wooden formers, in the construction of which no metal was to be employed. Rubber-covered wire was used. There was very keen competition between ship and ship. Attempts were made to use alternators instead of batteries, employing the coil as a transformer. We had no alternators and very few ventilating fans, the latter being regarded as a great innovation at that time. Then followed what was called C "tune," which was a set of apparatus, not a specific wavelength, and we considered this to be a great advance. We used a $2\frac{1}{2}$-kW motor, and, with an open spark-gap, the spark passed with a very loud report. With the object of increasing ranges, we tried flying a kite at the end of a long piece of wire over the end of the aerial, and obtained some extraordinary results which, however, did not last for very long, because the kites were not really strong enough for the purpose. The early coherer receivers were followed by magnetic detectors, and that marked the beginning of audible reception. In those far-off days there was no telegraphist branch in the Navy: the torpedo officer was placed in charge of the wireless apparatus. After the magnetic detectors, crystal receivers were introduced. The first crystal used was a dull red stone, named zincite. Then came electrolytic detectors, which we constructed for ourselves; we made up half a dozen at a time and tried them against one another. I think we can all feel a considerable amount of pride in the state of efficiency to which wireless communication in the Navy has been raised since the days of which I have been speaking.

Prof. C. L. Fortescue: For those members who have been in any way connected with the Naval Service the paper has an interest from the historical point of view, but to the many who have not been intimately in touch with the development of naval wireless telegraphy the interest is in the insight which the paper gives into the conditions under which naval wireless is carried on. These conditions are very different from any found elsewhere. For instance, the paper describes cases of single ships in which six or eight lines of communication are all operating simultaneously. Then, again, many special difficulties are encountered—for example, the effect of sea-spray, or a heavy coating of salt over the insulators—which have not generally to be provided for in ordinary wireless installations. The skill called for in the design of the trunk leads on board ship is demonstrated in Fig. 23, and very few designers of apparatus for wireless reception are prepared to make provision for mounting their instruments on a deck which, as a result of gunfire, may whip a matter of about $\frac{1}{2}$ in.! It is not surprising that the apparatus has the external appearance of being complicated, because so much has to be crowded into a small space. The master oscillator, with its exact electrical balance all the way through, is interesting.

Commander C. S. Daniel: Naval wireless-telegraph work has certain definite characteristics. Point-to-point working is by no means the most important; the most important communications are those of the main fleet, which require absolute certainty of interception and wireless discipline. In making enemy reports, the reporting ship or aeroplane obtains an answer from only one other ship or aeroplane. The rest of the fleet must rely on interception. Further, on certain lines, the fleet flagship must be able to stop one ship, direct some others to carry on, and generally control traffic. This requires most efficient listening-through and good discipline. Given this, it should be possible to pass a short manœuvring signal to a fleet of 20 to 30 ships, obtain the answers, unit by unit, and be ready to make the executive signal in not more than $1\frac{1}{2}$ to 2 minutes. Obviously, naval apparatus must be so designed that sets will keep as constant a frequency as possible; and the most accurate wavemeters must be provided in order to avoid tuning discrepancies, which would be fatal to interception. A difficulty arises here, as ships may have to change their wavelength in order to avoid jamming by the enemy, or if there is congestion in their own fleet. The wavelength to which they change must be accurate. In shore-station practice we could provide as many sets as there were wavelengths required, but, as pointed out in the paper, space on board ship is very limited. The design of naval wireless-telegraph apparatus is far from easy. What degree of constancy can be obtained in a set which has to change wavelength almost instantaneously, and what developments are taking place to improve this? It may sometimes appear that naval specifications are very exacting; this, however, is bound to be the case. The importance of the battle of communications which precedes the fleet action cannot be over-estimated. Any defect in the wireless apparatus on board a ship of the fleet may alter the course of a war. The various things which *may* go wrong are very numerous: e.g. an earthed aerial, a burnt-out filament, some tuning error in transmitter or receiver, etc. Obviously, many features in naval design are dictated by experience afloat. Reference has been made in the paper to the new graduations for condensers and inductances, i.e. decrease of capacity or inductance with increase of scale reading. At present an increase of scale reading implies an increase in capacity or inductance. In the fleet all reference to waves is now in terms of kilocycles per sec.; and nothing is more irritating, when a fleet is being tuned in, than the fact that operators must decrease their scale readings when ordered to increase their frequency. Referring to rotating-coil direction-finders, the paper states that the operator should be near the coil and that this imposes certain limitations. It is hoped to overcome these limitations by leaving the coil up above, putting the operator and his gear below, and rotating the coil by remote control. At the beginning of the paper the authors mentioned the good results which accrued from collaboration between the scientist and the naval officer. I should like to support that statement whole-heartedly. The naval officer has to take the responsibility for communications at sea; he has certain apparatus to do it with and he must get the best results from that apparatus. I am glad to have this opportunity of expressing my admiration of the way in which the scientist meets the very exacting demands of the naval officer. So long as this co-operation exists, I think that naval wireless-telegraph communications will not be found wanting.

Dr. C. V. Drysdale: As Commander Slee and Prof. Fortescue have remarked, the difficulties associated with naval wireless work are great, and this ought to be fully recognized when comparing some of the devices with those in general use. The problem of supporting the valves against the severe shocks of gunfire and yet to permit of their rapid replacement is by no means an easy one; the need for working with a number of wavelengths and rapid change-over from one to another introduces difficulties which will be readily appreciated; and the proximity of large metal structures and the necessity for bringing the leads through trunks and glands add seriously to those difficulties. Accurate direction-finding is obviously of great importance to the Navy, and here the effects of the hull, superstructure and stays are most in evidence; but, by careful choice of positions and compensation, accuracy has been secured. On the scientific side the existence of a large fleet under a single organization and working over such a large range of frequencies has enabled much valuable information to be obtained on transmission under varying conditions. Such information is bound in time to have useful effect not only on naval but upon general navigational and commercial wireless, and we may be grateful to the officers and the scientific and technical staff of the Navy for the great advances they have made.

Mr. L. B. Turner: From this interesting description of past and present naval practice and apparatus I have noticed what is, I think, a rather remarkable omission: I see no reference to telephony. At first I thought this might be because the telephone, for strategic or other reasons, is debarred in the Naval Service; but the reference in Capt. Dorling's opening remarks to the Nelson of the future putting a telephone to his blind ear suggests that this is not so. The value of American whitewood in high-frequency fields was the discovery, I think, of the Post Office engineers in their work in designing the Rugby inductances. It is pointed out that its good qualities are destroyed by a humid atmosphere. Has impregnation of any kind been tried? Paraffin-wax suggests itself, but probably this is ruled out owing to the danger of fire. My experience with cellulose acetate in acetone suggests that this might be a suitable material to apply. The authors urge us not to forget that there is an optimum spacing between the strands of the high-frequency cable, and that the greatest possible number of strands in a given space is not the best. I should like to know how the correct spacing is provided, i.e. whether there is a whipping of spacing material on the conductor, and what material is used. Presumably cotton is unsuitable because of the enormous losses introduced unless it is very dry. Can the authors give us some details of a typical piece of one of these cables? The $\sqrt{N}$ rule for tapping a coil of N turns, given on page 250, I find novel and pleasing. An interesting point arises in connection with Fig. 21, showing the frequency-doubling circuits. I notice that there is no d.c. supply to the anodes. With back-coupling present, operation without d.c. supply seems possible, but does Fig. 21 represent actual conditions? On page 250 it is stated that the power factor of a good mica condenser is of the order of 0·4 of 1 per cent. This seems to be a very high figure. Good-quality mica condensers in laboratory work have very much lower power factors than this; and the Dubilier condensers at Rugby are believed to show a power factor of 0·02 of 1 per cent.* Fig. 26 shows an amplifier having 3 high-frequency stages, with a wavelength range of 24 000 to 500 m, and yet without any sort of neutrodyne retroaction balance. This seems to be a most remarkable receiver, and it would be very interesting if the authors could tell us a little more about it.

Mr. F. S. Barton: In regard to the re-design of condensers and inductances so that a clockwise movement gives a decrease of inductance or capacity, I should prefer to see standard practice retained and the scales arranged to read anti-clockwise for increasing frequency. This would have the advantage of still retaining the use of conventional commercial components, in which, as at present, a right-hand or clockwise motion gives an increase in the quantity being varied.

Mr. F. C. Lunnon: One problem in the case of a ship short-wave transmitter to cover a large range of wavelengths is that of providing suitable coupling arrangements between the output circuit of the transmitter and the aerial, so that at every wavelength one can transfer sufficient energy to the aerial fully to load the transmitter. The difficulty arises because in a ship one is forced to use a fixed length of aerial for the complete range of wavelengths. With a reasonable length of wire clear of the deck insulator, plus, in many cases, a considerable length of wire through an aerial trunk from the deck to the wireless cabin, the total length of aerial, measured from the transmitter, will usually be several wavelengths at the shortest wavelength and more than $\frac{1}{4}$ wavelength at the longest wavelength. It follows that the correct termination for the aerial varies rapidly over wide limits between the shortest and longest wavelengths of the transmitter, and unless means are provided for approximating to the correct termination then, however much mutual inductance be provided between transmitter and aerial, there will be many wavelengths at which only a very small amount of energy can be transferred to the aerial. When the total length of aerial is a whole number of $\frac{1}{2}$ wavelengths the correct termination is given by a tuned parallel circuit of inductance and capacity; and for an odd number of

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* See *Journal I.E.E.*, 1927, vol. 65, p. 297.

¼ wavelengths a tuned series circuit is required. Moreover, the required values of capacity and inductance will themselves vary greatly over a range of, say, 14 to 70 m. I have found it necessary, for such a wave-band, to provide two variable condensers—one very small—and two equal inductances. Switches are provided to select either variable condenser and connect it in parallel, or in series, with the two inductances, which themselves may be switched in series or parallel. The latter provide the mutual inductance between transmitter and aerial. Even with these complicated arrangements the aerial, more often than not, is a reactive impedance requiring a large mutual inductance to transfer sufficient energy fully to load the transmitter. I was therefore surprised to note, from Fig. 19, that the coupling to the aerial for the short-wave transmitter, 14 to 70 m, is shown as a simple coupling coil. I should like to ask the authors whether in actual fact that is what is employed and whether, in that case, they do not experience many points in the wave-range where only a very small amount of energy can be transferred to the aerial. In ships where a very long aerial trunk is necessary between a short-wave transmitter and the deck, I should like to ask the authors whether the conductor through the trunk is used as a continuation of the aerial or as a feeder to the point where the aerial emerges from the trunk. The former makes for simple wave-changing but involves considerable losses at short wavelengths; the latter, of course, is a more efficient method but involves remote control of terminating apparatus located at the deck end of the trunk. I notice that reference is made to the extensive use of ebonite as an insulating material, both on receivers and transmitters. General experience of ebonite in tropical climates is that both its insulating and mechanical qualities deteriorate greatly. Mycalex, on the other hand, is free from both these defects. What is the authors' experience of ebonite in ships stationed for long periods in the tropics, and have they found mycalex generally satisfactory as a substitute for ebonite?

Mr. H. Faulkner: It seems to me at first sight that the protective arrangements provided on the transmitter are inadequate. There appear to be no overload relays provided on the switches, such as one would expect to see. The protective arrangements for the oscillating valves themselves consist simply of a single relay to protect the 3 valves which are connected in parallel. While I agree that such protection is adequate as protection, it is my experience that this arrangement is very often likely to cause needless delay because of the difficulty in tracing which of a number of valves has failed. My experience, perhaps, has been more concerned with cooled-anode valves, and the circumstances may be different; but certainly I would suggest that the fitting of a small indicator, if a relay cannot be fitted, to indicate which valve has taken an overload, would be an improvement. I have no doubt that valves do *sometimes* fail from loss of vacuum. I notice that horn-gap fuses are fitted in the rectifier. Are these the principal protective devices for the system in the case of a breakdown of the smoothing condenser, for instance, or other short-circuit on the supply, or is any other form of protection provided? If these are the only protective devices, I am interested to know whether they are completely satisfactory, and what kind of fuse wire is used. With regard to keying, I note that in Fig. 11 this is direct in the anode circuit. This seems to me rather a "hard" method of keying. A great deal of sparking must take place at the key when in that position in the circuit, and it would be practically impossible to do any high-speed work. Some time ago I tried a system of keying in the grid circuit and a.c. supply simultaneously, with the idea that the breaking of the grid circuit stopped the current, and the breaking of the a. c. supply prevented the undue rise of anode voltage from the rectifier through taking off the load. Some improvement of the sparking at the key might be obtained by such an arrangement. Further, no coupled circuit to the antennæ is shown; is this due to a lack of space, or to the fact that it is not found necessary? I should have thought that with large numbers of transmitters working on the same ship, and on a large number of ships comparatively close together working on widely different wavelengths, there would be considerable trouble from harmonic radiation. Referring to Fig. 13, it is observed that each valve is provided with its own grid leak. Have the authors any evidence as to whether this arrangement equalizes the load between the valves? Post Office practice has always been to provide a common grid-leak for the circuit. I do not think that individual grid-leaks can have any effect on possible spurious oscillations between the valves. In Fig. 14 the overload contacts on the anode relay, etc., are shown as opening the filament circuit—that is to say, when an overload occurs the filament of the valve is switched off. I should like to know whether that is found to be satisfactory. It is my experience that when a valve is very soft the overload may continue through the valve, even if the filament *is* switched off. With regard to Figs. 19 and 20, it seems remarkable that the arrangement provided for switching from short to long waves does not make the transmitter very unstable on the short waves. I should like to hear the authors' experience in this connection. I think that the frequency-doubler circuit should be made rather clearer in the diagram. What is the efficiency of this doubler circuit? I notice that the doubling takes place at high power; hence it would appear that it must be very effective, since otherwise much waste of power would take place.

Mr. G. Shearing and **Captain J. W. S. Dorling** (*in reply*): Commander Slee has given additional information relating to the earlier history of naval wireless communications and to some of the difficulties which were encountered in those days. One of the objects of the paper was to give a broad view of the requirements for naval wireless telegraphy apparatus and we are glad to note the remarks of Prof. Fortescue and of Dr. Drysdale in this connection. It is true that the varied requirements tend to make the apparatus look complicated; the limited space which is available for these requirements, particularly the requirement of the flexibility of sets over a wide wavelength range, necessitates the use of somewhat simple circuits. It is for this reason that coupled circuits for long-wave working are not usually employed in the high-power transmitters.

The necessity for rapid valve-change referred to by Dr. Drysdale has had to receive special attention, and the later designs of valve-holders for high-power sets enable any single valve to be replaced in a few seconds. Incidentally, the naval silica valve, which is largely employed for power transmitters, lends itself readily to replacement in the minimum of time.

The special requirements for naval ship working have been amplified by Commander Daniel, and these requirements emphasize the necessity for simple oscillatory-circuit apparatus. On the other hand, the control and operating circuits have to be fairly complex to ensure that the operations necessary for wave-change and for bringing various sets into use may be effected in the small time available for operating and manœuvring requirements. With regard to the need for extreme accuracy in the tuning of transmitters and the degree of constancy obtainable in a set which has to change wave almost instantaneously, the question can only be answered in general terms. The spark-transmitters formerly in use were tuned with carefully-calibrated wavemeters by skilled personnel, and no difficulty was experienced, since tuning was necessarily broad. The introduction of the valve transmitters for continuous waves or interrupted continuous waves, and the use of short waves, have naturally increased the difficulty of ensuring that all ships can transmit sufficiently accurately on any one of a number of waves. Wavemeters accurate enough for spark-transmitters lacked the necessary high degree of accuracy, particularly after extended use at sea. As a temporary expedient it has become necessary for one ship of the fleet, usually the flagship, to tune the transmissions of all ships to the same frequency; each ship, having noted the adjustments, can radiate the same frequency on subsequent occasions with reasonable accuracy. Improvements in wavemeters and the introduction of master-drive transmitters are leading to greater accuracy of initial tuning, although it is not yet certain that any sub-standard wavemeter of reasonable size, weight and simplicity, will be able to detect a small change of frequency as readily as can a receiver at a distance.

Mr. Turner has remarked upon the lack of reference to telephony in the paper. At one time it was thought that there would be great possibilities for wireless telephony in the naval service. Trial afloat showed, however, that the advantages were more apparent than real, except for certain definite applications. The main disadvantage is the lack of secrecy. Whatever system is used there can, at present, never be certainty that conversations cannot be overheard. Moreover, there can be no written record for future reference. The time taken to speak a message is often greater than would be sufficient to transmit the same message by morse, employing code, and the range of communication by telephony is less than the telegraph range. Again, even for the case when the morse is plain language the time taken is often less than for wireless telephony. Using wireless telephony, speech must be slow in order to avoid phonetic errors and repetitions. The use of wireless telephony in the naval service is therefore confined to those cases where secrecy is not essential and where direct communication between principals is required without intermediate links, or where conditions are such that it is not possible to arrange for operators trained in the Morse Code. With regard to American whitewood, impregnation with various bakelite compounds has been tried, but these have been found to be unsatisfactory. Experimental tests have been made of woods treated with paraffin-wax, also with cellulose-acetate in acetone, but the danger of fire has precluded their use. The heating adjacent to high-potential metallic contacts causes the solvent to give off a gas which is mainly hydrogen. This gas has a lower ionization-potential than air and therefore the danger of breakdown is increased. The experiments with paraffin-wax were definitely unsatisfactory. Also the addition of any form of impregnation to the wood provides an increase of permittivity and enhances the losses adjacent to high-potential metal contacts carried by the wood. An occasional flash-over has been found to destroy the insulation of wood so that replacement is necessary. In the case of ebonite, however, an occasional flash-over can usually be rectified by scraping away the burnt surface. A full discussion of the spacing of turns of stranded wire on a coil and of the effects of the size and spacing of the individual strands in the stranded wire has been published.* Although the effects of capacity between the strands and turns of a coil are not taken into account, the calculations give a valuable indication of the coil resistance to be expected. The size of the strand is usually fixed by manufacturing limitations. The spacing between the separate conductors of a strand is effected by enamel alone or by enamel together with a silk covering. The size of enamelled wire generally used is No. 38 S.W.G. When enamelling is employed alone, the separate conductors are liable to stretch, harden, and break during stranding and, in addition, the enamel may be rubbed at places so that contact with other strands is possible. Despite these disadvantages, large quantities of wire thus insulated are still used. For cases where it is necessary to ensure that the separate conductors are not broken, such as in the case of receiving coils using a smaller number of strands, No. 36 S.W.G. wire is used and each conductor is enamelled and then silk-covered. This affects the overall diameter of the wire and the spacing of the strands; difficulties are often encountered due to limitations of the space available for coils and for the tapping-points required. These limitations in many cases largely determine the design so that the actual resistance of the coil may have to take a secondary place, although its value is calculated as a check. Typical designs of stranded wire are indicated below:—

(*a*) 729/38 *Stranded Wire for Transmitter Coils.*—This is built up by stranding No. 38 S.W.G. enamel-insulated copper wires in groups of three (and continuing the operation). The lay of the groups should be right- and left-hand alternately. The stranded wire is covered with cotton braid which is coated with Ohmaline or Ozokerite. When assembling the wire without braided covering it was found that some of the wires snapped when bent over the combs in the coil-frameworks. These broken wires may cause brushing and insulation failure. The braiding overcomes this difficulty and provides a soft bed when bending the wire; also any broken strands are retained in place. In a few special cases transmitting-coils have been wound using wires with each strand silk-covered, but the cost of this is normally not considered to be justified.

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* S. Butterworth; "The Effective Resistance of Inductance Coils at Radio Frequency," *Experimental Wireless and Wireless Engineer*, 1926, vol. 3, pp. 203, 309, 417 and 483.

(*b*) 9/36 *Stranded Wire*.—This wire is used in coils for receiving apparatus. It is stranded as described above, but each strand is enamelled and silk-covered. The chief function of the silk covering is to provide a soft bed for the wires when building-up during stranding and thus to prevent elongation, hardening and breaking.

We agree that the value quoted for the power factor of a good mica condenser is too high; this value should have been 0·2 of 1 per cent, to which value the figure has been corrected.

With regard to the amplifier and tuner shown in Figs. 25 and 26, these instruments were designed several years ago and have had a very wide application at sea. Apart from the frequency-range requirements, the necessary features include the following: (*a*) Satisfactory selectivity and high-frequency amplification. (*b*) No difficult adjustments, on account of the necessity for changing from one wave to another in a few seconds. (*c*) Ease of handling. These requirements naturally necessitate compromise. In general, high selectivity cannot be reconciled with ease of handling and quick wave-change, whilst very high amplification cannot be reconciled with stability over a wide range of frequencies. In addition, very high amplification is not of great practical value in ships because of the large amount of extraneous noise from running machines, aerial and stay vibrations, etc. The technical advantages of neutralization and its application to service receivers have been considered not only with regard to the receiver of Figs. 25 and 26 but also in connection with other models. Reference has been made in the paper to the fact that this receiver has had considerable application. It was designed several years ago to employ the naval R.7 valve which has an amplification factor of 7 and a grid-anode capacity of the order of 1 cm only. General-purpose valves of modern design have an amplification factor of the order of 14, and a grid-anode capacity of the order of 4 cm. Since feed-back is proportional (as a first approximation) to the product of amplification factor and grid-anode capacity, it follows that the need for neutralization is much less in the case of an R.7 valve than for one of a more recent type. Again, neutralization introduces at least one extra adjustment for the setting of a neutralizing condenser is, in general, different for different wave-ranges and may not even be constant over a single wave-range. Hence, if a neutralizing condenser is fitted, the stability of the receiver will be entirely in the hands of the operator. Failure to make this extra adjustment may lead to serious trouble, since when one receiver oscillates it may jam reception for other ships. The introduction of screen-grid valves is clearly a development for the later long-wave amplifiers, since these valves offer the possibility of high amplification without the trouble and difficulty of neutralization; later designs of long-wave receivers employ these valves.

With reference to Mr. Barton's remarks concerning the adoption of clockwise movement for inductance and capacities to correspond to increase of frequency, we think that Commander Daniel has stated the case for this convention as regards naval practice.

Mr. Lunnon has referred to the effects which occur when a fixed length of aerial is used with a short-wave band of frequencies. A conductor through a long trunk in a ship can be considered to be a transmission line leading from the transmitter to the aerial, and standing waves of current and voltage will be set up in it unless means are employed whereby the aerial and the transmitter-circuit impedances can be matched with the surge impedance of the trunk. Series or parallel connection of adjustable condensers at the coupling coil of the set constitutes one half of a suppression system and is certainly of value in getting more power into the aerial. These methods are employed in naval transmitters operating on narrow bands of frequency, but they are not used in the case of high-power short-wave transmitters working on the main aerial of a ship. Experience has shown that where the aerial system corresponds to a large number of ¼-wavelengths (as for main aerials), it is possible to put sufficient energy into it to obtain communication at the required ranges. We agree, however, that the employment of parallel or series condensers, possibly with additional coils at the coupling-coil, does increase the energy input to the aerial. In short-wave sets of lower power working through trunks to an aerial much shorter than the main aerial system, partial suppression has been employed (utilizing both the parallel and series systems of connections of variable condensers at the coupling coil of the set) when difficulty has been experienced in energizing the aerial. Where ship transmitters operate on a fixed wavelength, complete suppression of the standing waves has been employed. This, however, necessitates the insertion of a suitable tuning-circuit immediately adjacent to the main-deck insulator additional to the suppressing apparatus inserted at the coupling coil of the set. The naval use of "Mycalex" in standardized apparatus has not yet been sufficiently extensive to warrant a definite conclusion, but, so far as it has been employed in high-frequency circuits, the material has proved very satisfactory. Recent designs of adjustable high-voltage short-wave condensers, valve-holders, and coils, have employed "Mycalex" as insulation. The fact that the surface of "Mycalex" is not damaged by occasional arcing is a great factor in its favour. Our experience is that high-quality ebonite has proved on the whole more satisfactory than any other insulating material which, until recently, has been available for use with high-power coils under tropical conditions; we admit that it is far from being an ideal insulator. Aerial coils with ebonite combs have had years of use in ships under tropical conditions. It is not yet possible to say whether "Mycalex" will replace ebonite for use with high-voltage aerial coils.

In reply to Mr. Faulkner, the single overload relay system has proved adequate for the three transmitting valves employed in parallel in high-power ship transmitters. The envelopes of the silica valves can be seen from the gangway in front of the valve panels, and the glow resulting from a loss of vacuum is readily visible. In actual practice, however, valve failure from this cause is rare. The horn-gap fuses constitute the high-tension protection in case of any breakdown of the rectifier system, but it has also to be noted that the main circuit breakers in the primary d.c. supply to the main motor-alternators will also operate in the event of a severe overload. Fig. 11 shows that the anode key in the long-wave circuits is inserted between the transmitting-valve anodes and the anode blocking-condensers, the other terminal of which goes to the anode tapping-point on the aerial inductance. The valves used have fairly open grids so that this key cannot be employed for signalling unless suitable grid-potential control is also employed during spacing. This key opens the circuit during spacing, solely to ensure that there is no loss of received signal-strength from valve-damping across a portion of the aerial inductance when listening-through. The signalling-key of this transmitter is in the primary circuit of the a.c. supply and is the magnetic key shown in Fig. 10. The bobbin circuit for the anode key of Fig. 11 is placed across the front and middle contacts of the master transmitting-key so that the anode key always makes circuit before, and breaks after, the magnetic key for signalling. The d.c. control circuits are shown in Fig. 15. Interference troubles undoubtedly occur when the main ship transmitter is in use, and certain of the other aerials have to be earthed. Thus Fig. 17 indicates that the second office and the direction-finding office aerials can be earthed during transmission, but the transmitters of lower power can usually be employed simultaneously without serious interference to reception on any one of the lines. The reason for the adoption of separate grid-leaks for the particular transmitter circuit described in the paper was to avoid spurious oscillations which were found to occur when a common grid-leak was used. In this way the very high-frequency parasitic oscillation which occurred between the anodes and grids of the valves with a common grid-leak was avoided. The switching-off of the valve transmitting- and rectifying-filaments by excess current operating the overload relay has proved satisfactory and this system has been in use for over 10 years in various ship-transmitters. It should be observed that each of the rectifying valves takes a proportion of the H.T. supply voltage when the filaments are switched off. Thus the voltage stress is not across the transmitting valves alone. The combined long-wave and short-wave transmitter of Fig. 19 has been designed so that the valves are double-acting or in " push-pull " as regards the generation of high-frequency short-wave oscillatory current. The circuit arrangements are thus of symmetrical design and have proved stable with suitable neutralization of the valve anode-grid capacities. The chief difficulty in the design of this transmitter arose from the effects of secondary emission of the grids of the transmitting valves.

In answer to Mr. Turner's and Mr. Faulkner's remarks regarding the frequency-doubling circuit, Fig. 21, the circuits are neutralized by means of the adjustable condensers, so that there is no back-coupling. A H.T. supply to each stage is required and this is now indicated in the diagram. The overall efficiency of the combined circuits of Figs. 20 and 21 is less than that of the circuits of Fig. 20. However, when alternative transmissions on either frequency are desired the arrangements are useful and less costly than a second transmitter, while the extra space required is small. Transmissions can be made readily on either of the two wavelengths without tuning readjustments, so that operation is simple. A transmitter designed solely for the higher frequency corresponding to the doubler value would undoubtedly have a greater overall efficiency as regards H.T. power supply, but its initial cost would naturally be much greater than the cost of adding the doubler circuit to an existing transmitter. Again, other factors, such as the space available for transmitting apparatus, had to be taken into consideration when deciding whether a frequency-doubler circuit for an existing transmitter, or an additional transmitter, was to be employed.

THE VALVE-MAINTAINED QUARTZ OSCILLATOR.[*]

By J. E. P. VIGOUREUX, M.Sc., Graduate.

[From the National Physical Laboratory : communicated by permission of the Radio Research Board.]

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SUMMARY.

A quartz resonator connected between the grid of a valve and either of the other electrodes gives rise to oscillations in the plate circuit when the constants of that circuit satisfy certain conditions. The frequency of the oscillations depends mainly upon the natural frequency of the quartz, and is, therefore, fairly constant when the temperature is constant. In addition to temperature effects, which are not considered in the present paper, variations of frequency can be produced by (i) variations of the air-gaps of the resonator, i.e. the air-gaps between the quartz and the two electrodes of the resonator; (ii) variations of the constants of the plate circuit; and (iii) variations of the inter-electrode capacities and conductances. The object of the investigation is the study of these variations, both theoretically and experimentally.

In the theoretical treatment, the quartz is replaced by a circuit made up of an inductance, a resistance and a capacity in series, the whole being in parallel with a second capacity. The validity of such a substitution has been studied experimentally by Dye.

The combination of quartz resonator, valve and plate circuit is represented by a network of admittances, from which three circuit equations are obtained; to these is added the fundamental equation of the valve. These four equations yield a single linear differential equation of the fifth order, with constant coefficients. In the case under investigation, it is only required to find the frequency and the amplitude of oscillations after the latter have reached a constant amplitude. This consideration affords a means of reducing the differential equation to one of the same type, but of the second order. From the latter equation, of which the general solution is known, formulæ are developed for the changes of frequency resulting from variations in the resistance and capacity of the plate circuit, in the resistance of the grid leak, in the inter-electrode capacities, and in the air-gap. These formulæ provide useful information as to the influence of each variable on the frequency, and can with advantage be applied to the choice of the best circuits and the best valve for a quartz oscillator.

As the oscillations build up after switching on, the average plate conductance of the valve alters gradually. When the amplitude of oscillation has reached its final value, the value of the average plate conductance is such as to annul the damping term, i.e. the coefficient of dy/dt in the differential equation. From this condition the average plate conductance can be determined for any values of the circuit variables. The amplitude of oscillations in the plate circuit is a function of this average plate conductance.

Formulæ are developed which give the conditions for the maintenance of oscillations, and an investigation is made of the variations of amplitude with variations in (*a*) capacity in the plate circuit, (*b*) resistance in the plate circuit, and (*c*) grid conductance.

Points of importance in the choice of circuits and valves are deduced from the formulæ and the theoretical curves.

Two types of quartz oscillator are investigated, namely, the cases in which the quartz resonator is connected between (i) the grid and the plate of the valve, and (ii) the grid and the filament of the valve.

A fairly complete experimental investigation is described. The admittances of the valve and of the circuits were measured, and the equivalent electrical network of the quartz was determined. The behaviour of the quartz oscillator was then investigated by altering in turn each variable in the circuits. The theoretical and experimental results are compared and discussed.

The paper does not deal with circuits especially devised for obtaining large outputs from quartz crystals. Its object is the study of the influence of the circuit variables on the frequency and on the power generated as regards the simple Pierce circuits.

INTRODUCTION.

W. G. Cady[†] and G. W. Pierce[‡] have shown that quartz resonators can be used for maintaining oscillations in a valve circuit. The frequency of the oscillations depends almost entirely on the natural frequency of vibration of the quartz, and is, therefore, very constant. The combination of resonator and valve circuit is known as a "quartz oscillator." Quartz oscillators are at present widely employed for controlling the frequency of wireless transmitting stations, in the same way that an ordinary master oscillator was used formerly, and give excellent results. They are also very convenient for calibrating wavemeters, and are extensively used for that purpose in America.

The circuits considered in this paper are all based on Pierce's circuit. A single valve is used, with the quartz connected between the grid and the plate, or between the grid and the filament, and, under certain conditions, oscillations are maintained in the plate-filament circuit. This latter circuit may be a high non-inductive resistance, of approximately the same value as the valve impedance; but for powerful oscillations an oscillatory circuit is used, made up of a condenser and an inductance coil in parallel, and oscillations are maintained for a wide range of condenser settings.

The type of connection in which the resonator is connected between the plate and the grid of the valve will be called the "plate-to-grid connection," and the other type the "grid-to-filament connection."

Besides temperature effects, which need not be considered here, variations in frequency are caused by (*a*) variations of the air-gap; (*b*) variations of the constants of the plate circuit; and (*c*) variations of the inter-electrode capacities and conductances.

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (excepting those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] See Reference (1).

[‡] *Ibid.*, (2).

E. M. Terry[*] and J. W. Wright[†] have recently given a method of predicting the variations of frequency due to variations of the circuit constants. We are dealing here with the same problem and, in addition, an attempt is made to obtain an idea of the power to be expected for various values of the circuit constants.

(1) THEORETICAL TREATMENT.

The Fundamental Equations.

The circuit may be represented in a general way by Fig. 1, in which G_1, G_2 and G_3 represent admittances. They include the inter-electrode admittances as well as the admittances of external circuits.

Let g be the anode conductance of the valve and m its amplification factor. The fundamental equation of the valve is

$$i_1 + i_2 = g(v + me) \quad . \quad . \quad . \quad . \quad (1)$$

with the currents and potential differences indicated in Fig. 1.

It is assumed that the variations of current are such as would be produced by a straight-line characteristic for the valve. This assumption is never realized in practice, for, once oscillations start, they must of necessity increase in amplitude until the anode conductance g alters in such a way that the exponential term in the solution of the differential equation connecting current and time becomes unity. Here, however, it is assumed that g does not change. It is also assumed that the conductance between the grid and the filament is constant throughout a complete oscillation. This is not, in general, the case, because for part of the cycle the grid is at a negative potential with respect to the filament, when the conductance is only that of the grid leak; and for the rest of the cycle it is at a positive potential with respect to the filament, and the conductance becomes larger owing to thermionic effect.

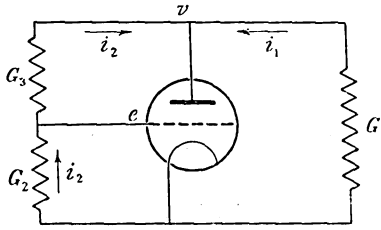

FIG 1.

In addition to equation (1) we can write down the three circuit equations:—

$$\left.\begin{aligned} i_1 &= -G_1 v \\ i_2 &= -G_2 e \\ i_2 &= -G_3(v - e) \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (2)$$

In general, G_1, G_2 and G_3 will all contain the differential operator D and the resultant equations in i_1, i_2, v or e will be identical, which means that the complementary function is of the same form for i_1, i_2, v and e.

From equations (1) and (2) we obtain

$$\begin{vmatrix} 1 & 1 & -g & -mg \\ 1 & 0 & G_1 & 0 \\ 0 & 1 & 0 & G_2 \\ 0 & 1 & G_3 & -G_3 \end{vmatrix} y = 0$$

where y stands for either i_1, i_2, v or e.

This determinant gives the simple equation

$$\left[G_3\left\{G_1 + G_2 + (m+1)g\right\} + G_2(G_1 + g)\right]y = 0 \quad . \quad (3)$$

Expressions must now be obtained for G_1, G_2 and G_3 in terms of the circuit constants and of the valve constants.

Consider G_1 first; it is a circuit similar to that in Fig. 2, in which the capacity C includes the capacity C_1 of the plate to the filament. The capacity C is therefore always greater than zero. The inter-electrode plate-to-filament conductance is denoted by g_1.

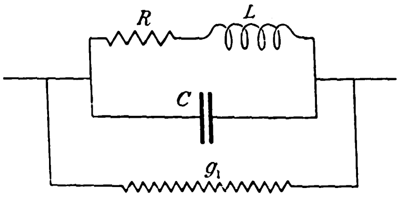

FIG 2.

The conductance of a capacity C is denoted by DC, and that of an inductance L by $1/DL$, where D stands for the differential operator d/dt.

We therefore have

$$G_1 = \left\{1/(R + DL)\right\} + DC + g_1 \quad . \quad . \quad (4)$$

We also have to evaluate G_2 and G_3. Let g_2 and C_2 be the inter-electrode conductance and capacity between grid and filament, and let g_4 be the conductance of a grid leak. That part of G_2 due to the above quantities is $(g_2 + g_4 + DC_2)$.

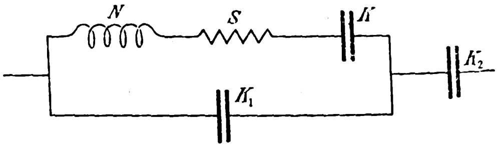

FIG 3.

Let g_3 and C_3 be the inter-electrode conductance and capacity between the plate and the grid. That part of G_3 due to them is $(g_3 + DC_3)$.

The admittance of the quartz circuit is added to either of these, depending upon whether the quartz is placed between the plate and grid, or between the filament and grid.

It has been shown by W. G. Cady,[*] D. W. Dye[†] and others, that a fairly accurate electrical representation of the behaviour of the quartz is given by the circuit NSKK$_1$ of Fig. 3; the capacity K_1 is approximately equal[‡] to the static capacity between the two faces of the quartz perpendicular to the electrical axis e, whilst K is only an equivalent capacity depending upon the piezo-electric and elastic constants. The resistance S accounts for the damping of the quartz vibrator, K_2 is the capacity of the air-gap between the electrodes, and K_3 the stray capacity between the electrodes and between the leads.

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[*] See Reference (3). [†] *Ibid.*, (9).

[*] See Reference (1). [†] *Ibid.*, (4). [‡] *Ibid.*, (5).

The admittance of the quartz will then be

$$DK_3+1\Big/\left[\frac{1}{DK_2}+1\Big/\left\{DK_1+1\Big/\left(DN+S+\frac{1}{DK}\right)\right\}\right]$$

$$=DK_3+\frac{DK_2(D^2NKK_1+DSKK_1+K_1+K)}{D^2NK(K_1+K_2)+DSK(K_1+K_2)+K_1+K_2+K}$$

Using Dye's notation, we obtain

$$K_1+K_2=K_t \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Then the admittance of the quartz system is

$$D\left[K_3+\frac{D^2NK+DSK+1+(K/K_1)}{D^2NK+DSK+1+(K/K_t)}\cdot\frac{K_1K_2}{K_t}\right]$$

For a further simplification, let

$$D^2NK+DSK+1+\frac{K}{K_1}=\sigma \quad . \quad . \quad (6)$$

$$D^2NK+DSK+1+\frac{K}{K_t}=\nu \quad . \quad . \quad (7)$$

The admittance of the quartz is then given by

$$. \quad . \quad . \quad DK_8+D(K_1K_2/K_t)(\sigma/\nu)$$

The values of G_1, G_2 and G_3 are thus obtained in terms of the circuit constants and of the valve constants. It remains only to substitute these values in equation (3), and to use this equation to find the condition for maintenance of oscillations, the frequency, and the amplitude of oscillations.

Before dealing with the complicated equation resulting from the substitution of G_1, G_2 and G_3 in equation (3), consider the simple general equation of an oscillating system:

$$(D^2A+DB+C)y=0$$

The solution is obtained by solving the quadratic

$$\lambda^2A+\lambda B+C=0$$

which gives

$$\lambda=\left\{-B\pm\sqrt{(B^2-4AC)}\right\}/2A$$

and the complementary function is

$$y=F\epsilon^{\left\{-\frac{B}{2A}+\sqrt{\left(\frac{B^2}{4A^2}-\frac{C}{A}\right)}\right\}t}+F'\epsilon^{\left\{-\frac{B}{2A}-\sqrt{\left(\frac{B^2}{4A^2}-\frac{C}{A}\right)}\right\}t}$$

where F and F' are constants.

If $B^2>4AC$ the function increases or decreases exponentially, but there are no oscillations.

If $B^2<4AC$, the above solution is equivalent to

$$y=\epsilon^{-\frac{B}{2A}t}\left\{F''\cos\sqrt{\left(\frac{C}{A}-\frac{B^2}{4A^2}\right)}t+F'''\sin\sqrt{\left(\frac{C}{A}-\frac{B^2}{4A^2}\right)}t\right\}$$

and oscillations take place. These oscillations may be either damped or maintained.

If $B/2A>0$ they will be damped, and any disturbance set up will gradually die away; if, on the other hand, $B/2A<0$ oscillations are maintained, and, starting from any small disturbance, their amplitude increases until the original quantity $B/2A$ is balanced by the increase in damping which in general accompanies an increase in amplitude. At this moment the effective B is zero, and the equation of oscillations is

$$y=F''\cos\sqrt{\left(\frac{C}{A}\right)}t+F'''\sin\sqrt{\left(\frac{C}{A}\right)}t$$

The circular frequency ω is thus given by the equation

$$\omega^2=C/A$$

The final amplitude of y must be some function of the original value of $-B/2A$; it is not easy to estimate this function, in general, but in some cases the initial value of $-B/2A$ may be used to predict the final amplitude.

The following rules for the study of oscillations can thus be stated:

(i) If the coefficients of D^2 and D^0 are opposite in sign, no oscillations can take place.

(ii) If the coefficients of D^2 and D are of the same sign, no oscillations can be maintained.

(iii) If the coefficients of D^2 and D^0 are of the same sign, and opposite in sign to that of D, and if $4AC$ is greater than B^2, oscillations will be maintained at a frequency eventually given by $(1/2\pi)\sqrt{(C/A)}$.

(iv) The original value of $-B/2A$ may, in some cases, afford a means of calculating the final amplitude.

PLATE-TO-GRID CONNECTION.

Returning now to the particular problem of the quartz oscillator, suppose that the quartz resonator is connected between the grid and the plate of the valve. In this case

$$G_1=\left\{1/(DL+R)\right\}+DC+g_1 \quad . \quad . \quad . \quad . \quad (8)$$

$$G_2=g_2+g_4+DC_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

$$G_3=g_3+D(C_3+K_3)+D(K_1K_2/K_t)\,(\sigma/\nu) \quad . \quad (10)$$

The conductance of the grid leak is denoted by g_4. As for g_2 and g_3, they include not only the direct-current conductance of the glass and valve-holder, which is usually extremely small, but also the effective conductance due to dielectric loss in the glass and holder between the electrodes and the thermionic effect, if any. The direct-current component and the dielectric component of g_3 are different in their effects, which will be discussed later in the paper.

Substituting for G_1, G_2 and G_3 in equation (3), the following equation is obtained:—

$$\begin{aligned}&\left[D(K_1K_2/K_t)(\sigma/\nu)+g_3+D(C_3+K_3)\right]\\&\qquad\left[g_1+g_2+g_4+(m+1)g+D(C+C_2)+1/(DL+R)\right]\\&\qquad\quad+\left[g_2+g_4+DC_2\right]\\&\qquad\qquad\left[g_1+g+DC+1/(DL+R)\right]=0 \quad . \quad . \quad (11)\end{aligned}$$

The quantity operated on is y, standing for i_1, i_2, v or c, and will not be repeated each time.

For brevity, we can write

$$C_2+C_3+K_3=C_5 \quad . \quad . \quad . \quad . \quad (12)$$

Equation (11) can be put in the form

$$(K_1K_2/K_t)\,(\sigma/\nu)a+C_5=0 \quad . \quad . \quad (13)$$

in which a is a fraction whose numerator and denominator are both of the third degree in D.

The numerator of a will be

$$\begin{aligned} &D^3L(C+C_2) \\ &\quad + D^2\left[R(C+C_2)+\left\{g_1+g_2+g_4+(m+1)g\right\}L\right] \\ &\qquad + D\left[1+\left\{g_1+g_2+g_4+(m+1)g\right\}R\right] \quad . \quad (14) \end{aligned}$$

and the denominator will be a similar expression, with a term independent of D.

The evaluation of a is greatly simplified by neglecting mRg in comparison with unity. This can be done only when G_1 is an oscillatory circuit. The case when it is made up of a high resistance should be treated separately, and is simpler.

If the frequency were, say, 100 000 cycles per sec., and a low-impedance valve were used, the quantities considered might be as follows:

$$\begin{aligned} L &= 2\,000 \text{ microhenrys} \\ R &= 10 \text{ ohms} \\ m &= 10 \\ g &= 0{\cdot}0003 \text{ mho} \end{aligned}$$

Then $mRg = 0{\cdot}03$.

This is, however, an extreme case. It will be proved later that the resistance R of the coil L should be as small as possible if large powers are to be obtained. Moreover, quartz oscillators are in general worked at frequencies well above 100 000 cycles per sec. The value of mRg is, therefore, in most cases well under 0·01 and can be neglected in comparison with unity.

From equations (6), (7) and (13) we obtain

$$\begin{aligned} &\left\{D^2NK+DSK+1+(K/K_1)\right\}(K_1K_2/K_t)a \\ &\qquad + (D^2NK+DSK+1+K/K_t)C_5 = 0 \end{aligned}$$

$$\therefore\ D^2NK+DSK+1+\frac{K}{K_t}\cdot\frac{aK_2+C_5}{a(K_1K_2/K_t)+C_5}=0 \quad (15)$$

For brevity, we can write

$$1+\frac{K}{K_t}\frac{aK_2+C_5}{a(K_1K_2/K_t)+C_5}=\beta \quad . \quad . \quad (16)$$

The equation of oscillations is then

$$D^2NK+DSK+\beta=0 \quad . \quad . \quad . \quad (17)$$

and β can be put into the form

$$\frac{\phi_1(D^2)+D\phi_2(D^2)}{\phi_3(D^2)}$$

If it were possible to obtain an approximation for D^2, the equation would take the simple form

$$D^2NK+DSK+D\beta_2+\beta_1=0 \quad . \quad . \quad (18)$$

where β_1 and β_2 are real functions of the variables of the circuits.

When oscillations are just on the point of starting, or when oscillations are being maintained at a constant amplitude, the damping term is zero, that is

$$\beta_2+SK=0 \quad . \quad . \quad . \quad . \quad (19)$$

Therefore, also,

$$D^2NK+\beta_1=0 \quad . \quad . \quad . \quad . \quad (20)$$

The latter equation gives the required approximation for D^2.

It is here convenient to define a frequency f_0 by the formulæ

$$\left.\begin{aligned} \omega_0 &= 2\pi f_0 \\ \omega_0^2NK &= 1 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (21)$$

The frequency f_0 is that frequency at which the quartz vibrates when it is used as a resonator with no air-gap.

Having thus defined ω_0, let C_0 be a capacity determined by the relation

$$\omega_0^2LC_0=1 \quad . \quad . \quad . \quad . \quad . \quad (22)$$

The capacity C_0 will be that value of C, including the inter-electrode plate-to-filament capacity C_1, for which the natural frequency of the oscillatory circuit is equal to the natural frequency of vibration of the piece of quartz, used as a resonator with no air-gap.

Having written $\quad \beta=\beta_1+D\beta_2$

we can write $\quad a=a_1+Da_2$

where a_1 and a_2 are also real functions of the circuit variables.

Equation (20) gives

$$D^2=-\omega_0^2\beta_1 \quad . \quad . \quad . \quad . \quad . \quad (23)$$

Substituting this in the expression for a as derived from equation (11), we find that the numerator of a is $G+DH$, where

$$G=C+C_2-(C_0/\beta_1) \quad . \quad . \quad . \quad (24)$$

and

$$H=-(C_0/\beta_1)\left[R(C+C_2)+\left\{g_1+g_2+g_4+(m+1)g\right\}L\right] \quad (25)$$

If we write

$$U=C-(C_0/\beta_1) \quad . \quad . \quad . \quad . \quad (26)$$

and $\quad W=-(C_0/\beta_1)\left[RC+(g_1+g)L\right] \quad . \quad . \quad (27)$

we find that the denominator of a is $E+DF$, where

$$E=\frac{C_3+K_3}{C_5}G+\frac{C_2}{C_5}U+g_3\frac{H}{C_5}+(g_2+g_4)\frac{W}{C_5}$$

and

$$F=\frac{C_3+K_3}{C_5}H+\frac{C_2}{C_5}W-\frac{1}{\omega_0^2\beta_1}g_3\frac{G}{C_5}-\frac{1}{\omega_0^2\beta_1}(g_2+g_4)\frac{U}{C_5}$$

Finally, since

$$a=\frac{G+DH}{E+DF} \quad . \quad . \quad . \quad . \quad . \quad (28)$$

we have

$$a_1=\frac{GE+\omega_0^2HF\beta_1}{E^2+\omega_0^2F^2\beta_1} \quad . \quad . \quad . \quad (29)$$

and

$$a_2=\frac{HE-GF}{E^2+\omega_0^2F^2\beta_1}$$

$$HE-GF=-\frac{C_2}{C_5}\frac{mg}{\omega_0^2\beta_1}\left[C-\frac{C_0}{\beta_1}-\frac{C_2}{m}\left(1+\frac{R}{g}\frac{C_0}{L}\frac{1}{\beta_1}\right)\right]+\frac{1}{\omega_0^2\beta_1C_5}\left[g_1C_2^2+g_3(\omega_0^2H^2\beta_1+G^2)+(g_2+g_4)(\omega_0^2WH\beta_1+U^2)\right] \quad . \quad (30)$$

The expressions for E and F are

$$E = C + C_2 - \frac{C_2^2}{C_5} - \frac{C_0}{\beta_1} + g_3\frac{H}{C_5} + (g_2 + g_4)\frac{W}{C_5} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (31)$$

$$F = -\frac{C_0}{\beta_1}\left[R\left(C+C_2-\frac{C_2^2}{C_5}\right)+\left(m\frac{C_3+K_3}{C_5}+1\right)gL+g_1L+\frac{C+C_2-(C_0/\beta_1)}{C_5}g_3L+\frac{C+C_3+K_3-(C_0/\beta_1)}{C_5}(g_2+g_4)L\right] \quad . \qquad (32)$$

The expressions for β_1 and β_2 in terms of a_1 and a_2 can be obtained from equation (16). They are

$$\beta_1 = 1 + \frac{K}{K_t}\,\frac{(a_1K_2 + C_5)\left\{a_1(K_1K_2/K_t) + C_5\right\} + a_2^2\omega_0^2\beta_1(K_1K_2^2/K_t)}{\left\{a_1(K_1K_2/K_t) + C_5\right\}^2 + a_2^2\omega_0^2\beta_1(K_1K_2/K_t)^2} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (33)$$

$$\beta_2 = \frac{a_2C_5(K_2/K_t)^2}{\left\{a_1(K_1K_2/K_t) + C_5\right\}^2 + a_2^2\omega_0^2\beta_1(K_1K_2/K_t)^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (34)$$

When oscillations are just on the point of starting, or are being maintained at a constant amplitude, $\beta_2 + SK = 0$, and therefore β_2 is negative, and of the same order of magnitude as SK. Equation (34) shows that a_2 must be negative when β_2 is negative.

When
$$a_2 < 0$$
$$GF > HE$$
$$G > \frac{HE}{F}$$

Hence
$$a_1 = \frac{GE + \omega_0^2HF}{E^2 + \omega_0^2F^2} > \frac{H}{F}$$

Moreover, since $a_2 < 0$, equation (30) shows that $C > C_0/\beta_1$.

Under these conditions, it is easily seen from equations (25) and (32) that H/F is positive, that is, greater than zero; hence a_1 is also greater than zero, and $a_1(K_1K_2/K_t) + C_5$ is of the same order of magnitude as C_5.

Equation (34) gives two negative roots for a_2 in terms of β_2. Since K/K_t is small, β_1 does not differ greatly from $1 + (K/K_t)$, that is, from unity, whatever be the value of a_2. The order of magnitude of one root of a_2 is therefore small and equal to SC_5. The second root is large, and its order of magnitude is $1/(\omega_0^2SK_1)$. This second root must, however, be rejected, for equations (29) and (30) show that the numerical value of a_2 is, except in some cases, over a very small range of values of C, less than $1/(\omega_0^2SK_1)$.

Since a_2 is small, we may write

$$\beta_1 = 1 + \frac{K}{K_t}\cdot\frac{a_1K_2 + C_5}{a_1(K_1K_2/K_t) + C_5} \quad . \quad . \qquad (35)$$

and
$$\beta_2 = \frac{a_2C_5K}{\left\{a_1(K_1K_2/K_t) + C_5\right\}^2}\cdot\frac{K_2^2}{K_t^2} \quad . \quad . \qquad (36)$$

If the capacity C be of such a value that $\beta_2 + SK < 0$, oscillations start and build up. As the amplitude of the oscillations increases, the modulus $|\beta_2 + SK|$ decreases, and therefore $|\beta_2|$ becomes more and more nearly equal to SK. The change in β_2 can be produced only by a change in the anode conductance g. Finally the amplitude of oscillations reaches such a value that the corresponding mean value of g makes the expression $\beta_2 + SK$ equal to zero. The amplitude ceases to increase, and the oscillations are maintained at constant amplitude.

The frequency of the oscillations depends upon β_1, and therefore upon a_1. This quantity changes with g, so that the frequency of the oscillations changes slightly during the process of building up. The time taken for this building up is, in general, of the order of 1 or 2 seconds.

The frequency with which we are concerned is, of course, the frequency corresponding to the constant amplitude. When the amplitude has reached its constant value, $\beta_2 + SK = 0$ and the order of magnitude of a_2 is SC_5. This being very small, and the denominator $E^2 + \omega_0^2F^2$ of a_2 being very small, it is necessary that the numerator $HE - GF$ should be very small, namely, of the order of $SC_5C_0^2$. When the amplitude has reached a constant value, it is, therefore, permissible to write

$$a_1 = \frac{G}{E} = \frac{H}{F} = \frac{C + C_2 - (C_0/\beta_1)}{C + C_2 - \dfrac{C_2^2}{C_5} - \dfrac{C_0}{\beta_1} - (g_2 + g_4)\left[\dfrac{C_0}{C_5\beta_1}(RC + gL)\right] - g_3\left[\dfrac{C_0}{C_5\beta_1}\left\{R(C + C_2) + (m + 1)gL\right\}\right]} \quad . \qquad (37)$$

This approximation will give a reasonably accurate value for the frequency. The effect of g_2, g_3, g_4 and R on the frequency will be considered later. It will be sufficient here to neglect the terms in g_2, g_3 and g_4, and to write

$$a_1 = \frac{C + C_2 - C_0/\beta_1}{C + C_2 - (C_2^2/C_5) - (C_0/\beta_1)} \quad . \qquad (38)$$

For brevity, we shall write a and β instead of a_1 and β_1.

The frequency of oscillations is given by

$$\omega^2 = \omega_0^2\beta$$

and, since β never departs much from unity,

$$f = f_0(\tfrac{1}{2} + \tfrac{1}{2}\beta) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (39)$$

The ratio of the coefficient of D to that of D^2 is

$$SK\omega_0^2 + \beta_2\omega_0^2 = SK\omega_0^2 + K\left(\frac{K_2}{K_t}\right)^2 \frac{g_1C_2^2 + g_3(\omega_0^2H^2 + G^2) + (g_2 + g_4)(\omega_0^2WH + U^2)}{E^2\left\{1 + (\omega_0^2F^2/E^2)\right\}\left\{\alpha(K_1K_2/K_t) + C_5\right\}^2}$$
$$- \frac{K(K_2/K_t)^2mgC_2\left[C - \frac{C_0}{\beta} - \frac{C_2}{m}\left(1 + \frac{R}{g}\frac{C_0}{L}\right)\right]}{E^2\left\{1 + (\omega_0^2F^2/E^2)\right\}\left\{\alpha(K_1K_2/K_t) + C_5\right\}^2} \quad . \quad . \quad . \quad (40)$$

This expression shows that S, g_1, g_2, g_3 and g_4 all tend to oppose the production of oscillations. It is also permissible to state that they tend to make the final amplitude smaller. In the case of the grid leak g_4 this rule, however, is not rigid, because the grid leak may alter the grid potential so as to cause oscillations to take place about a more favourable point on the characteristic curve of the valve.

If we substitute for α by equation (38), remembering that this is only an approximation which assumes $HE = GF$, we find for the ratio of the terms in D and D^2:—

It has been shown (p. 269) that $\alpha > 0$. Over the range

$$0 < \alpha < \infty$$

we have

$$\tfrac{1}{2}(K/K_t) < (\Delta f/f_0) < \tfrac{1}{2}(K/K_1)$$

Hence $(\Delta f/f_0)$ is always smaller than 1/280, which is the theoretical value of $\frac{1}{2}(K/K_1)$ for good quartz,* and is rarely reached in practice with resonators vibrating along the electric axes.

We have

$$\alpha = \frac{C + C_2 - (C_0/\beta)}{C + C_1 - (C_2^2/C_5) - (C_0/\beta)} \quad . \quad . \quad (45)$$

$$SK\omega_0^2 + K\left(\frac{K_2}{K_t}\right)^2 \frac{g_1C^2 + g_3(\omega_0^2H^2 + G^2) + (g_2 + g_4)(\omega_0^2WH + U^2)}{\left(1 + \frac{\omega_0^2F^2}{E^2}\right)\left(\frac{K_1K_2}{K_t} + C_5\right)^2\left(C + C_2 - \frac{C_0}{\beta} - \frac{C_2^2}{(K_1K_2/K_t) + C_5}\right)^2}$$
$$- K\left(\frac{K_2}{K_t}\right)^2 \frac{mgC_2\left[C - \frac{C_0}{\beta} - \frac{C_2}{m}\left(1 + \frac{R}{g}\frac{C_0}{L}\right)\right]}{\left(1 + \frac{\omega_0^2F^2}{E^2}\right)\left(\frac{K_1K_2}{K_t} + C_5\right)^2\left(C + C_2 - \frac{C_0}{\beta} - \frac{C_2^2}{(K_1K_2/K_t) + C_5}\right)^2} \quad . \quad (41)$$

When C is gradually increased from zero, the expression is positive and there can be no oscillations. When C reaches the value

$$C = \frac{C_0}{\beta} + \frac{C_2}{m}\left(1 + \frac{R}{g}\frac{C_0}{L}\right)$$

the expression is still positive; a small increase in C, however, makes it zero; a further increase makes it negative, and oscillations start. As C is still further increased, the expression quickly reaches a minimum, then increases again, gradually, until a certain large value of C is attained for which it becomes zero. At this point the oscillations stop. It is easy to find this limit, because for large values of C, G and F are large compared with ω_0H and ω_0F. It is given by

$$(mgC_2/C - C_0) = g_2 + g_3 + g_4 + S\omega_0^2\left\{K_1 + C_5(K_t/K_2)\right\}^2 \quad (42)$$

The lower limit of C is given by

$$C > \frac{C_0}{\beta} + \frac{C_2}{m}\left(1 + \frac{R}{g}\frac{C_0}{L}\right) \quad . \quad . \quad . \quad (43)$$

Closer approximations to this lower limit, or "cut-off point," will be obtained in the Sections dealing with amplitude, pp. 273 and 274. Equation (41) will also be used to study the changes in amplitude with respect to C and to the other circuit variables.

Relation between frequency and total capacity in the oscillatory circuit.—It is convenient to work in frequency differences above f_0. The difference

$$\Delta f = f - f_0 = \tfrac{1}{2}f_0(\beta - 1)$$

$$\therefore \frac{\Delta f}{f_0} = \frac{1}{2}\frac{K}{K_t}\frac{\alpha K_2 + C_5}{\alpha(K_1K_2/K_t) + C_5} \quad . \quad . \quad (44)$$

The quantity β is itself a function of α. The rigid procedure would therefore be to choose various values of α, to calculate β, and then obtain C from equation (45) and Δf from equation (44). The limits of α corresponding to the limits of C are easily found, from equation (45), to be

$$\infty > C > \frac{C_0}{\beta} + \frac{C_2}{m}\left(1 + \frac{R}{g}\frac{C_0}{L}\right)$$

$$1 < \alpha < \frac{m + 1 + (R/g)\,(C_0/L)}{m(C_3 + K_2/C_5) + 1 + (RC_0/gL)} \quad . \quad (46)$$

In view, however, of the fact that $\beta - 1$ is small and does not change much, it is simpler to substitute at once for α in equation (45) and to evaluate $\Delta f/f_0$.

$$\frac{\Delta f}{f_0} = \frac{1}{2}\frac{K}{K_t}\frac{\left\{C + C_2 - (C_0/\beta)\right\}(K_2 + C_5) - C_2^2}{\left\{C + C_2 - (C_0/\beta)\right\}\left\{(K_1K_2/K_t) + C_5\right\} - C_2^2} \quad (47)$$

$$\frac{\partial}{\partial C}\left(\frac{\Delta f}{f_0}\right) = -\frac{1}{2}K\left(\frac{K_2}{K_t}\right)^2$$
$$\frac{C_2^2}{\left\{C + C_2 - (C_0/\beta)\right\}\left\{(K_1K_2/K_t) + C_5\right\} - C_2^2} \quad (48)$$

This is always negative, and it increases numerically as C decreases. It is zero when C is infinite.

When C is very large, the frequency is given very nearly by

$$\frac{\Delta f}{f_0} = \frac{1}{2}\frac{K}{K_t}\frac{K_2 + C_5}{(K_1K_2/K_t) + C_5} \quad . \quad . \quad . \quad (49)$$

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* See Reference (6).

As C is decreased, the frequency increases gradually, and the rate of increase increases until the oscillations stop.

Relation between Frequency and the Various Resistances of the Circuits.—Equation (37) shows that the effect of g_2, g_3, g_4, g and R is to increase a, and therefore also to increase the frequency. This increase, moreover, becomes greater and greater as C approaches its lower limit.

Relation between Frequency and the Inter-electrode Capacities.—We have, from equation (47):—

$$\frac{\partial}{\partial C_2}\frac{\Delta f}{f_0} = -\frac{1}{2}K\left(\frac{K_2}{K_t}\right)^2 \frac{\{C-(C_0/\beta)\}^2}{[\{C+C_2-(C_0/\beta)\}\{(K_1K_2/K_t)+C_5\}-C_2^2]^2} \quad . \quad (50)$$

It is always negative, and $\left|\frac{\partial}{\partial C_2}\frac{\Delta f}{f_0}\right|$ decreases with C_2. In this respect, a large C_2 would be an advantage.

On the other hand, equation (48) shows that the greater C_2 becomes, the greater is $\left|\frac{\partial}{\partial C}\left(\frac{\Delta f}{f_0}\right)\right|$; from this point of view a large C_2 would be a disadvantage. The value of C_2 is, in general, more important in its relation to the amplitude of oscillations than in its effect on the frequency.

For the variation of frequency with respect to C_3 we find

$$\frac{\partial}{\partial C_3}\frac{\Delta f}{f_0} = -\frac{1}{2}K\left(\frac{K_2}{K_t}\right)^2 \frac{\{C+C_2-(C_0/\beta)\}^2}{[\{C+C_2-(C_0/\beta)\}\{(K_1K_2/K_t)+C_5\}-C_2^2]^2} \quad . \quad (51)$$

The frequency therefore decreases with C_3, and the larger C_3 becomes, the smaller is the modulus of the rate of decrease. Variation of K_3 has exactly the same effect.

Relation between Frequency and Air-gap.—The variation of frequency with variation of air-gap is a little more complicated than with an ordinary resonator, in which case it is given by

$$\Delta f/f_0 = \tfrac{1}{2}(K/K_t) \quad . \quad . \quad . \quad . \quad (52)$$

For the oscillator a straight line could, in theory, be obtained by plotting Δf against the right-hand term of equation (47). There would be a different graph for each value of C.

In view of the fact that, even in a resonator, the frequency changes are not governed by relation (52) above, there would be no point in carrying out the more complicated computation in the case of the oscillator.

Amplitude of Oscillations.—The amplitude is closely related to the shape of the characteristic curves of the valve. If general algebraical expressions for those characteristics were available, general expressions might be obtained for the amplitude, but the problem would present great difficulties. It is possible, however, to arrive at interesting qualitative results, by general considerations of the shape of the characteristics.

The amplitude is greatly dependent upon the capacity C. Consider a circuit like that shown in Fig. 4. The resistance of the coil is small in comparison with the anode resistance of the valve, and the mean potential at A is very nearly equal to the difference of potential V between the terminals of the battery. If the grid potential e be varied, at a frequency f, between the limits e_1 and e_2, the plate current will alternate between, say, i_1 and i_2, but will never, of course, be less than zero. If the impedance of the oscillatory circuit to current of frequency f be Z, the amplitude $v_1 - v_2$ of the alternations in potential at A will be equal to $Z(i_2 - i_1)$.

In a self-maintained oscillator, the amplitude of the oscillations, starting from a small disturbance, increases until the swing of grid potential is such that a further increase would not produce any increase in the amplitude of variation of the current.

The impedance Z of the oscillatory circuit is a maximum when C is adjusted so that $4\pi^2LCf^2$ is unity. The impedance is then equal to L/RC. Hence the amplitude is approximately inversely proportional to the resistance R of the oscillatory circuit. The law is not exact. The variations in voltage across Z are produced by variations in the plate current. The plate current is itself, however, a function of plate voltage. On the straight part of the characteristic curve of the valve,

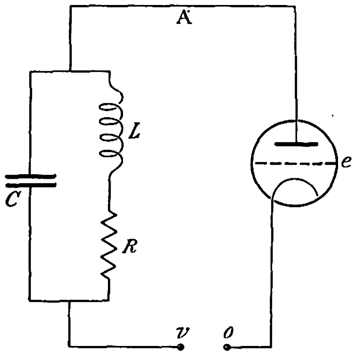

FIG. 4.

$$v_1 - v_2 = \frac{gZ}{1+gZ}m(e_2 - e_1)$$

It is nevertheless always true to say that the smaller R becomes, the greater is the amplitude V. The power, however, is not, in general, a maximum at this point; it is equal to $\frac{1}{2}RC^2\omega^2V^2$, and the "useful power" is zero.

If a resistance R' be added to R, the amplitude of the oscillations will be reduced to, say, V', and the total power will be $\frac{1}{2}(R + R')C^2\omega^2V'^2$. This may, or may not, be greater than $\frac{1}{2}RC^2\omega^2V^2$. The useful power is now $\frac{1}{2}R'C^2\omega^2V'^2$. In practice the increase of resistance R' is not produced by an actual resistance added to R; it is the effective increase of resistance due to the coupling between L and the circuit in which the power supplied by the quartz oscillator is being usefully employed.

In the case of the quartz oscillator, the simple relation $LC\omega^2 = 1$, that is, $C = C_0$, cannot be used to find the value of C for maximum amplitude, because of the presence of the inter-electrode capacities.

Suppose that, in a self-oscillatory valve circuit, the potential of the grid, before any oscillations start, is E_1 (Fig. 5). The corresponding point on the characteristic is A_1. When oscillations start, but the amplitude is still small enough, say E_2E_3, there is no change in the mean plate current. On the other hand, there is nothing to prevent the oscillations from building up, and the amplitude increases until, during part of the swing, the grid potential is positive. During this part of the swing, grid current flows and tends to lower the grid potential. During the rest of the cycle, there is no effect tending to increase the grid potential. In other words, there is a tendency for the swing of grid potential to be opposed on the positive side, but not on the negative side; as a consequence the mean grid potential falls to the left of E_1, say to E_4. The average plate current is not, in general, that corresponding to A_4, but to a point somewhere between A_4 and A_1. If, by some alteration in the valve circuits the amplitude is made to increase still more, and the maximum grid potential is, say, E_5, the effect due to grid current becomes still more pronounced, and the swing on the other side, namely, E_4E_6, is much greater than E_4E_5; the mean grid potential decreases further to E_7, and there is a fall in the average plate current, which now corresponds to some point A between A_7 and A_4. This decrease of plate current with amplitude is well exhibited by the experimental curves in Fig. 25. The rule does not hold quite as rigidly when the resistance in the oscillatory circuit is large, because in that case the maximum amplitude is small, and the swing of grid voltage towards the positive side does not exceed, say, E_8. It may then occur that the increase in average plate current with amplitude, due to the anode rectification, more than compensates for the decrease due to the lowering of mean grid potential, itself a result of the flow of grid current.

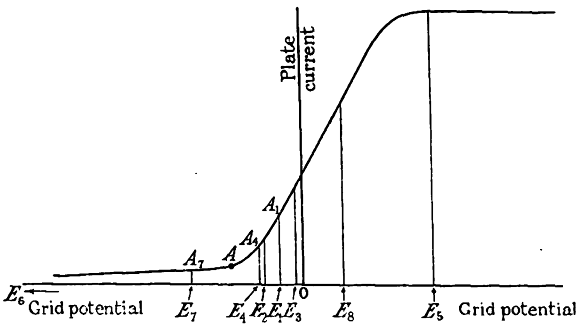

FIG. 5.

If we ignore this slight departure from the rule, we may state that the average plate current falls as the amplitude increases. Under those conditions, the average plate conductance g will also fall with increasing amplitude, as can best be seen by the shape of the plate-volts/grid-volts characteristics of a valve, for various plate currents.

Consider now expression (41), and suppose that the capacity is at first very large; no oscillations can take place because the expression is positive. The plate current is fixed solely by the plate, filament, and grid voltages. We may suppose, for the sake of argument, that there is a grid leak; the potential of the grid is then equal to the potential of the filament; denote the corresponding plate current and plate conductance by I_0 and g_0. Let C be decreased gradually. When it reaches the limit given by equation (42), expression (41) is just zero, and oscillations are on the point of starting. The value of g to be used in equation (42) is therefore g_0. Suppose C to be decreased further. If the value of g were still g_0, expression (41) would be negative. Oscillations therefore build up, and the amplitude increases, until g reaches the value such that expression (41) becomes equal to zero. This new value of g will depend upon the setting of C, and the amplitude will be some function of $1/g$. It might be possible to find the amplitude in terms of the average g from a complete set of characteristics, but the process would, undoubtedly, be complicated. It will, nevertheless, be interesting for us to plot the value of $1/g$ against C, and to compare the curve thus obtained with the amplitude curves obtained experimentally. The curves must not, of course, be expected to coincide. All that can be expected is that (d/dC) should have the same sign for both curves.

When the value of C is that given by equation (42), oscillations are just on the point of starting, the amplitude is zero, and the plate conductance is g_0. It is therefore convenient to plot $(1/g) - (1/g_0)$, or $r - r_0$, against C, where r, the reciprocal of g, is the mean internal plate resistance of the valve.

The effect of some of the circuit variables on the amplitude can be predicted without actually plotting the curves.

The terms in S, g_1, g_2, g_3, g_4 and R, all tend to raise the value of g which makes expression (41) equal to zero. All the damping terms are, therefore, in general, detrimental. It may occur, however, that by a judicious choice of the grid leak g_4 the mean grid potential becomes such that oscillations take place about a more favourable point on the characteristic curve of the valve. Under these conditions the effect of g_4 would be beneficial.

The conductance g_3 between anode and filament may be considered as being made up of two parts: the first, g_3', a small direct-current conductance due to want of perfect insulation, and the second, g_3'', due to the dielectric losses in the glass and holder. This latter component, by far the larger of the two, merely increases the damping and slightly reduces the amplitude of oscillations; the component g_3' tends to equalize plate and grid potential, and therefore to stop the oscillations. It is, however, very small, being probably less than 10^{-8} mho in most valves.

The third term of expression (41) contains as a factor $C_2/\{K_1 + C_5(K_t/K_2)\}^2$.

When C_2 is zero, expression (41) will be positive, and no oscillations can take place. In the same way, large values of C_2 make the third term small numerically, and the expression will again be positive. There will therefore be, for each value of C, an optimum value of C_2.

The inter-electrode plate-to-grid capacity C_3, and the stray capacity K_3 in parallel with it, increase C_5, and therefore increase the term in S in expression (41). Their presence is, therefore, always detrimental; hence the use, by J. R. Harrison, of a screened plate, to do away with the capacity C_3. Hence also the importance of keeping as low as possible the stray capacity K_3 between the electrodes and leads of the resonator.

The term in S is multiplied by

$$\{K_1 + C_5(K_t/K_2)\}^2$$

The amplitude obtainable with a small air-gap will thus be larger than the amplitude with a large air-gap, because the smaller the air-gap the smaller is (K_t/K_2).

The value of g obtained by equating expression (41) to zero is independent of the initial value g_0, other things being equal. In a low-impedance valve, however, the swing of plate current required to produce a given change in the mean plate conductance is larger than in a high-impedance valve. Hence, the lower the normal plate impedance r_0, the greater will the amplitude be.

The third term in expression (41) contains the amplification constant m as a factor. The greater m, the smaller will be the value of g which makes the expression equal to zero; a large amplification factor is therefore beneficial, other things being the same.

The analysis of expression (41) is greatly simplified by supposing that

$$C_2 + C - \frac{C_0}{\beta} - \frac{C_2^2}{C_5}$$

and

$$C_2 + C - \frac{C_0}{\beta} - \frac{C_2^2}{(K_1K_2/K_t) + C_5}$$

are nearly equal. In numerical computation this supposition is not even necessary.

Writing, for brevity, $C - (C_0/\beta) = x$, we can put expression (41) into the form

$$\Sigma[(a_1x+a_2)^2+(a_3x+a_4g+a_5)^2]+a_6+a_7g-a_8gx \quad . \quad (53)$$

in which the coefficients a_1, . . . etc., are all positive. The Σ includes four similar terms, which contain, as factors, S, g_1, g_3, and $g_2 + g_4$ respectively; some of the coefficients a_1, a_2, . . . etc., may be zero. We see at once that there cannot be any maintained oscillations unless x be positive. The expression can then be put into the simpler form

$$\phi = x^2 + Ax + B + Cg^2 + Dg - Exg \quad . \quad (54)$$

where the coefficients A, B, C, D and E are all positive.

Since x is positive, oscillations cannot be maintained unless

$$Ex > D$$

This, however, is not the only condition, because some positive values of x might give imaginary roots for g in the equation $\phi = 0$. We therefore require the further condition

$$\phi_2 = (Ex - D)^2 - 4C(x^2 + Ax + B) \geqq 0 \quad . \quad (55)$$

Since Ex is positive and greater than D, this condition requires that

$$E^2 > 4C$$

Whenever the inequality (55) is satisfied, the two values of g given by the equation $\phi = 0$ are real. They are, moreover, both positive, since their sum and their product are positive.

The differential coefficient of ϕ_2 is

$$2E(Ex - D) - 4C(2x + A)$$

But we also have

$$(Ex - D)^2 - 4C(x^2 + Ax + B) \geqq 0$$
$$\therefore \quad Ex(Ex - D) - 4C(x^2 + Ax + B) > 0$$
$$2Ex(Ex - D) - 4C(2x^2 + 2Ax + 2B) > 0$$
$$2E(Ex - D) - 4C(2x + A) > 0$$

The differential coefficient of expression (55) is thus positive for all values of x over which oscillations may take place. Expression (55) therefore increases with x.

Denote by ξ_2 the larger of the two roots of the equation $\phi_2 = 0$. For the maximum amplitude, that is, for the minimum value of g with respect to x or C, we have the equations

$$\phi = 0 \quad \text{and} \quad dg/dx = 0$$

But

$$\frac{\partial\phi}{\partial x} + \frac{\partial\phi}{\partial g}\frac{dg}{dx} = 0$$

The condition for a minimum g is therefore

$$\left.\begin{aligned} \phi &= 0 \\ \partial\phi/\partial x &= 0 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (56)$$

The second of these equations is

$$2x + A - Eg = 0 \quad . \quad . \quad . \quad (57)$$

Substituting for g in the first, we find

$$(Ex - D)^2 - 4C(x^2 + Ax + B) = BE^2 + A^2C + ADE + D^2 - 4CB \quad (58)$$

But since $E^2 > 4C$, the right-hand term of expression (58) is always positive, and the value ξ_1 of x given by expression (58) is greater than ξ_2. The amplitude therefore reaches a maximum before the point of cut-off.

In general, the two equal values of g corresponding to ξ_2, namely $\dfrac{E\xi_2 - D}{2C}$, are smaller than g_0, and the corresponding value of r is larger than r_0. As soon as C is reduced to $\xi_2 + (C_0/\beta)$, oscillations stop suddenly. For this reason the value of C corresponding to ξ_2 will be called the "cut-off point." If the damping terms were large, ξ_2 would be large, and the corresponding value of r might be less than r_0. In such a case the curve of r against C would cut the line $r = r_0$ at some point ξ_3 between ξ_1 and ξ_2. If C were decreased gradually, the amplitude would rise to a maximum and then decrease gradually, and become zero at $C = (\xi_3 + C_0/\beta)$, but there would be no sudden cut-off.

Two other interesting points are obtained by substituting g_0 for g in equation (54) and solving for x.

Unless the damping terms be very large, Eg_0 is greater than A and there are two positive roots. If A were greater than Eg_0, no oscillations could ever start of themselves. It is easily seen by inspection that the smaller the damping terms, the smaller will be the product of the roots and the larger will be the difference between the roots. The smaller of the two roots, say ξ_4, is larger than ξ_2, since ξ_2 is the limiting value of C below which no real values of g can satisfy the equation $\phi = 0$. The second root ξ_5 corresponds to the limiting value of C above which no oscillations can take place. The above method gives this limit a little more accurately than the simpler formula (42).

For values of x greater than ξ_5 no oscillations can be started and maintained. When x is decreased gradually and reaches ξ_5, oscillations start; the amplitude is very small when x is only slightly less than ξ_5; as x is further decreased the amplitude increases and reaches a maximum at ξ_1, then decreases rather rapidly, and just past ξ_2 the oscillations stop suddenly. If x is then increased, oscillations cannot start at ξ_2; they only start after x has been further increased to ξ_4. If x is kept at ξ_4, the oscillations start, and the amplitude builds up in a very short time. It is easy to find the point g on the curve, corresponding to this amplitude, by substituting ξ_4 for x in equation (54), and solving for g. The sum of the roots is equal to $(E\xi_4 - D)/C$, and one of them is g_0. Moreover, since ξ_4 is small, the value of g_0 is itself not very different from the above sum when the damping terms A and B are small. The second root is therefore small in comparison with g_0, and corresponds to a fairly large amplitude.

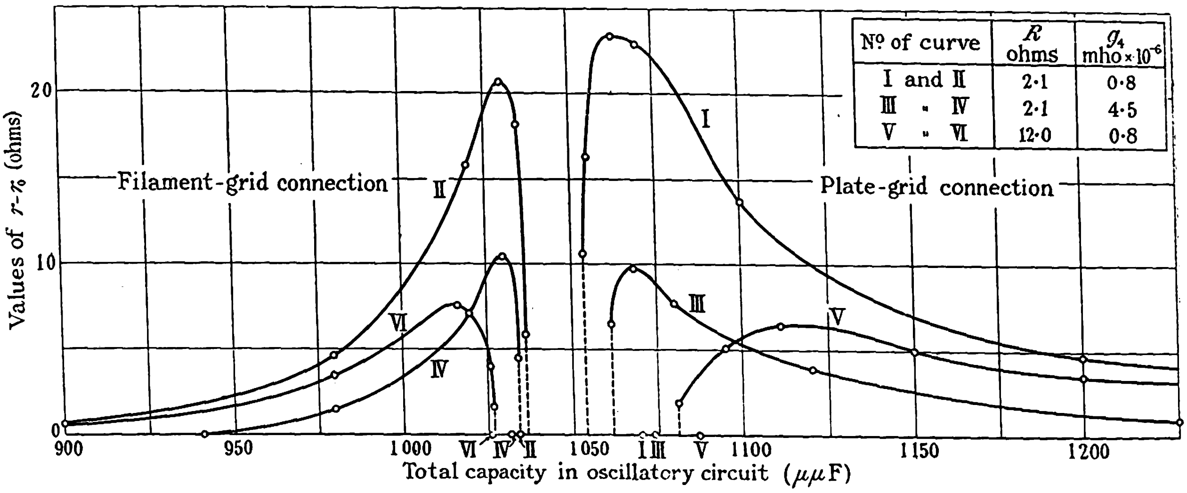

FIG. 6.—Curves of increase in mean plate resistance with variation of capacity in the oscillatory circuit. D.E.R. valve.

TABLE 1.

S = 400 ohms

For curves I, II, III and IV R = 2·1 ohms

For curves V and VI .. R = 12·0 ohms

K = 0·018 $\mu\mu$F

K_2 = 136 $\mu\mu$F

K_1 = 9·6 $\mu\mu$F

C_2 = 6·4 $\mu\mu$F

C_3 = 2·4 $\mu\mu$F

K_3 = 15·2 $\mu\mu$F

$C_2 + C_3 + K_3 = C_5$ = 24 $\mu\mu$F

C_0 = 1 043 $\mu\mu$F

C_0/β for plate-grid connection = 1 042·3 $\mu\mu$F

C_0/β for filament-grid connection = 1 042·5 $\mu\mu$F

L = 160·6 μH

g_1 = $0{\cdot}2 \times 10^{-6}$ mho

g_2 = $0{\cdot}5 \times 10^{-6}$ mho

g_3 = $0{\cdot}05 \times 10^{-6}$ mho

For curves I, II, V and VI g_4 = $0{\cdot}8 \times 10^{-6}$ mho

For curves III and IV .. g_4 = $4{\cdot}5 \times 10^{-6}$ mho

g_0 = 42×10^{-6} mho

m = 8·6

ω_0 = $2{\cdot}442 \times 10^6$ per sec.

Other points on the curves can be calculated by choosing particular values of x and solving for g.

This has been done in Fig. 6. The points marked (I), (III) and (V) on the axis of capacities are the points corresponding to ξ_4.

The values of the circuit variables used in the computation of the curves were obtained by direct measurements, to be described later, on the valve, the oscillatory circuits and the quartz resonator. The measurements were quite independent of any experimental results obtained by using the quartz as an oscillator.

The values adopted are given in Table 1. Curves II, IV and VI refer to the grid-to-filament connection.

The shape of these theoretical curves will be compared with that of the experimental curves in a later Section of the paper.

FILAMENT-TO-GRID CONNECTION.

The case in which the electrodes of the quartz resonator are connected to the grid and to the filament of the valve will be treated very briefly, for the procedure is analogous to that adopted in the previous case.

We have

$$G_1 = DC + \left\{1/(R + DL)\right\} + g_1 \quad . \quad . \quad . \quad . \quad . \quad (59)$$

$$G_2 = g_2 + g_4 + D(C_2 + K_3) + D(K_1K_2/K_t)(\sigma/\nu) \quad (60)$$

$$G_3 = g_3 + DC_3 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (61)$$

and substituting in equation (3) it is seen that the resulting equation is identical with equation (11) after interchanging

$g_2 + g_4$ and g_3

C_2 and C_3

$(m + 1)g$ and g

We then find:

$$G' = (C_0/\beta) - C - C_3 \quad \ldots \quad (62)$$

$$H' = (C_0/\beta)\left[R(C + C_3) + L(g + g_1 + g_3)\right] \quad \ldots \quad (63)$$

$$U' = (C_0/\beta) - C \quad \ldots \quad (64)$$

$$W' = (C_0/\beta)\left[RC + L(g_1 + (m + 1)g)\right] \quad \ldots \quad (65)$$

$$E' = (C_0/\beta) - C - C_3 + (C_3^2/C_5) + (g_2 + g_4)(H'/C_5) + g_3(W'/C_5) \quad \ldots \quad (66)$$

$$F' = \frac{C_2 + K_3}{C_5}H' + \frac{C_3}{C_5}W' - \frac{1}{\omega_0^2\beta C_5}\left[(g_2 + g_4)G' + g_3U'\right] \quad \ldots \quad (67)$$

$$a = \frac{(C_0/\beta) - C - C_3}{(C_0/\beta) - C - C_3 + (C_3^2/C_5) + (g_2 + g_4)(H'/C_5) + g_3(W'/C_5)} \quad \ldots \quad (68)$$

$$= \frac{1}{2}\frac{K}{K_t}\frac{aK_2 + C_5}{a(K_1K_2/K_t) + C_5} \quad \ldots \quad (69)$$

$$= \frac{1}{2}\frac{K}{K_t}\frac{\left\{(C_0/\beta) - C - C_3\right\}(K_2 + C_5) + C_3^2}{\left\{(C_0/\beta) - C - C_3\right\}\left\{(K_1K_2/K_t) + C_5\right\} + C_3^2} \quad \ldots \quad (70)$$

The ratio of the coefficient of D to that of D^2 is

$$SK\omega_0^2 + K\left(\frac{K_2}{K_t}\right)^2\frac{g_1C_3^2 + (g_2 + g_4)(G'^2 + \omega_0H'^2) + g_3(U'^2 + \omega_0^2W'H')}{\left(\frac{K_1K_2}{K_t} + C_5\right)^2\left(1 + \frac{\omega_0^2F'^2}{E'^2}\right)\left(\frac{C_0}{\beta} - C - C_3 + \frac{C_3^2}{(K_1K_2/K_t) + C_5}\right)}$$

$$- K\left(\frac{K_2}{K_t}\right)^2\frac{mgC_3\left[\frac{C_0}{\beta} - C_3 - \frac{C_3}{m}\left(1 + \frac{R}{g}\frac{C_0}{L}\right) - C\right]}{\left(\frac{K_1K_2}{K_t} + C_5\right)^2\left(1 + \frac{\omega_0^2F'^2}{E'^2}\right)\left(\frac{C_0}{\beta} - C - C_3 + \frac{C_3^2}{(K_1K_2/K_t) + C_5}\right)^2} \quad . \quad (71)$$

For maintenance of oscillations, we must have the inequality

$$\frac{C_0}{\beta} > C + C_3 + \frac{C_3}{m}\left(1 + \frac{R}{g}\frac{C_0}{L}\right) \quad . \quad . \quad (72)$$

The corresponding value of a is

$$\frac{1 + \frac{R}{g}\frac{C_0}{L}}{m\frac{C_3}{C_5} + 1 + \frac{R}{g}\frac{C_0}{L}}$$

The value of C below which oscillations cannot be maintained is given by

$$\frac{mgC_3}{C_0 - C} = g_2 + g_3 + g_4 + S\omega_0^2\left(K_1 + \frac{C_5K_t}{K_2}\right)^2 \quad . \quad (73)$$

Hence the total range of capacity C over which oscillations are possible with the grid-to-filament connection is to the corresponding range in the plate-to-grid connection as C_3 is to C_2. The value of a corresponding to formula (73) is very nearly unity, but never reaches unity.

Relation between Frequency and Total Capacity in the Oscillatory Circuit.—We have

$$\frac{\partial}{\partial C}\frac{\Delta f}{f_0} = -\frac{1}{2}K\left(\frac{K_2}{K_t}\right)^2\frac{C_3^2}{\left[\left\{(C_0/\beta) - C - C_3\right\}\left\{(K_1K_2/K_t) + C_5\right\} + C_3^2\right]^2} \quad \ldots \quad (74)$$

This shows that, all over the range, the frequency decreases as C increases. Moreover, the rate of decrease increases with C and becomes very large when C approaches the cut-off point.

The asymptotic frequency, corresponding to the small values of C, is given by

$$\frac{\Delta f}{f_0} = \frac{1}{2}\frac{K}{K_t}\frac{K_2 + C_5}{(K_1K_2/K_t) + C_5}$$

just as in the case of the plate-to-grid connection. The frequency lies entirely below this asymptotic frequency, and is therefore always less than the frequency for the plate-to-grid connection, but it is never as low as the response frequency of the resonator used as such, given by

$$\frac{\Delta f}{f_0} = \frac{1}{2}\frac{K}{K_t}$$

Since a is positive and finite, whichever be the type of connection of the resonator to the valve, the maximum variation of $(\Delta f/f_0)$ is less than $\frac{1}{2}(K/K_1)$, which is only a small fraction of the frequency.

Relation between Frequency and the Various Resistances of the Circuits.—Expression (68) shows that the effect of g_2, g_3, g_4, g and R is to decrease a, and therefore to decrease the frequency. This decrease is, moreover, greater and greater as C approaches its upper limit.

Relation between Frequency and the Inter-electrode Capacities.—We have, from equation (70),

$$\frac{\partial}{\partial C_3}\frac{\Delta f}{f_0} = -\frac{1}{2}K\left(\frac{K_2}{K_t}\right)^2 \frac{\left\{(C_0/\beta) - C\right\}^2}{\left[\left\{(C_0/\beta) - C - C_3\right\}\left\{(K_1K_2/K_t) + C_5\right\} + C_2^2\right]^2} \quad . \quad . \quad . \quad . \quad . \quad (75)$$

This is always negative, and therefore the frequency decreases with increase of C_3.

Similarly, we have

$$\frac{\partial}{\partial C_2}\frac{\Delta f}{f_0} = -\frac{1}{2}K\left(\frac{K_2}{K_t}\right)^2 \frac{\left\{(C_0/\beta) - C - C_3\right\}^2}{\left[\left\{(C_0/\beta) - C - C_3\right\}\left\{(K_1K_2/K_t) + C_5\right\} + C_3^2\right]^2} \quad . \quad . \quad . \quad . \quad . \quad (76)$$

which shows that the frequency decreases with increase of C_2, but that the rate of decrease decreases.

Amplitude of Oscillations.—Expression (71) shows that, when C_3 is zero or infinite, no oscillations can take place. There is, therefore, for each value of C, a particular optimum value of C_3 which makes g a minimum when expression (71) is equated to zero and solved for g.

The capacity $C_2 + K_3$, in parallel with the quartz resonator, is always detrimental.

Curves II, IV and VI in Fig. 6 show the excess mean internal resistance, $r - r_0$, for various values of C.

When C is very small—it can never be zero, because it includes the inter-electrode capacity C_1 and the self-capacity of the coil L—there may or may not be oscillations, depending upon whether C is above or below the limiting value given by equation (73). When C is increased past this value, oscillations start at a very small amplitude, which increases slowly at first, then more rapidly, until it reaches a maximum. Past this point the amplitude decreases very rapidly, until a certain value of C is reached at which the oscillations stop suddenly. The capacity at cut-off is very near to the capacity for a maximum, especially if the damping terms, that is, the terms containing S, g_1, g_2, g_3, g_4 and R, are small.

(2) EXPERIMENTAL INVESTIGATION.

DESCRIPTION AND BEHAVIOUR OF THE QUARTZ DISC.

Only one piece of quartz was used throughout the experiments. It was a disc 4·85 cm in diameter and 0·752 cm thick. The electric axis was perpendicular to the plane of the disc, and the only mode of vibration studied was that which took place along the electric axis.

According to Hund's empirical formula, the frequency should have been equal to 287/0·752, or 382 kilocycles per sec.

The piece of quartz, however, gave two strong responses at frequencies of approximately 389 and 385 kilocycles per sec. respectively. Besides these, there were several weak responses at frequencies not very different from the above.

The response at 389 kilocycles per sec. was a little stronger than that at 385. When the quartz electrodes were connected to the grid and plate of the valve, oscillations were, in general, maintained only at 389 kilocycles per sec.; when the filament-to-grid connection was used, and the capacity in the oscillatory circuit was very small, no oscillations were maintained. As the capacity was gradually increased, oscillations started, and their amplitude gradually increased to a maximum; the frequency of these oscillations was approximately 389 kilocycles per sec. A further slight increase in the capacity would alter the circuit conditions, and the oscillations stopped. At this point the quartz started oscillating in the other mode and, as the capacity was further increased, the amplitude increased, and then decreased almost abruptly to zero at the value of capacity for which the circuit conditions for the maintenance of oscillations at 385 kilocycles per sec. were no longer fulfilled. The difference between the two limiting capacities was, of course, approximately equal to (2 × 4)/390, or 2 per cent of the total capacity.

Under certain conditions it was possible to obtain the two oscillations simultaneously: an audible note of approximately 4 000 cycles per sec. was then produced.

AIR-GAP AND ELECTRODES.

For the air-gap and electrodes use was made of an apparatus designed by Dr. Dye for the interferometric examination of vibrating quartz plates. The apparatus as used for the present purpose is shown in Fig. 7. The quartz disc Q rests by its own weight upon a brass electrode D, which, in turn, is supported upon three small steel balls (by hole, slot and plane location) upon the main base-plate B. The base-plate carries 3 well-fitted levelling screws S with ball ends and knurled ebonite heads. Each screw is fitted with a graduated circle C. The pitch of the screw is ½ mm, and the circumference of the circle is divided into 50 equal parts, of which a tenth part can be estimated without much difficulty. This is equivalent to 0·0001 cm. The position of the circle is read by means of the index I, fixed to the base-plate. The screws support a glass plate P, of which the lower surface is plane polished. To this lower surface are wrung 4 polished brass discs, 3 of which, H, rest directly on the screws; the fourth, L, constitutes the upper electrode; its diameter exceeds that of the quartz disc by 2 mm. To this disc is soldered

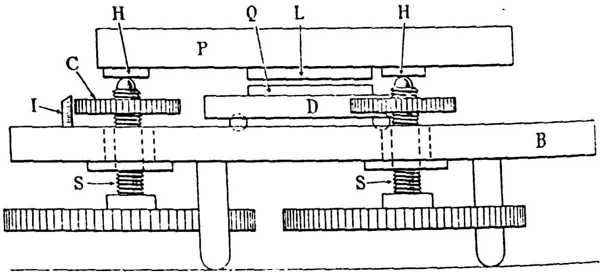

FIG. 7.

a thin copper wire which connects it to a terminal of the apparatus; the second terminal is in electrical connection with the base-plate. When the quartz is used as a resonator, the insulated terminal of the main condenser is connected to the disc, because the capacity to earth of the disc is much smaller than the capacity to earth of the base-plate. For the same reason the disc is always connected to the grid when the quartz is used with a valve.

In order to obtain the screw readings for zero air-gap, the discs H are connected together and to one terminal of a telephone. The base-plate is connected to the other terminal of the telephone through a source of alternating current of audible frequency. The 3 screws are lowered until the ball ends are out of contact with the discs H. The upper electrode L is then resting on the upper face of the quartz, and the air-gap is zero. Each of the screws is adjusted until the slightest further upward motion would bring them into contact with the discs H, and the position of the circles is noted. Contact is, of course, indicated by the telephone.

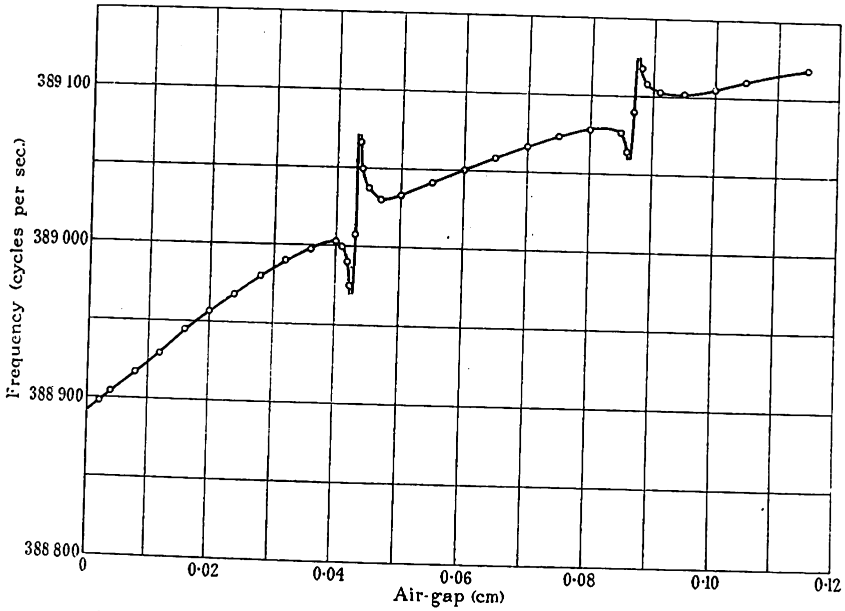

FIG. 8.—Response frequency of the resonator at various air-gaps.

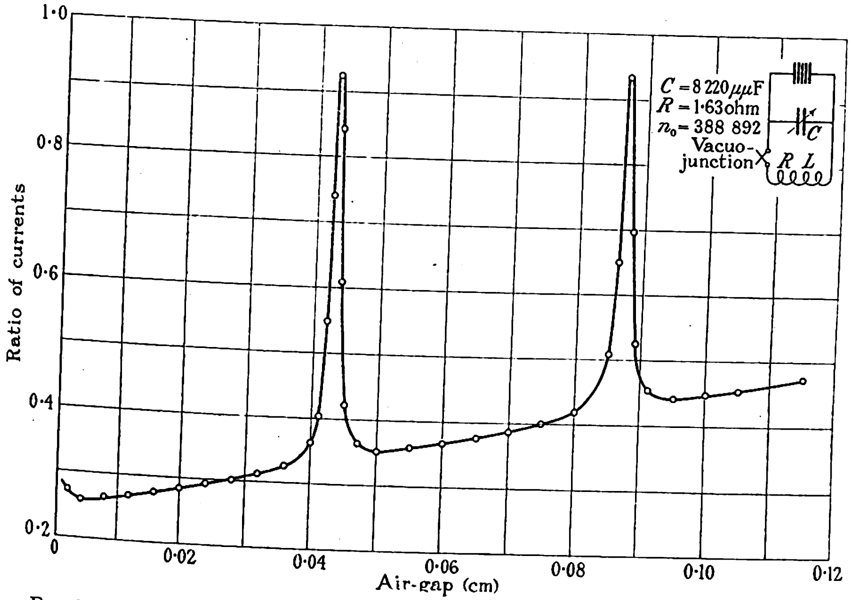

FIG. 9.—Ratio of minimum current to current when the quartz is not vibrating.

ELECTRICAL CONSTANTS OF THE QUARTZ.

The constants were measured by Dye's method. The quartz electrodes are connected to the terminals of the condenser of an oscillatory circuit, and the inductance coil of the circuit is loosely coupled to a source of alternating power at approximately the quartz frequency. The frequency is varied and the current in the oscillatory circuit is measured by means of a thermo-junction placed in series with the inductance coil. The reader who desires more information on this method should consult Dye's paper.*

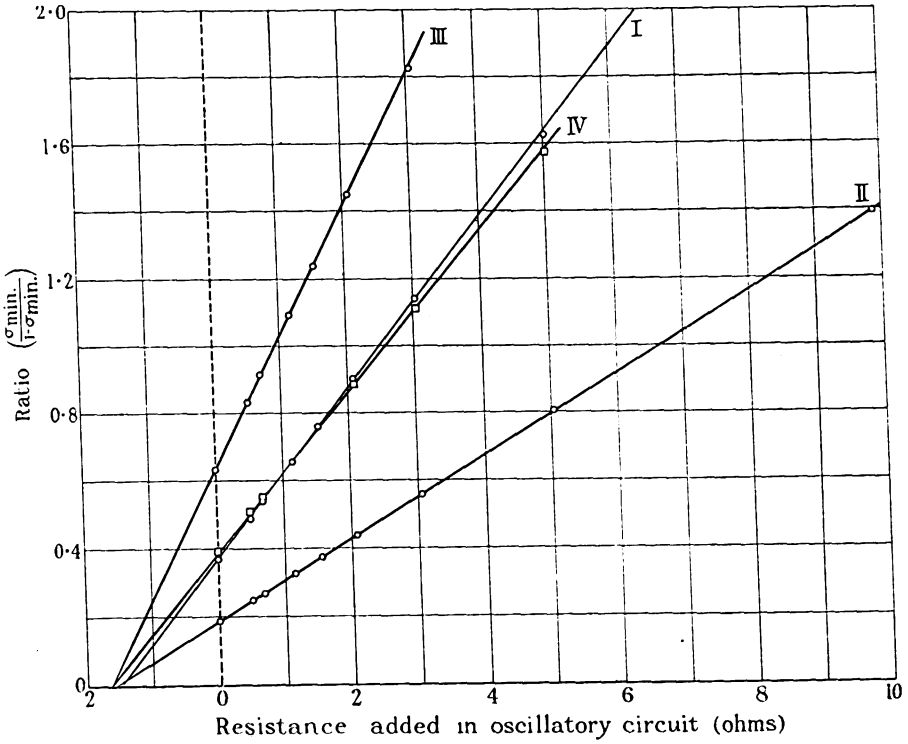

FIG. 10.—Determination of resistances of the circuits of the resonator.

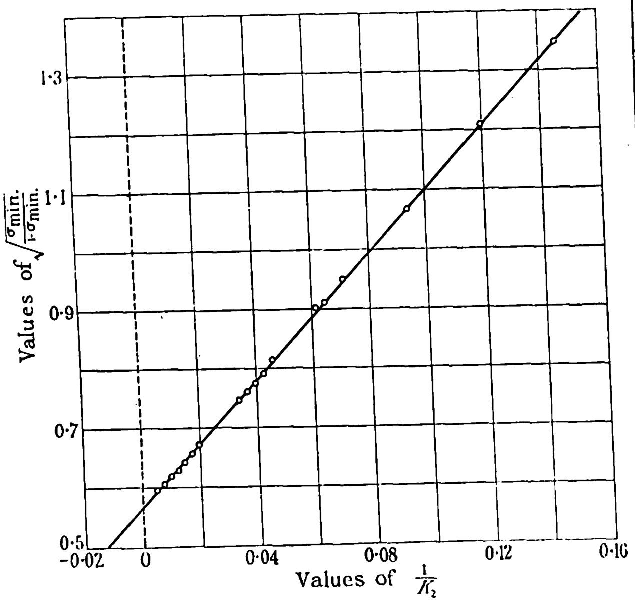

FIG. 11.—Determination of K_1, and of S, the damping of the resonator.

This method of analysis necessitates a variation of air-gap and a knowledge of the corresponding capacity K_2. This capacity is calculated by the formula $S/3\cdot6\,\pi g$ micro-microfarads, where S is the area of the surface of the quartz, and g the length of the air-gap in cm. With the dimensions given above, $K_2 = 1\cdot633/g$ micro-microfarads.

Fig. 8 shows the frequency for various air-gaps, and Fig. 9 the corresponding value of the minimum current in the inductance coil. The large increase of damping at air-gaps of 0·043 cm and 0·087 cm is due to the resonance of the air in the gap. The corresponding velocity of propagation of the waves is 34 200 cm per sec. The average room temperature was 16·5° C.

Fig. 10 gives the resistances of the two circuits used. The capacities of the two circuits were obtained by direct reading of the condensers. Fig. 11 gives $K_1 = 9\cdot6\ \mu\mu$F, and also the damping S of the quartz.

This damping S depends upon the mode of support of the quartz and upon the atmospheric conditions. It is therefore necessary to measure it anew whenever experiments are being carried out on the quartz. Once K_1 has been obtained, S can be calculated from a measurement of the minimum current for a single value of the air-gap K_2. The value of S varied between 350 and 500 ohms.

Resonance curves like Fig. 12 were obtained for four different air-gaps. They give the value of $f_2 = SK\omega$, and, since S can be obtained from the minimum σ as explained above, the value of K is found. This is equal to 0·018 $\mu\mu$F.

The graph of frequency against $1/(K_1 + K_2)$ should, according to the formulæ, be a straight line, and would give a means of checking the value of K. In practice, however, this graph is not a straight line, as Fig. 13 shows. This want of agreement occurs in all resonators, and deserves careful consideration. We cannot, however, dwell upon this point here, because we are mainly concerned with quartz oscillators.

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* See Reference (4).

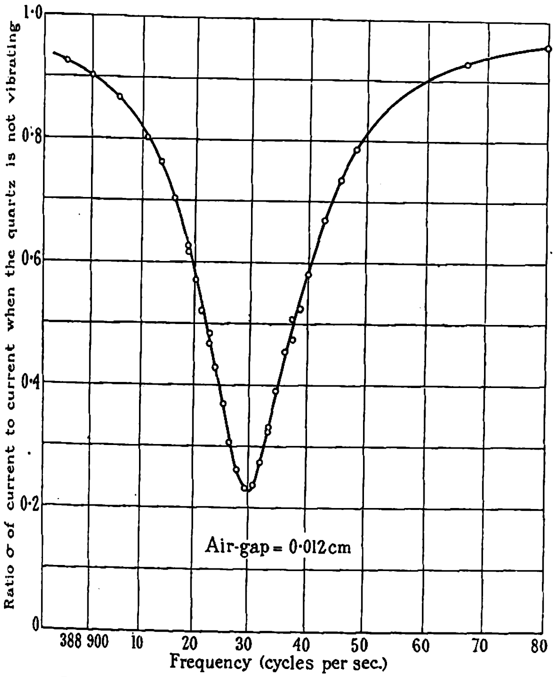

FIG. 12.—Resonance curve of the resonator.

The ratio of K_1 to K is 530, instead of the theoretical value 140. The value of K_1, calculated from a permittivity of 4·55, is 9·9, which does not differ much from the experimental figure 9·6 found above.

The investigation on the quartz used as an oscillator, in connection with a valve, was carried out for only one value of the air-gap, namely 0·012 cm. The corresponding value of K_2 is 136 $\mu\mu$F, and the value of (K_2/K_t) is 0·935.

The stray capacity K_3 between the two electrodes and their leads was deduced from measurements of the total capacity between the ends of those leads for various frequencies on each side of the resonance frequency. The value was 15 $\mu\mu$F.

The curve in Fig. 12 gives the response frequency of the resonator at an air-gap of 0·012 cm and a room temperature of 20·5° C. It is 388 930 cycles per sec. All the frequencies given in this paper have been reduced to the same room temperature, namely 20·5° C.

Fig. 8 also gives f_0, the response frequency for zero air-gap; it is 388 892 cycles per sec.

If the frequency at an air-gap of 0·012 cm were calculated from f_0 by the formula

$$f - f_0 = (f_0/2)\,(K/K_t)$$

the result would be 388 916 cycles per sec. instead of the experimental value given above, namely 388 930 cycles per sec.

An analysis similar to the above was also made for the response occurring at a frequency of approximately 385 kilocycles per sec., with a view to explaining why the quartz disc oscillated more readily at 389 than at 385 kilocycles per sec. The results of the two measurements are given in Table 2. The two values of S were obtained at a few minutes' interval, and are therefore

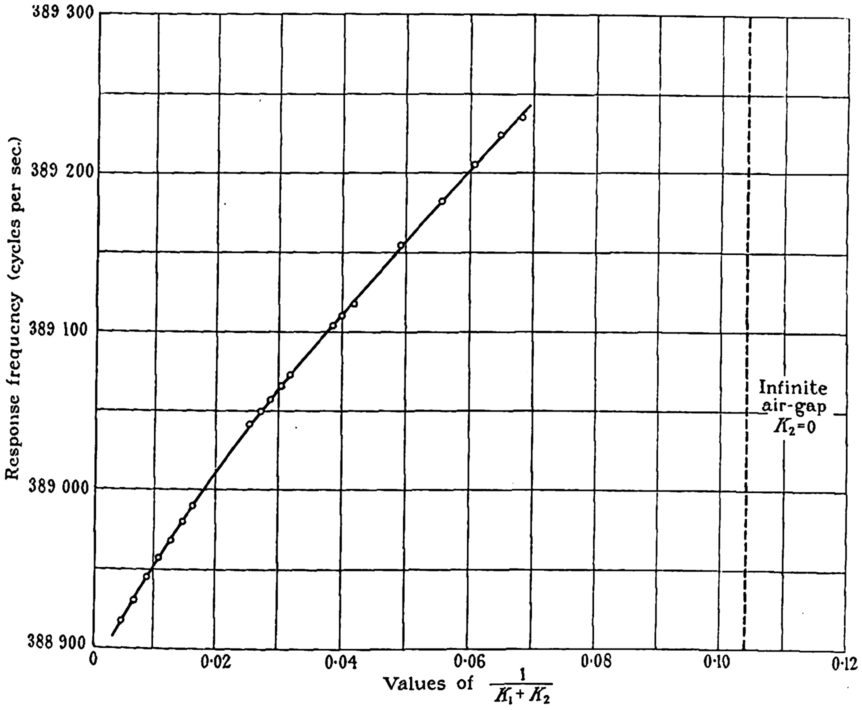

FIG. 13.—Relation between response frequency of the resonator and air-gap.

comparable. They would not be comparable if they had been obtained under different atmospheric conditions.

The reason why the quartz disc oscillates more readily at the higher frequency is now obvious from Table 2.

TABLE 2.

	First response	Second response
K_1 ($\mu\mu$F)	9·6	9·4
K ($\mu\mu$F)	0·018	$0{\cdot}013_3$
S (ohms)	400	540
f_0 (cycles per sec.) ..	388 890	385 210
Logarithmic decrement ..	55×10^{-6}	55×10^{-6}

The logarithmic decrement is approximately the same in both cases, but its constituent parts are different. In one case S is small and K is large; this is equivalent to saying that the damping is small and that a relatively large proportion of the quartz takes part in the vibration. For the second response, S is rather larger, and K is smaller. The damping is therefore larger, and the vibrations take place over a smaller portion of the face of the disc. Alternatively, a small K might indicate that the vibrations in certain parts of the disc are opposite in phase to the vibrations in other parts.

VALVES.

For most of the tests a D.E.R. valve was used. The values of g and m, which occur in the equation $i = g(v + me)$, were determined from the characteristics. They are given in Table 3.

TABLE 3.

D.E.R. Valve No. 3343.

Plate current	Plate conductance g
mA	mho × 10^{-6}
0·5	27
1·0	31
2·0	40
3·0	41·7

Amplification factor $m = 8{\cdot}6$

The tests on the quartz oscillator were made with 100 volts between the plate and the filament, and 2 volts on the filament. Under those conditions the plate current was 3 mA when the grid was kept at filament potential by means of a grid leak or in any other way.

In some cases a D.E.P. 610 valve was used for comparison with the D.E.R. valve. The filament voltage was 6·4 and the plate voltage 100. The amplification factor m was approximately 8, and the conductance g was as given in Table 4. With the grid at filament potential, the plate current was 15mA for a plate voltage of 100.

Inter-electrode Conductances and Capacities of the D.E.R. Valve.—The inter-electrode capacities and conductances of the valve are represented diagrammatically by Fig. 14. The three pairs of quantities were measured on the Schering radio-frequency bridge by a method analogous to that described two years ago by Hartshorn.* There were slight modifications because the radio-frequency bridge and the bridge used by Hartshorn are not identical. The results obtained are given in Table 5. The measurements were taken with the filament hot, and do not differ much from the results obtained with the filament cold.

TABLE 4.

Valve D.E.P. 610.

Plate current	Plate conductance g
mA	mho × 10^{-6}
5	290
10	260
15	200

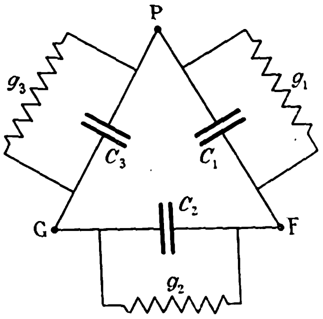

FIG. 14.

TABLE 5.

D.E.R. Valve.

$\mu\mu$F	mho × 10^{-6}
$C_1 = 4{\cdot}0$	$g_1 = 0{\cdot}2$
$C_2 = 6{\cdot}4$	$g_2 = 0{\cdot}5$
$C_3 = 2{\cdot}4$	$g_3 = 0{\cdot}05$

The relatively large capacity between grid and filament is due to the extra terminals between which the grid leak is inserted. The capacities are accurate to within 0·2 $\mu\mu$F, but the accuracy of the conductance figures is much less; it is probably 30 per cent, and might be as low as 50 per cent. To obtain accurate values, the valve should have been screened.

GRID RESISTANCES.

The grid resistances used were Loewe high-vacuum resistances, type FZ 128, which are platinized glass rods enclosed *in vacuo*.

The resistances were measured on a Wheatstone bridge and also on the Schering radio-frequency bridge, at a frequency of approximately 400 000 cycles per sec.

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* See Reference (7).

The results are given in Table 6.

For the radio-frequency measurements it was assumed that the grid resistances were equivalent to a pure resistance in parallel with a pure capacity. In the radio-frequency measurements the amplitude of the alternating voltage applied to the resistances was 4 volts; measurements were also taken with an amplitude of 10 volts on the 1-megohm grid leak, and no difference could be detected.

TABLE 6.

Loewe Grid Resistances.

Nominal resistance	Conductance		Parallel capacity at 400 000 cycles per sec.
	To direct current	At 400 000 cycles per sec.	
megohms	mho × 10^{-6}	mho × 10^{-6}	μμF
3	0·34	0·36	0·1
2	0·43	0·45	0·2
1	0·87	0·8	0·1
0·5	1·78	1·7	0·1
0·25	4·4	4·5	0·2
0·1	11·1	11·2	0·2
0·075	11·9	12	0·2
0·05	17·0	17	0·3

The accuracy of the radio-frequency measurements is well within 5 per cent.

OSCILLATORY CIRCUITS.

The circuit used during the greater part of the investigation had an inductance of 160 μH, a self-capacity of 20 μμF and a total resistance of 2·08 ohms. In series with the condenser was a vacuo-junction of resistance 1·12 ohms, so that the resistance of the coil, leads and condenser was approximately 0·96 ohm.

In some of the experiments another circuit was used. Its inductance was 325 μH and its self-capacity 25 μμF. The total resistance was 4·3 ohms, 1·1 ohms being due to the vacuo-junction and 3·2 ohms to the coil, leads and condenser. The inductances were measured in each case by the capacity-variation method at frequencies in the neighbourhood of 400 000 cycles per sec., and the accuracy is probably better than 0·5 per cent.

With the D.E.P. 610 valve the currents in the condenser were large, and a thermo-junction with constantan heater was used instead of the vacuo-junction. The heater resistance was 0·61 ohm both on direct current and at a frequency of 390 000 cycles per sec. The total resistances of the two circuits were then 1·57 ohms and 3·8 ohms respectively.

Throughout the paper the term "total capacity in the oscillatory circuit" includes the self-capacity of the circuit and the parallel inter-electrode capacity C_1 between the plate and the filament.

Complete Circuits.—The circuits used are shown in Figs. 15 and 16. The telephones had a total resistance of 300 ohms to direct current, and a by-pass condenser of 0·02 μF was connected between the filament and the screen of the condenser of the oscillatory circuit. Resistance could be added at B in the oscillatory circuit.

Measurement of Alternating Voltage across the Condenser.—The heater of the thermo-junction was in series with the condenser, and not in series with the coil, because the plate current also flows through the coil and would vitiate the readings. The R.M.S. voltage across the coil is then given by the well-known formula $V = I/(C\omega)$; the current I is itself obtained from the reading of the galvanometer. Each thermo-junction was calibrated at the outset of the investigation, and the heater current was found to be proportional to the galvanometer deflection, as read on a square-law scale. The galvanometer is a moving-coil instrument and the scale is at a distance of 150 cm from the mirror.

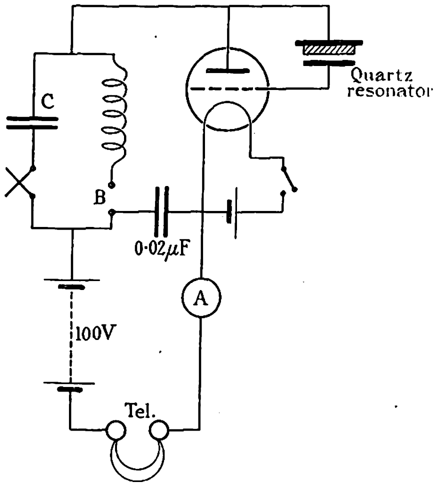


FIG. 15.—Plate-to-grid connection.

The instrument repeats with an accuracy of about 0·2 per cent, but the absolute value of the voltage across the condenser is only known to the accuracy of the standard milliammeter used in the calibration of the thermo-junctions. This was about 0·5 per cent. It is clear that a high degree of accuracy in the absolute value is not necessary in the present case.

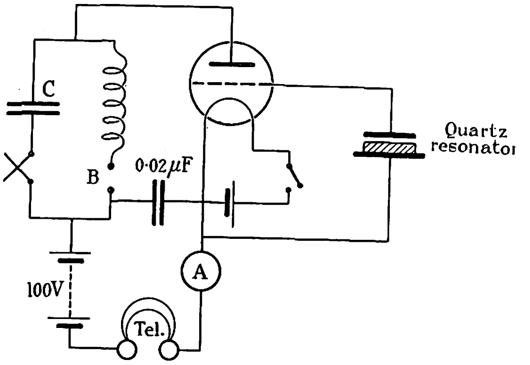


FIG. 16.—Filament-to-grid connection.

Measurement of Frequency.—The inductance coil of the quartz oscillator was very loosely coupled to the grid coil of a sensitive tuned-anode amplifier. The output coil of an auxiliary valve-oscillator was also made to induce in the amplifier coil, but was given by trial a position such that its coupling to the inductance coil of the quartz oscillator was as small as possible. The auxiliary generator was provided with variable condensers which ensured smooth and continuous variation of frequency. One of the condensers gave a variation of 2·65 cycles per sec. for 1 $\mu\mu$F, and it was a simple matter to read to within 0·1 $\mu\mu$F.

The oscillations from the quartz oscillator and the oscillations of approximately the same frequency from the auxiliary generator are received and amplified by the first two stages of the tuned-anode amplifier; if the two radio frequencies are nearly equal, an audible beat tone is produced which is amplified in the last two stages of the amplifier and reproduced by the loudspeaker.

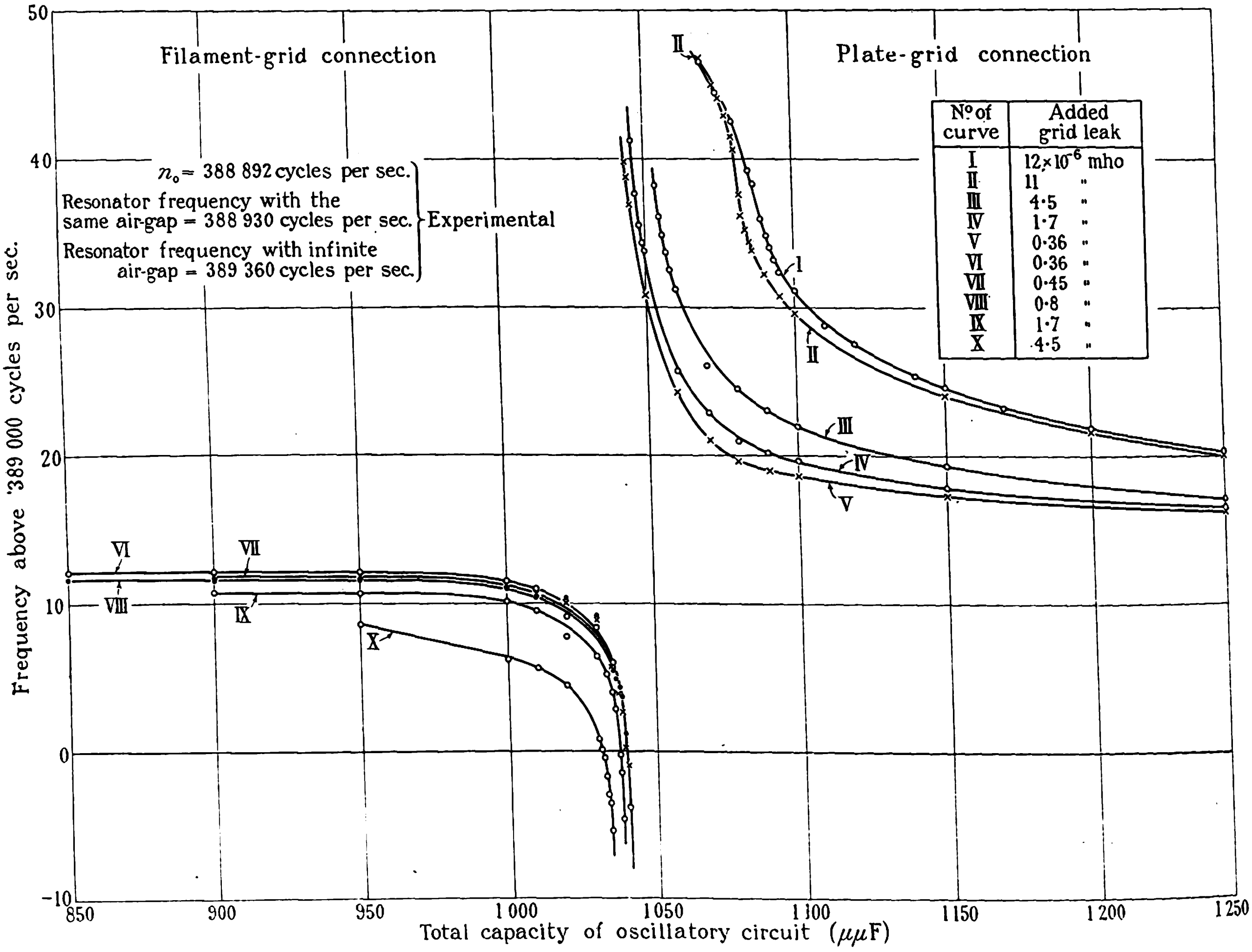
In order to compare the two radio frequencies, the condenser of the auxiliary generator is varied until the frequency of the beat tone coincides with the frequency of a tuning-fork. In the present case a tuning-fork of 1 000 cycles per sec. was used.

When the frequency of the quartz oscillator is varied by an alteration in one or more of the constants of its circuit the frequency of the beat tone alters, and the reading of the condenser of the auxiliary generator must be altered to restore coincidence between the beat-tone frequency and the tuning-fork frequency. Variations in the frequency of the quartz oscillator can thus be estimated from the readings of the condenser of the auxiliary generator.

This condenser is calibrated by taking readings corresponding to beat tones of various frequencies, the frequencies being those of known tuning-forks.

The absolute frequency is given by the multi-vibrator wavemeter. This instrument induces known frequencies, multiples of 20 000, in the tuned-anode amplifier. Any one of those frequencies can be reinforced at will by tuning the grid circuit of the amplifier. The condenser of the auxiliary generator is adjusted until its frequency coincides with the multi-vibrator frequency. Equality is indicated by a characteristic beat. Other characteristic beats indicate equality between the auxiliary generator frequency and multiples of 1 000, and also multiples of still smaller numbers. In the present case it was quite easy to obtain calibration points 500 cycles per sec. apart.

The variations in frequency due to variations in the



Nº of curve	Added grid leak
I	12×10^{-6} mho
II	11 "
III	4·5 "
IV	1·7 "
V	0·36 "
VI	0·36 "
VII	0·45 "
VIII	0·8 "
IX	1·7 "
X	4·5 "

FIG. 17.—Relation between the frequency and capacity of the oscillatory circuit for various grid leaks.

Valve: D.E.R. H.T. voltage = 100; L.T. voltage = 2; R = 2·1 ohms; L = 160 μH; air-gap = 0·012 cm.

temperature of the quartz are much larger than many of the variations that we are concerned with here. It was found, moreover, that the temperature of the quartz was a function of the amplitude of its vibrations. Such effects were allowed for by returning to a standard state between successive readings. In parallel with the calibrated condenser A of the auxiliary generator was a small condenser B by which any frequency drift could be corrected. The following example will illustrate the mode of procedure: Suppose it is desired to obtain a relation between the frequency of the quartz oscillator and the reading C of the condenser in the oscillatory circuit. Condenser C is set at a standard value C and condenser A at a standard value A. The other condensers of the auxiliary generator are varied until the beat tone is, say, 1 000 cycles per sec. Condenser C is moved to a value C_1 and A is altered until the beat tone is again 1 000, to A_1, say, giving the frequency difference looked for. Condensers A and C are then brought back to A and C, and the beat tone should then be 1 000. If there has been a small drift, it is taken on B, and the whole process is repeated for other values C_2, C_3, etc., of the condenser C. Variations of the quartz circuit are measured in the same way, and the complete set of results afterwards correlated. Only a single measurement of the absolute frequency is therefore necessary. In practice several were taken to serve as checks.

Relation between Frequency and Total Capacity in the Oscillatory Circuit.—A set of curves, reproduced in Fig. 17, was obtained by the method described in the previous Section. Simultaneous readings of the condenser of the auxiliary generator, of the deflection of the galvanometer spot and of the milliammeter in the plate circuit, were taken, and, for correcting drifts, readings were frequently taken for one and the same setting of the condenser in the quartz circuit. Curves were obtained with grid leaks of widely different values; the actual figures are given in the table in Fig. 17.

The capacity in Fig. 17 is the total capacity C, obtained by adding to the condenser reading 20 $\mu\mu$F for the self-capacity of the oscillatory circuit, 4 $\mu\mu$F for the inter-electrode plate-to-filament capacity C_1 and 6 $\mu\mu$F for the stray capacity between the plate lead and the leads of the by-pass condenser.

The shape of the curves confirm in a general way the conclusions arrived at by theoretical considerations on pages 270 and 275; namely, that

(i) With the resonator connected between the plate and the grid:

- (*a*) The frequency increases when C decreases;
- (*b*) The rate of variation increases as C decreases;
- (*c*) The greater the conductance of the grid leak, the higher the frequency; and
- (*d*) The rate of variation of frequency for a given value of C is greater with large grid conductances than it is with small grid conductances.

(ii) When the resonator is connected between the grid and the filament:

- (*a*) The frequency decreases when C increases;
- (*b*) The rate of variation of frequency increases as C increases;
- (*c*) The greater the conductance of the grid leak, the lower the frequency; and
- (*d*) The rate of variation of frequency for a given value of C is greater with large grid conductances than it is with small grid conductances.

The curves obtained when there was no added grid resistance do not fit in well with the others. The reason is that when no grid leak was used, simultaneous oscillations were produced at two different frequencies, as described on page 276, even with the plate-to-grid type of connection. It is quite conceivable that the mode of vibration under investigation, giving the frequency of approximately 389 kilocycles per sec., would be affected by the other, of frequency approximately 385 kilocycles per sec.

When the resonator is connected between the grid and the plate, the frequency without a grid leak should be slightly lower than the frequency with a grid leak. In the present case, however, it was found to be 0·9 cycle per sec. higher than with a grid leak of 3 megohms.

Another reason why it is better to consider only those curves obtained with grid leaks is that the added grid conductance, even though small, fixes the grid potential. With the D.E.R. valve used, the plate current was only 2·7 mA when there was no grid leak and when no oscillations were being maintained; with a grid leak, the corresponding value was 3·0 mA.

The next step is to calculate the frequency at various condenser readings and to compare the results with the curves of Fig. 17. This has been done for both types of connection for the case when the added grid conductance was $0{\cdot}36 \times 10^{-6}$ mho.

Consider first the plate-to-grid type of connection. The general procedure is to select particular values of α between the limits $\alpha = 1$ and $\alpha = 1{\cdot}301$, and to calculate β from equation (35) and then C from equation (45). The frequency is given by $f = f_0(\frac{1}{2} + \frac{1}{2}\beta)$.

The computation is, however, greatly simplified by making use of the fact that, as α varies between its limits 1 and 1·3, as given by equation (46), β only varies between the values $1 + (6 \times 10^{-4})$ and $1 + (7 \times 10^{-4})$. Regarding first β as constant and equal to the latter value, the frequency is calculated from equation (44) or (47).

The circuit variables were as follows:—

$C_2 = 6{\cdot}4\ \mu\mu\text{F}$
$C_3 = 2{\cdot}4\ \mu\mu\text{F}$
$K_3 = 15\ \mu\mu\text{F}$
$C_5 = 24\ \mu\mu\text{F}$
$\omega_0 = 2{\cdot}442 \times 10^6$ per sec.
$R = 2{\cdot}1$ ohms
$L = 160\ \mu\text{H}$

The value of C_0 is also required; it is calculated from L and ω_0 and found to be 1 047 $\mu\mu$F, It would be found that, with this value of C_0 and the values of C as read on the curves of Fig. 17, the calculated frequency curves would be 4 $\mu\mu$F to the right of the experimental curves. It is therefore necessary to alter C_0 slightly, so as to obtain agreement. An approximate formula for C_0 in terms of the experimental points of cut-off, C' and C'', is

$$(C_0/\beta) = \tfrac{1}{2}(C' + C'') + \tfrac{1}{2}C_3$$

The experimental cut-offs of the two curves under consideration are 1 043 and 1 040 $\mu\mu$F, and C_0, as calculated from the approximate formula, is 1 043 $\mu\mu$F. We shall, for convenience, adopt this value throughout the paper.

There is not much to choose between the two determinations of C_0. In the first case, the inductance L of the oscillatory circuit is required; it is not known, however, to much better than 5 parts in 1 000. In the second case, the final experimental figures for C' and C'' demand the estimation of the stray capacity between the leads connecting the plate and the filament to the condenser terminals. This stray capacity was taken as 6 $\mu\mu$F, which is perhaps under-estimated. Perfect agreement would be obtained by making it 10 $\mu\mu$F. The alternative, which has been adopted here for convenience, is to suppose L slightly larger, namely, 160·6 μH; and C_0 correspondingly smaller, namely, 1 043 $\mu\mu$F instead of 1 047 $\mu\mu$F.

TABLE 7.

Resonator Connected between Plate and Grid.

C	$a-1$	$f=389\,000+$	f (adjusted to fit the experimental value for large values of C) $= 389\,000 +$
1	2	3	4
1 250	0·008	9·4	16·4
1 150	0·015	10	17
1 100	0·027	10·6	17·6
1 070	0·053	12·5	19·5
1 050	0·142	18	25
1 047	0·189	21	28
1 045	0·243	24	31
1 044	0·283	27	34

Calculations have been performed using the values already adopted for the various constants, and the results are given in Table 7. Col. 3 gives the calculated frequency. This frequency is, for large values of the capacity, say 1 150 $\mu\mu$F, approximately 7 cycles per sec. below the experimental value. This constitutes an error of about 6 per cent in the value of $f - f_0$. Greater accuracy cannot, however, be expected, since repeated experimental work has proved that, even in the simpler case of a quartz resonator, the formula

$$f = f_0\left\{1 + \tfrac{1}{2}(K/K_t)\right\}$$

does not account for the change of frequency which actually accompanies a change in air-gap.

The values in col. 4 of Table 7 were obtained by adding 7 to the figures in col. 3; this is equivalent to making the theoretical curve fit the experimental curve for large values of C, that is, for points where the rate of change of frequency with respect to C is small. A fair test of the theory is then to see how far the theoretical curve fits the experimental curve at the other points, in particular at points where the rate of variation of frequency is large. The two curves are shown in Fig. 18; the theoretical curve bends more sharply than the experimental curve. If the value of C_2 were made slightly larger than 6·4 $\mu\mu$F the two curves could be made to fit everywhere. In fact, the effective value of C_2 is larger than 6·4, because the grid leak introduces from 0·1 to 0·2 $\mu\mu$F, and there must be some capacity between the filament lead and the lead joining the resonator to the grid of the valve.

TABLE 8.

Resonator Connected between Grid and Filament.

C	$1-a$	$f = 389\,000 +$	f (adjusted to fit the experimental value for small C) $= 389\,000 +$
850	0·0014	8·8	12·1
950	0·0029	8·6	11·9
1 000	0·0065	8·4	11·7
1 020	0·013	8·0	11·3
1 030	0·025	7·1	10·4
1 035	0·049	5·5	8·8
1 038	0·113	1·0	4·3
1 039	0·200	− 5·5	− 2·2
1 039·5	0·325	− 15	− 12

Similar calculations were performed for the grid-to-filament type of connection, and the calculations are given in Table 8.

TABLE 9.

Resonator Connected between Grid and Filament.

C	$1-a$	$f = 389\,000 +$	f (adjusted to fit the experimental value for small C) $= 389\,000 +$
850	0·003	8·7	12·1
950	0·006	8·5	11·9
1 000	0·014	8	11·4
1 020	0·027	7	10·4
1 030	0·052	5·2	8·6
1 035	0·095	2·3	5·7
1 038	0·190	− 1·0	− 2·4
1 039	0·285	− 12	− 9

The value of C_3 was taken as 2·5 $\mu\mu$F as measured on the Schering bridge. The theoretical curve and the experimental curve are shown in Fig. 18. Here, again, the theoretical curve has a sharper bend than the experimental curve. The points marked on or near the experimental curve were calculated for a value of C_3

equal to $3 \cdot 7\ \mu\mu$F, and a value of C_0 equal to $1\,044 \cdot 6$; the values are given in Table 9.

It is thus seen that a larger value of C_3, accompanied by a slight adjustment of C_0, brings the theoretical and experimental values into almost complete agreement. The small adjustment in C_0 is necessary to make the capacity C, at which the oscillations cease, equal in both cases. The alteration of C_3 is in the right direction because, in addition to the capacity between grid and plate, measured on the bridge, there is some capacity between the lead connecting the plate to the condenser, and the lead connecting the grid to the resonator. This may well have been $1\ \mu\mu$F.

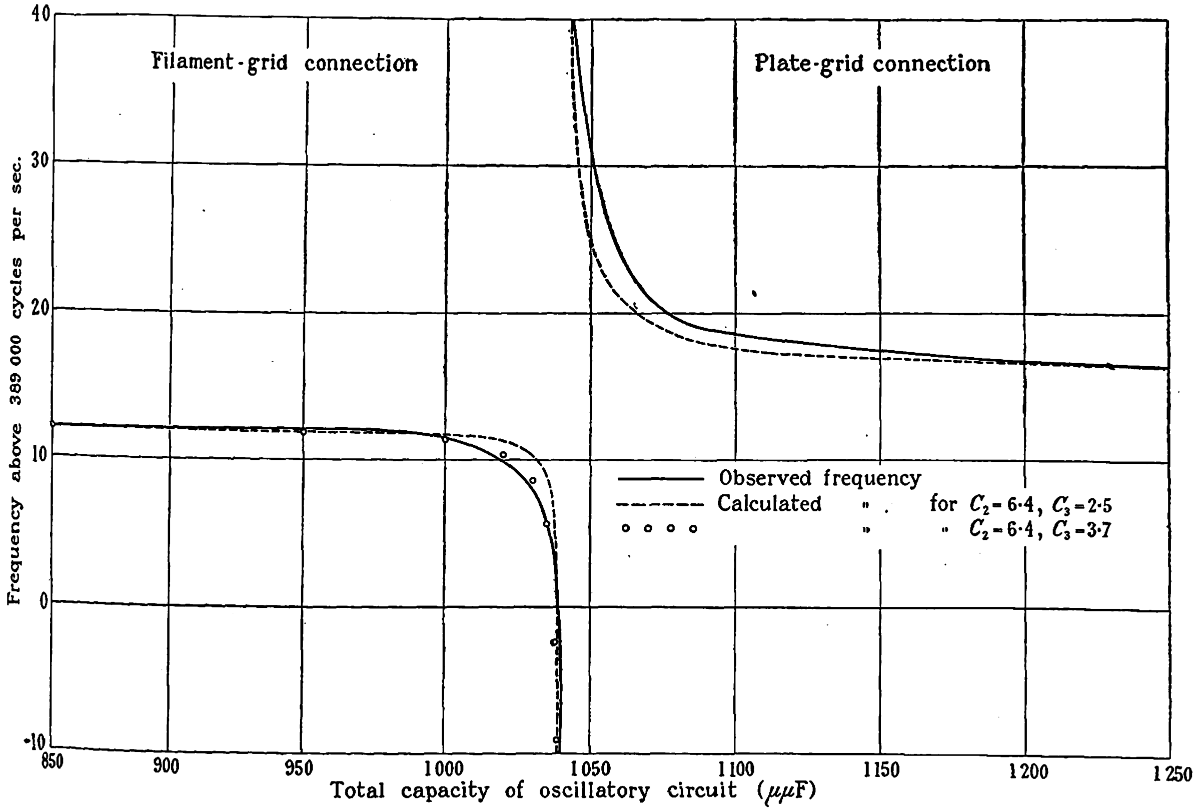


FIG. 18.—Comparison between calculated and observed frequencies for various capacities.

Valve: D.E.R. $L = 160\ \mu$H; $R = 2 \cdot 1$ ohms; grid leak $= 0 \cdot 36 \times 10^{-6}$ mho.

The frequency for large values of C in the plate-to-grid type of connection, and the frequency for small values of C in the grid-to-filament type of connection, should be almost equal to each other, and should be independent of the grid leaks. The asymptotic frequency is given by equation (49). Fig. 17 shows, however, that the asymptotic value varies by one or two cycles when the grid conductance is increased from $0 \cdot 4 \times 10^{-6}$ mho to 10 or 12×10^{-6} mho. This variation may be accounted for by the small capacity introduced by the grid leaks.

When it is desired to change from one type of connection to the other, the resonator lead is disconnected, say, from the plate, and connected to the filament; the other resonator lead is left permanently connected to the grid. In this process of changing over, the capacity between the two resonator leads may be altered by a considerable amount, say $1\ \mu\mu$F. This alters the value of K_3 and therefore of C_5. Suppose in one case C_5 was $24\ \mu\mu$F and in the other case $23\ \mu\mu$F. The corresponding difference in frequency, obtained from equation (49), is just 3 cycles per sec., which is about equal to the difference found experimentally.

Curves I and II, Fig. 17, exhibit a decrease of $|df/dC|$ with decreasing values of C in the neighbourhood of the cut-off point. This decrease is not in accordance with the approximate formulæ worked out in the paper; it is nevertheless a real effect, and not an experimental error. The reason why it is apparent with large grid conductances and not with small ones may be due to the fact that the range of capacity over which this effect occurs becomes smaller and smaller as the grid conductance is decreased.

This divergence between predicted results and experimental results might be due to the variation of the valve plate conductance g with plate current. The decrease in conductance g would tend to reduce the increase in α, as can be seen from equation (37). It is quite as possible, however, that the cause lies in the approximations made when establishing the formulæ.

Relation between Frequency and Inter-electrode Capacities.—It has been shown on pages 000 and 000 that the frequency decreased with C_2 and that the modulus $|dn/dC_2|$ of the rate of change also decreased with C_2

for both types of connection. It has also been shown that the frequency decreases with C_3 for both types of connection.

In order to confirm this prediction, a small-variable condenser, of capacity 4 to 24 $\mu\mu$F, was placed in parallel with either C_2 or C_3, and the frequency was measured for various settings of that condenser.

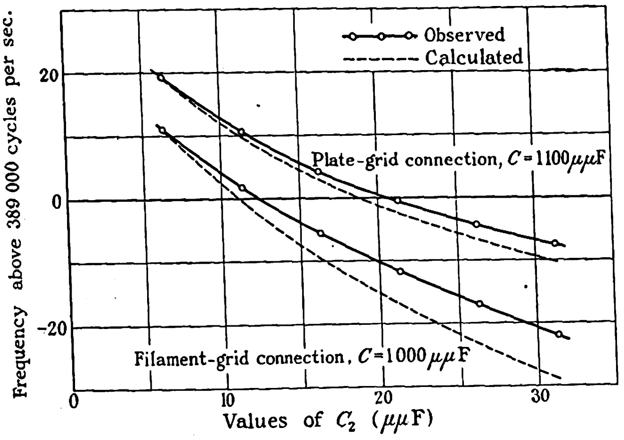


FIG. 19.—Relation between frequency and filament-grid capacity C_2.

Valve: D.E.R. $L = 160\ \mu$H; $R = 2{\cdot}1$ ohms; grid leak $= 0{\cdot}8 \times 10^{-6}$ mho; $C_3 = 2{\cdot}4\ \mu\mu$F.

The experimental curves are shown in Figs. 19 and 20, and their shape confirms the theoretical conclusions. The theoretical curves were made to fit the experimental curves at one point only, namely, the point for which $C_2 = 6{\cdot}4$ and $C_3 = 2{\cdot}4$.

The theory is thus being tested for frequency differences from a point on the curve, not for frequencies above f_0. The reason for this has already been given on page 271.

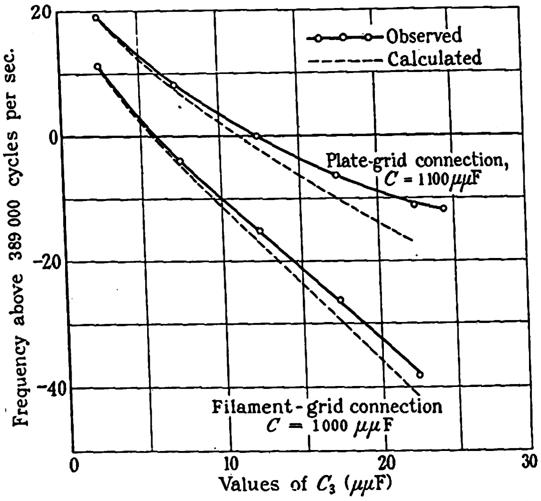


FIG. 20.—Relation between frequency and plate-grid capacity C_3.

Valve: D.E.R. $L = 160\ \mu$H; $R = 2{\cdot}1$ ohms; grid leak $= 0{\cdot}8 \times 10^{-6}$ mho; $C_2 = 6{\cdot}4\ \mu\mu$F.

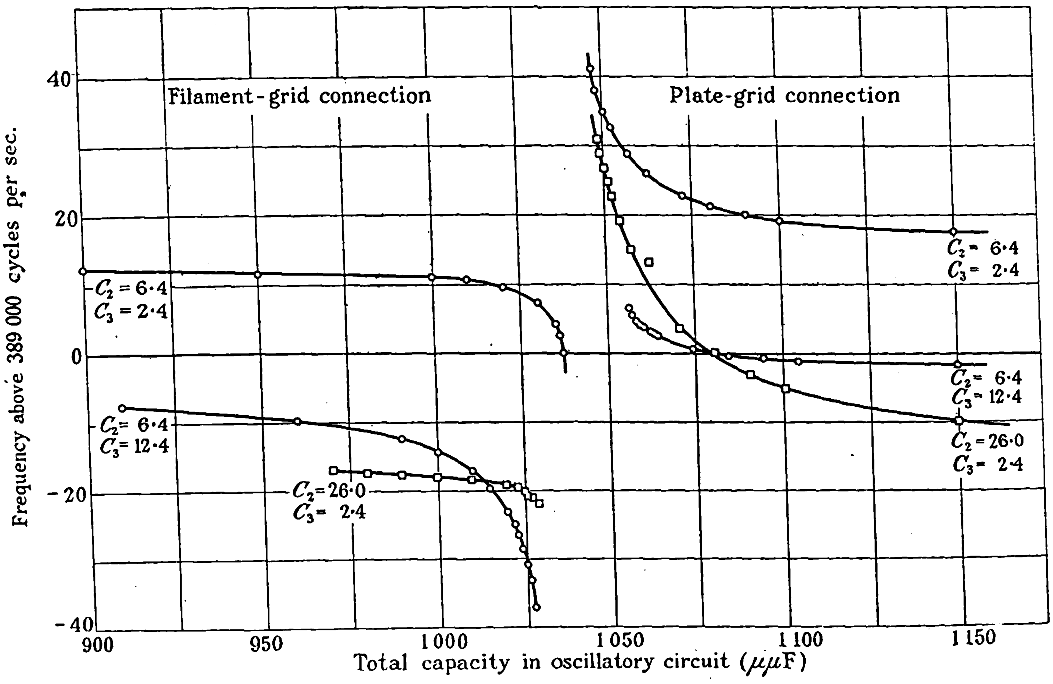


FIG. 21.—Relation between frequency and inter-electrode capacities.

Valve: D.E.R. $L = 160\ \mu$H; $R = 2{\cdot}1$ ohms; grid leak $= 0{\cdot}8 \times 10^{-6}$ mho.

Equations (47) and (70) were used to calculate Δf, so that the effect of the resistance R and the inter-electrode conductances on the frequency differences were neglected. The values taken for C_2, C_3 and K_3 were obtained by separate measurements, entirely independent of the experiments on the oscillator. The theoretica curves could be made to fit the experimental curves much more nearly by slightly altering those values, but it has not been deemed necessary to do this here.

Fig. 21 shows the frequency variations with respect to C for various values of C_2 and C_3. The shape of the curves agrees with the deductions made on theoretical grounds.

As an example, consider the plate-to-grid type of connection, for which df/dC is given by equation (48). It is always negative and increases numerically with C_2. Hence, for given values of C_3 and K_3, the slope of the curve is greater when C_2 is large than it is when C_2 is small. This point is well borne out by the experimental curves.

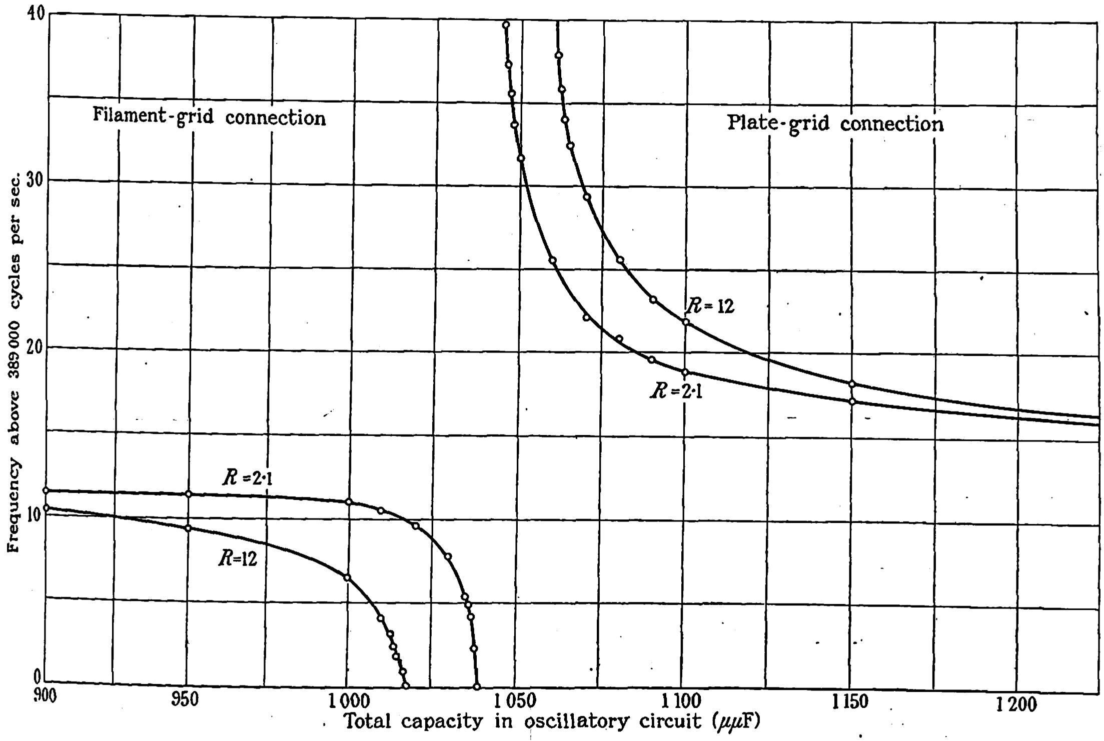


FIG. 22.—Relation between frequency and resistance of oscillatory circuit.
Valve: D.E.R. $L = 160\ \mu$H; grid leak $= 0{\cdot}8 \times 10^{-6}$ mho.

Relation between Frequency and Resistance of the Oscillatory Circuit.—Curves of frequency against total capacity C were taken for various values of the resistance R of the oscillatory circuit. In order to alter the resistance of that circuit, the link closing the circuit was replaced by non-inductive resistances. The resistances were originally made for the measurement of the effective resistance of circuits at radio frequencies by the resistance-variation method, and their effect on the inductance and on the capacity of the circuit is known to be negligible.

The curves obtained are shown in Fig. 22. The variations are in the direction predicted on page 271, and when the oscillatory circuit is considerably out of tune the frequency is practically independent of the resistance. The actual variations in frequency are, however, larger than the figures to be expected from equations (37) and (68). These formulæ give α in terms of R, other things being the same, and the frequency is calculated by the formula

$$f = f_0 + \frac{1}{2} f_0 \frac{K}{K_t} \frac{\alpha K_2 + C_5}{\alpha (K_1 K_2 / K_t) + C_5}.$$

For any given value of the total capacity C, the amplitude of oscillations decreases considerably with R; it is to be expected that the effective anode conductance g alters considerably in the process. Even then the formula could not account for the large variations of frequency taking place.

As an example, with $g_2 = 0{\cdot}5 \times 10^{-6}$, $g_3 = 0{\cdot}05 \times 10^{-6}$, $g_4 = 0{\cdot}8 \times 10^{-6}$, and $g = 25 \times 10^{-6}$, when R increases from 2 to 12 ohms, the frequency for $C = 1\,100\ \mu\mu$F increases by 0·7 cycle per sec., according to the formula. If at the same time g is supposed to have increased from 25×10^{-6} to 40×10^{-6}, the total calculated increase in frequency is 1 cycle per sec.

The experimental figure is 3 cycles per sec. Part of the difference may, of course, be due to the uncertainty in the values of the inter-electrode conductances g_2 and g_3.

It must be remembered that equation (37) for α is only an approximation, which supposes that $HE - GF = 0$. This is equivalent to writing $\beta_2 = 0$ [see equations (29) and (36)]. But when a constant amplitude is being maintained, we have, from equation (19), $\beta_2 + SK = 0$. The same expression also shows that, near the cut-off point, the terms H, W and F become important, especially when R is large. The error in the approximation is then larger.

Relation between Amplitude of Oscillations and Capacity *of Oscillatory Circuit.*—A number of curves were obtained for various values of added grid-to-filament conductance, ranging between zero and 12×10^{-6} mho. These are all reproduced in Fig. 23.

The shape of the curves is analogous to that which was predicted from theoretical considerations. The amplitude is small when the oscillatory circuit is considerably out of tune. As the capacity C is varied towards C_0, the amplitude increases more and more rapidly and reaches a maximum at a value of C which is not very different from C_0. From this maximum it decreases very rapidly and then drops suddenly to zero. The value of C at cut-off is very close to the value of C for maximum amplitude.

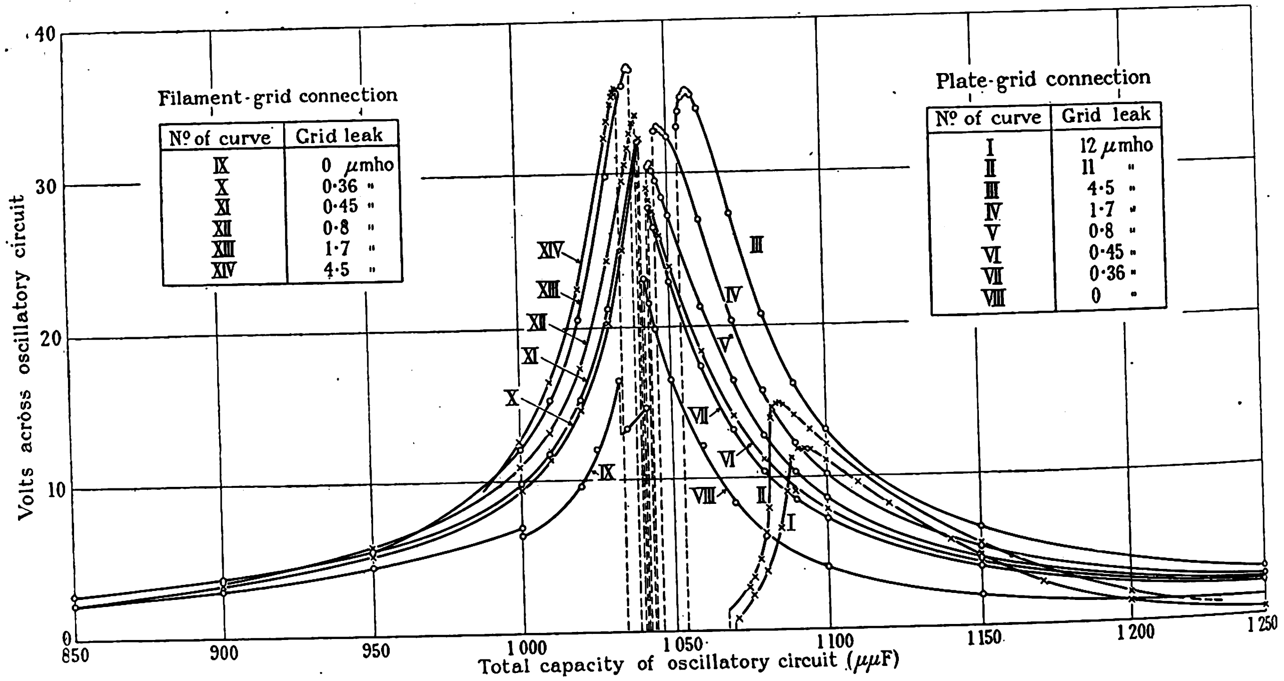


FIG. 23.—Relation between amplitude and capacity of oscillatory circuit.

Valve: D.E.R. $L = 160\ \mu$H; $R = 2 \cdot 1$ ohms.

It is seen from the curves that the largest maximum amplitude is given in one case by an added grid conductance of $4 \cdot 5 \times 10^{-6}$ mho, and in the other case by an added grid conductance of $1 \cdot 7 \times 10^{-6}$ mho. The formulæ developed do not explain this; on the contrary, the theoretical curves (Fig. 6) indicate that an increase in the grid conductance g_4 is accompanied by a decrease in maximum amplitude. It has already been mentioned, however, that other considerations arise; for example, the grid leak may tend to keep the mean potential of the grid at the most favourable place on the characteristic curve of the valve.

In Fig. 23 the amplitude curve for the filament-to-grid connection without any grid leak shows discontinuities at a few points. The reason for this is that the second mode of vibration already mentioned caused oscillations simultaneous with those under observation, for certain values of the capacity C.

On all other points there is fair agreement between theory and experiment. The plate-to-grid curves do not fall off as rapidly as the grid-to-filament curves, the reason being that C_2 was larger than C_3. The effect of the grid leaks on the cut-off point is in the direction predicted by theory, and the order of magnitude is also the same.

Oscillations could not be started in the filament-to-grid case when the added grid conductance was 11×10^{-6} mho or larger.

The maximum point and the cut-off point are nearer together in practice than was to be expected from the theoretical curves of Fig. 6, especially in the case when the added grid conductance was small, namely $0 \cdot 8 \times 10^{-6}$ mho. In fact, the points were so near together in practice that it was impossible to distinguish them. The reason for this divergence seems to be that the value of 400 ohms taken for S is too large. It was obtained by measurements on the quartz when used as a resonator. It is conceivable that, in an oscillator, the piece of quartz will vibrate itself more readily into the position giving minimum damping.

TABLE 10.

Type of connection	Added grid conductance	Range	
		Calculated	Observed
	mho × 10⁻⁶		
Plate-grid ..	0·8	1 540 to 1 053	1 800 to 1 044
Plate-grid ..	4·5	1 290 to 1 061	1 350 to 1 053
Filament-grid	0·8	850 to 1 036	800 to 1 040
Filament-grid	4·5	940 to 1 034	880 to 1 034

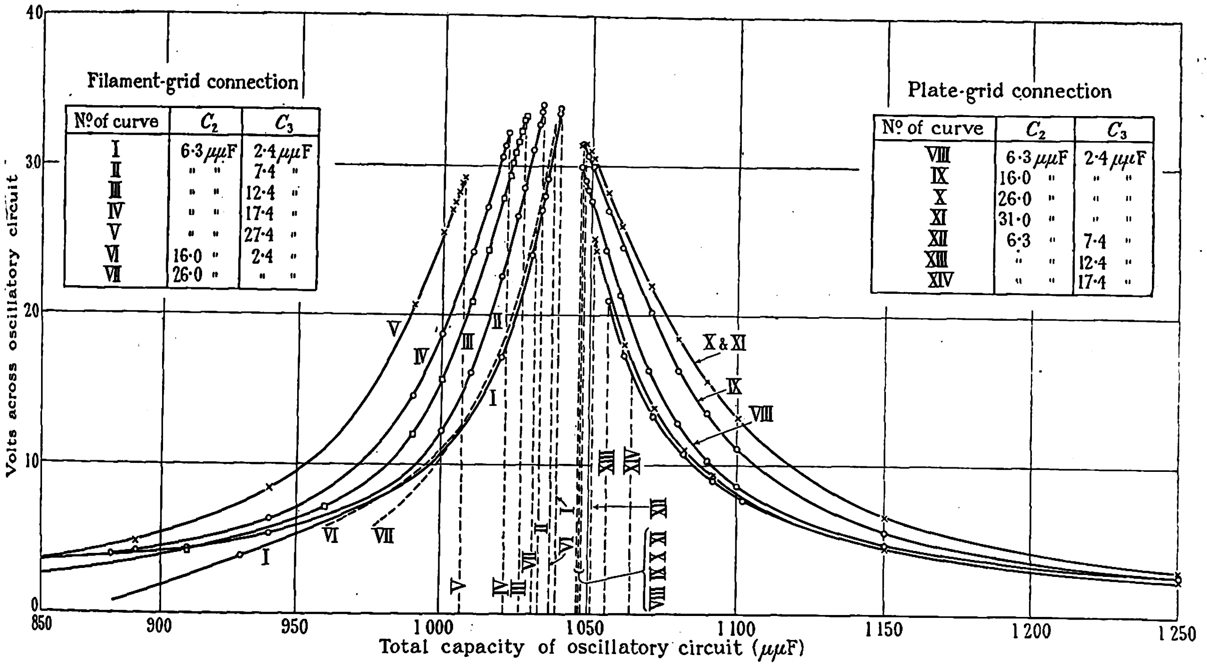


FIG. 24.—Relation between amplitude and inter-electrode capacities.

Valve: D.E.R. $L = 160\ \mu$H; grid leak $= 0{\cdot}8 \times 10^{-6}$ mho.

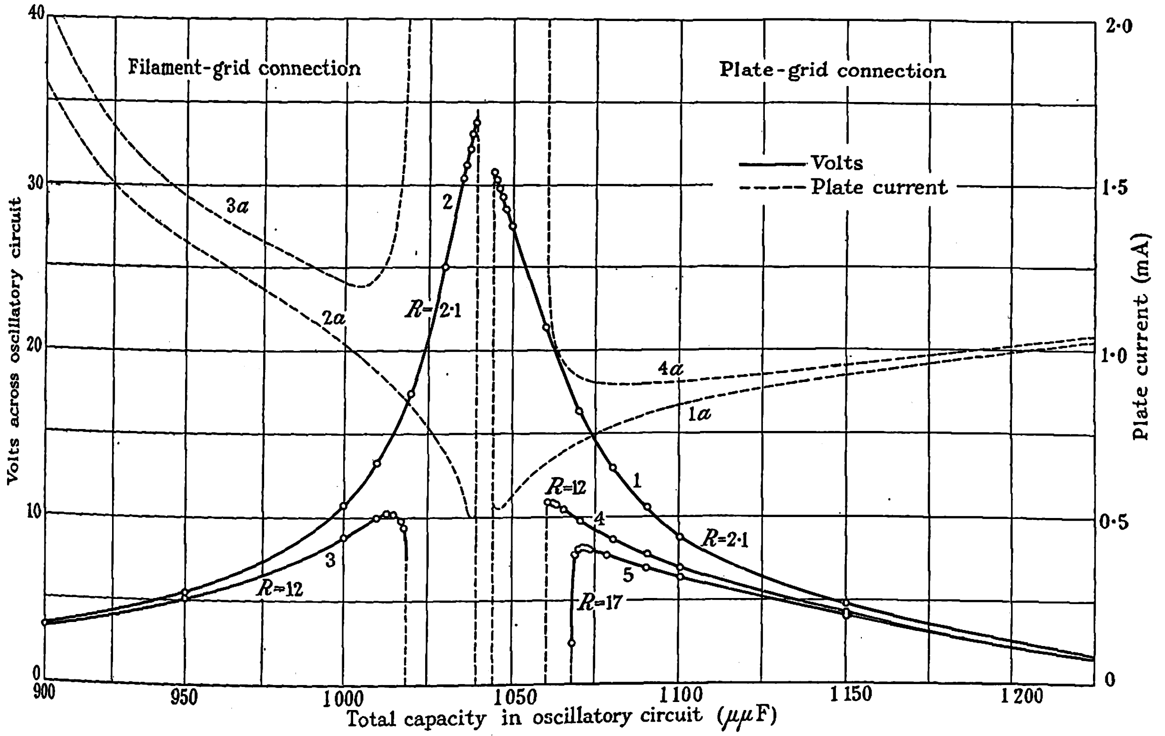


FIG. 25.—Relation between amplitude and resistance of oscillatory circuit.

Valve: D.E.R. $L = 160\ \mu$H; grid leak $= 0{\cdot}8 \times 10^{-6}$ mho.

The difference between the range of capacity over which oscillations were maintained might also be accounted for by this over-estimation of S. In Table 10 some figures are given to show the difference.

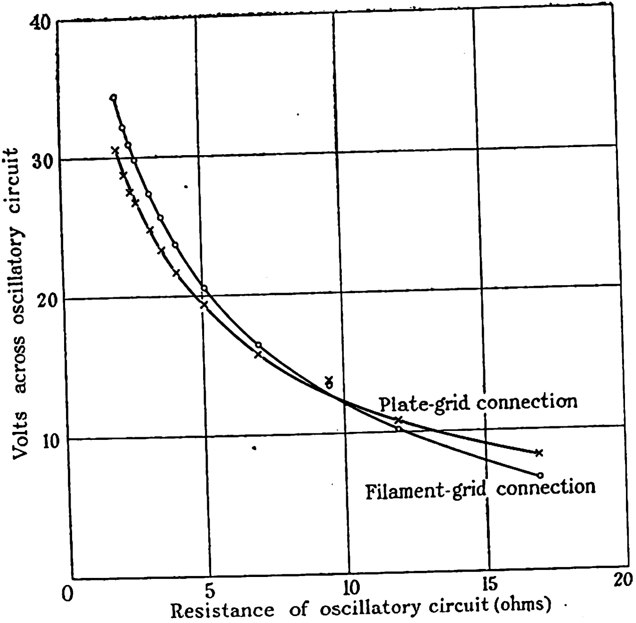


FIG. 26.—Relation between maximum amplitude and resistance of oscillatory circuit.
Valve: D.E.R. $L = 160\ \mu$H; grid leak $= 0{\cdot}8 \times 10^{-6}$ mho.

Relation between Amplitude of Oscillations and Inter-electrode Capacities.—The experimental results are embodied in the curves of Fig. 24. The variations are in accordance with the theory.

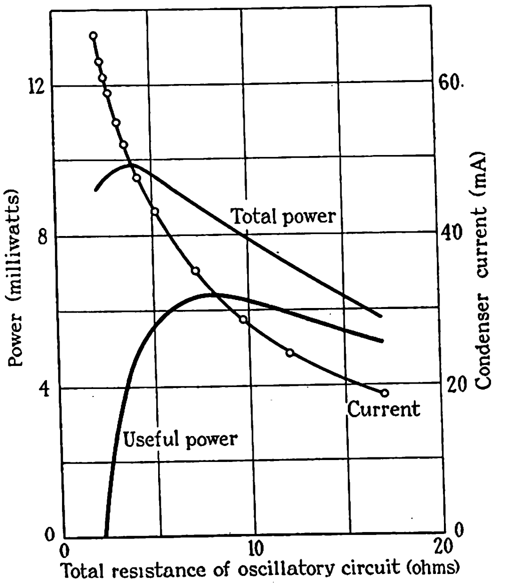


FIG. 27.—Relation between power dissipated and resistance of oscillatory circuit. Plate-grid connection.
Valve: D.E.R. $L = 160\ \mu$H; $R = 2{\cdot}1$ ohms; grid leak $= 0{\cdot}8 \times 10^{-6}$ mho.

In the case of the plate-to-grid connection, the amplitude increases at first as C_2 is increased. There is an optimum value of C_2 past which the amplitude would decrease. In the present case this optimum seems to be between 26 and 31 $\mu\mu$F, since the curves for those two capacities are identical. No measurements were made with a capacity exceeding 31 $\mu\mu$F.

An increase in C_3, the capacity in parallel with the quartz resonator, is always disadvantageous, as shown by curves XII, XIII and XIV. Not only does the amplitude decrease, but the value of the capacity C at which the cut-off occurs is increased. This variation in the cut-off point is readily explained by the theory.

In the plate-to-grid connection, an increase in C_3 or K_3 is equivalent to a decrease in E in equation (54). The value of x required to satisfy the equation $\phi_2 = 0$ [see equation (55)] is therefore increased.

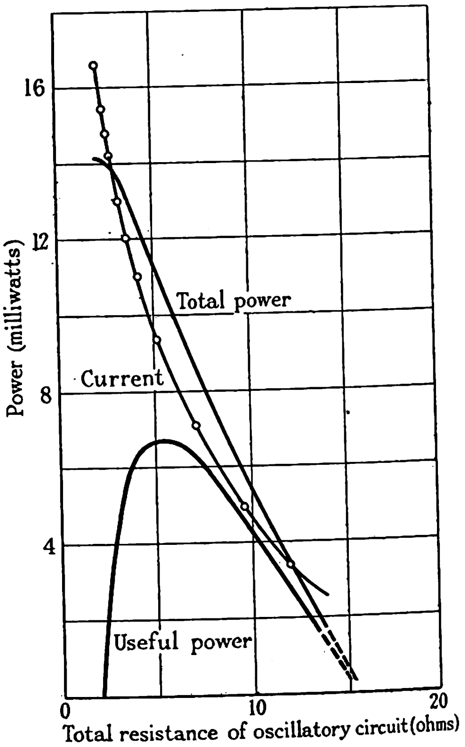


FIG. 28.—Relation between power dissipated and resistance of oscillatory circuit. Filament-grid connection.
Valve: D.E.R. $L = 160\ \mu$H; $R = 2{\cdot}1$ ohms; grid leak $= 0{\cdot}8 \times 10^{-6}$ mho.

An increase in C_2, on the other hand, may or may not mean an increase in the coefficient E, depending upon whether C_2 is below or above its optimum value. Moreover, the coefficients in equation (54) may be such that $|\partial\phi_2/\partial C_2|$ is small over a large range of values of C_2. This seems to be the case here, and an alteration in C_2 has no appreciable effect on the cut-off.

Similar considerations show that in the filament-to-grid case an increase in C_2 or in K_3 always produces a decrease in the cut-off point. An increase in C_3 may or may not produce a decrease in the cut-off point. It does so in the present case. It is to be noted that a decrease in the cut-off capacity is not necessarily accompanied by a decrease in the maximum amplitude.

Relation between Amplitude of Oscillations and Resistance of the Oscillatory Circuit.—Complete amplitude curves for different resistances are shown in Fig. 25. When the resistance of the oscillatory circuit is large, the maximum amplitude is small, and the values of C for maximum amplitude and for cut-off are further apart than is the case with a low-resistance oscillatory circuit.

When the oscillatory circuit is considerably out of tune the amplitude is approximately inversely proportional to the impedance of the oscillatory circuit, which is nearly equal to

$$\omega_0 L/\sqrt{\{\omega_0^2 R^2 C^2 + (1 - \omega_0^2 LC)^2\}}$$

This expression is practically independent of R when $1 - \omega_0^2 LC$, that is, $1 - (C/C_0)$ is as large as, say, $0\cdot3$ or $0\cdot4$.

The added resistance, just as the added grid conductances, produces an earlier cut-off. This is in perfect agreement with the theoretical curves (Fig. 6). Theory and experiment both show, moreover, that the other limiting capacity, given by equations (42) and (73), is not appreciably altered by addition of resistance; the range is therefore approximately the same, whatever be the resistance of the oscillatory circuit, whereas it is greatly reduced by addition of grid conductance, or by an increase in the damping S of the quartz.

The curves in Fig. 26 give the maximum amplitude for various values of the resistance R of the oscillatory circuit. They confirm the prediction that the amplitude is approximately inversely proportional to the resistance of the oscillatory circuit. The departure from the hyperbolic law is also in the direction predicted. This rule is not confined to quartz oscillators: it is perfectly general, and demonstrates the importance of designing low-resistance coils for valve oscillators.

When the resistance of the oscillatory circuit is large, the maximum amplitude for the plate-to-grid connection is larger than the maximum amplitude for the filament-to-grid connection. This was found to be the case for all the valves and all the inductances used. From the theoretical curves (Fig. 6) one might have expected just the reverse phenomenon. Here, again, the mean grid

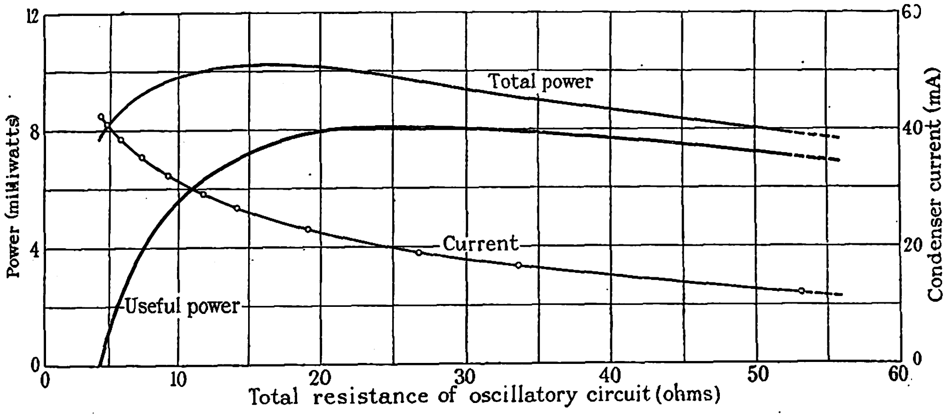


FIG. 29.—Relation between power dissipated and resistance of oscillatory circuit. Plate-grid connection.
Valve: D.E.R. $L = 325\ \mu$H; $R = 4\cdot3$ ohms; grid leak $= 0\cdot8 \times 10^{-6}$ mho.

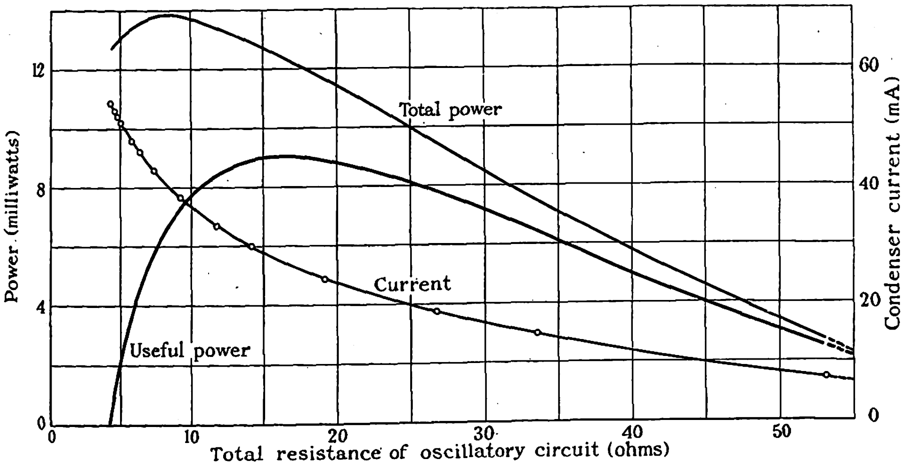


FIG. 30.—Relation between power dissipated and resistance of oscillatory circuit. Filament-grid connection.
Valve: D.E.R. $L = 325\ \mu$H; $R = 4\cdot3$ ohms; grid leak $= 0\cdot8 \times 10^{-6}$ mho.

potential is probably governed by other factors besides the grid leak and the amplitude.

The point could easily be studied further by eliminating x between the equations

$$\phi = 0 \quad \text{[see equation (54)]}$$

and

$$(\partial\phi/\partial x) = 0 \quad \text{[see equation (57)]}$$

solving for $1/g$ and assigning various values to R for both types of connections.

Relation between Power Dissipated and Resistance of Oscillatory Circuit.—In all the measurements described below, the condenser current measured was the maximum current with respect to the capacity C. It corresponds to the maximum ordinates of the curves of Fig. 25. It is not always possible or advisable to work at maximum amplitude, because the maximum amplitude is so very near to the cut-off position, especially when the resistance of the oscillatory circuit is low. In cases where a large power is taken from the oscillator, it is possible to work at maximum amplitude, because, as can be seen from curves III and V, Fig. 25, the maximum is flatter, and not too near to the cut-off position. Also, since curves III and V lie wholly within curves II and I, Fig. 25, on sudden removal of the load the oscillator will go on working at a stable point of curves II or I.

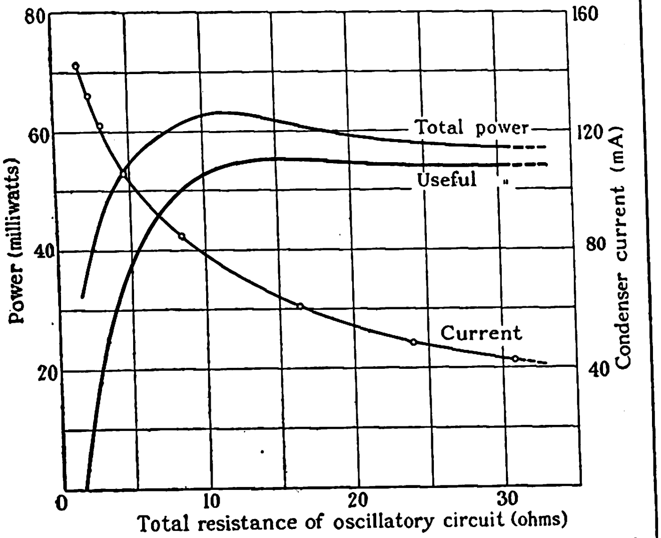


FIG. 31.—Relation between power dissipated and resistance of oscillatory circuit. Plate-grid connection.

Valve: D.E.P. 610. $L = 160\ \mu$H; $R = 1{\cdot}57$ ohms; grid leak $= 0{\cdot}8 \times 10^{-6}$ mho.

For all the power measurements below, the added grid conductance was $0{\cdot}8 \times 10^{-6}$ mho.

For the sake of comparison, measurements were made with both types of connection, for the two circuits the constants of which are given on page 281 and the two valves the constants of which are given on page 280. The same plate voltage, viz. 100 volts, was used throughout.

The useful power is the product of the square of the current in the condenser C and of the added resistance R'. Under normal working conditions, R' is an equivalent series resistance, due to a coupled circuit or some other form of load. The total power is the product of $R + R'$ and the square of the condenser current. It is a more instructive figure than the former because it is dependent only on the sum of the resistances R and R', and not on R. It represents the available power in a circuit of zero inherent resistance.

If the amplitude were strictly inversely proportional to the resistance, the total power dissipated would vary in an exactly similar manner to the amplitude. A glance at Figs. 27 to 34 shows that this is not so. The total power would in practice be very small for a very small total resistance; as the total resistance is increased it reaches a maximum, and then decreases gradually. For large values of the total resistance, its variation becomes very similar to the variation of amplitude; for larger values still, no oscillations can be started.

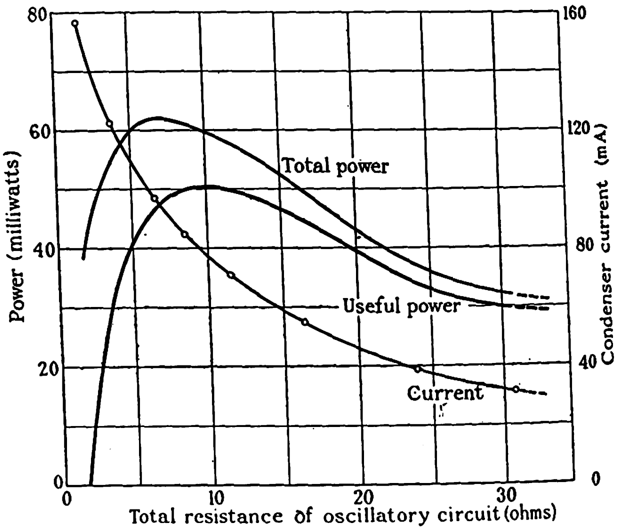


FIG. 32.—Relation between power dissipated and resistance of oscillatory circuit. Filament-grid connection.

Valve: D.E.P. 610. $L = 160\ \mu$H; $R = 1{\cdot}57$ ohms; grid leak $= 0{\cdot}8 \times 10^{-6}$ mho.

The curves show in striking manner the difference between the plate-to-grid and filament-to-grid types of connection. In the filament-to-grid type, the maximum total power is in some cases higher than the corresponding power for the plate-to-grid connection. In all cases, however, the curve is sharper and the maximum power corresponds to a smaller total resistance than with the plate-to-grid connection. The plate-to-grid connection is therefore preferable, because it is advantageous to dispose of approximately maximum power over as wide a range of current as possible. Another advantage of the plate-to-grid connection is that subsidiary resonances of the quartz plate, in the neighbourhood of the main resonance frequency, do not produce secondary oscillations as readily as they seem to do with the filament-to-grid connection. On the other hand, for a given amplitude of plate voltage, the voltage across the quartz resonator is higher in the plate-to-grid type of connection than it is in the filament-to-grid connection. The swing E of grid voltage is, in general, smaller than half the amplitude V of the plate voltage. In consequence

$$|V - E| \geqslant |V| - |E| > |E|$$

The high-conductance valve gives, other things being equal, much more power than the low-conductance valve. Moreover, oscillations are maintained for a much larger range of the resistance $R + R'$ and the curve of total power dissipated against total resistance of the oscillatory circuit is much flatter with the high-conductance valve. This provides greater flexibility for the use of the maximum output, and is a distinct advantage.

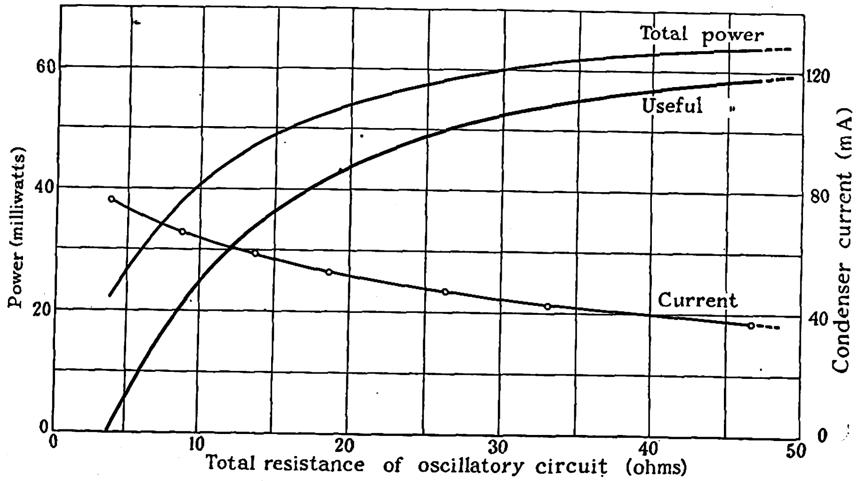


FIG. 33.—Relation between power dissipated and resistance of oscillatory circuit. Plate-grid connection.
Valve: D.E.P. 610. $L = 325\ \mu$H; $R = 3{\cdot}8$ ohms; grid leak $= 0{\cdot}8 \times 10^{-6}$ mho.

The amplitude of the voltage across the condenser increases when the inductance L is made larger, and the capacity C correspondingly smaller. The increase in amplitude for a given resistance is not, however, in the proportion of the square of the inductance.

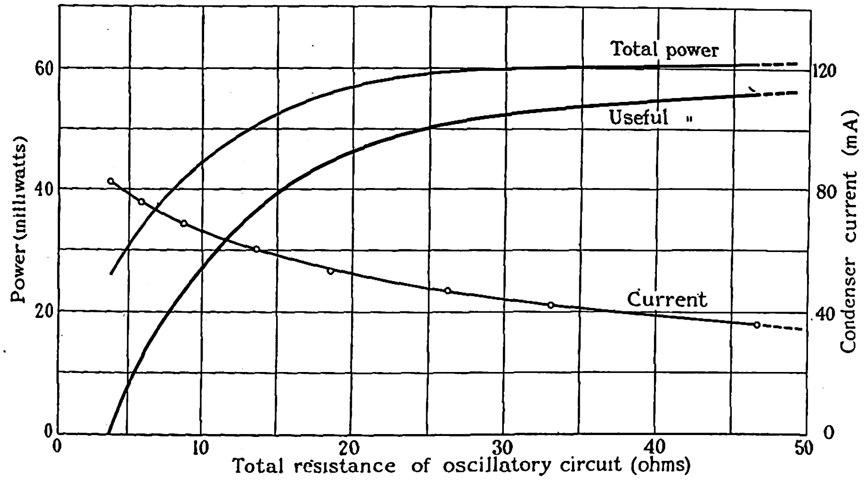


FIG. 34.—Relation between power dissipated and resistance of oscillatory circuit. Filament-grid connection.
Valve: D.E.P. 610. $L = 325\ \mu$H; $R = 3{\cdot}8$ ohms; grid leak $= 0{\cdot}8 \times 10^{-6}$ mho.

The maximum is not very different for the two inductances, but oscillations are maintained for a much larger range of total resistance, and the power curves are much flatter, with the high inductance. It is, therefore, advisable to work with a fairly large ratio of L to C_0. In the present case, with the D.E.R. valve, the ratio $L/C = 0{\cdot}6 \times 10^6$ is more advantageous for most purposes than the ratio $0{\cdot}15 \times 10^6$. The optimum ratio of L to C_0 depends upon the valve and the requirements of the user. Thus, with the D.E.P. valve the maximum power dissipated is approximately the same with the 160-μH and 325-μH coils. Suppose it is required to pass current through a resistance of 10 ohms and obtain as much power as possible. Figs. 31 to 34 show that the 160-μH coil is much more suitable than the 325-μH coil.

When the power is dissipated in a circuit of inductance L_1 and resistance R_1 coupled to the coil L the above considerations are not so important, because a new variable is provided by the mutual inductance M. The equivalent resistance $R + R'$ is equal to $R + \left\{(\omega^2 M^2 R_1)/(R_1^2 + \omega^2 L_1^2)\right\}$ and, with a given value of R_1, can be altered by altering M until the condition for maximum power is reached.

In the case of Figs. 27 and 28, oscillations could not be started with resistances of 24 ohms and above. In the other six cases oscillations could have been produced with resistances even larger than the largest used. In the case of Fig. 33, the maximum power was not reached although the total resistance was nearly 50 ohms.

The modifications of the Pierce circuits with a view to obtaining large powers from a crystal have not been included in this investigation. Circuits for this purpose have already been devised by others. Particular mention should be made of the work of J. M. Miller and A. Crossley,* who use, among other improvements, a choke coil and grid battery instead of a grid leak; the potential of the grid is thus kept negative over the greater part of the cycle, and the loss due to grid current is considerably reduced.

(3) CONCLUSION.

In the first part of the paper the behaviour of the valve-maintained quartz oscillator has been studied theoretically. The only circuits considered were the two variations of the Pierce circuit, namely:

(i) The plate-to-grid connection, in which the quartz resonator is connected between the plate and the grid; and

(ii) The filament-to-grid connection, in which the resonator is connected between the filament and the grid.

In both cases there was an oscillatory circuit between the plate and the filament.

The quartz oscillator has been represented by a network of admittances, and an equation obtained for the oscillations in the plate circuit. An approximate solution of this equation has been obtained, and expressions have been developed for the frequency and the amplitude of the oscillations in the plate circuit. From these expressions it could be deduced that:

(i) With the plate-to-grid connection:

(*a*) When the capacity C in the oscillatory plate circuit is several times as large as the value C' which would make the natural frequency of the oscillatory circuit equal to the frequency of the quartz resonator, no oscillations take place. As the capacity C is reduced gradually, a value is reached at which oscillations start at a very small amplitude. Further decrease of C is accompanied by increase in the amplitude, until the amplitude reaches a maximum at a value of C which is in general less than 1 per cent above C'. A further small decrease in C produces a rapid decrease in amplitude, until a value is reached at which the oscillations stop suddenly. This value also is greater than C'.

(*b*) The resistance of the oscillatory circuit, the grid leak, and, in general, any resistances or leaks in the circuit, tend to decrease the maximum amplitude of oscillations.

(*c*) A certain amount of capacity, either in the valve or outside, between the grid and the filament, is essential to the maintenance of oscillations. On the other hand, large values of this capacity will make the amplitude small. There is an optimum value which gives maximum power.

(*d*) Any capacity in parallel with the quartz resonator, whether inter-electrode capacity between the plate and the grid, stray capacity between the electrodes of the resonator, or capacity between the leads connecting the resonator to the valve, is always disadvantageous and reduces the power.

(*e*) A large plate conductance and a large amplification factor are beneficial.

(*f*) Any variation of frequency produced by changing the air-gap, the valve or the circuits is in all cases a small fraction only of the response frequency of the resonator when the air-gap is zero, i.e. when the electrodes of the resonator are in contact with the quartz crystal.

(*g*) When the capacity C is gradually decreased from a large value, the frequency increases slowly at first, then more and more rapidly, until the sudden cut-off of the oscillations.

(*h*) The greater the conductance of the grid leak, the greater the frequency.

(*j*) The variation of frequency for a given change of C is greater with large grid conductances than it is with small grid conductances.

(ii) With the filament-to-grid connection:

(*a*) When the capacity C in the plate circuit is zero, oscillations are weak or do not take place at all. As the capacity is gradually increased the amplitude of oscillations increases gradually, and reaches a maximum at a value of C which is, in general, less than 1 per cent below C'. A further small increase of C produces a rapid decrease in amplitude, until a value of C, also smaller than C', is reached, at which the oscillations stop suddenly.

(*b*) The resistance of the oscillatory circuit, the grid leak, and, in general, any resistances or leaks in the circuit, tend to decrease the maximum amplitude of oscillations.

(*c*) A certain amount of capacity, either in the valve or outside, between the grid and the plate, is essential to the maintenance of oscillations, but when this capacity is very large no oscillations take place. There is an optimum value of this capacity, which gives maximum power.

(*d*) Any capacity in parallel with the resonator, either in the valve or outside, reduces the power.

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* See Reference (8).

(*e*) The frequency is always lower than the frequency in the plate-to-grid connection, but it is never as low as the response frequency of the resonator.

(*f*) Any variation of frequency produced by changing the air-gap, the valve or the circuits is in all cases a small fraction only of the response frequency of the resonator for zero air-gap.

(*g*) When the capacity C is gradually increased from a small value, the frequency decreases slowly at first, then more and more rapidly, until the sudden cut-off of the oscillations.

(*h*) The greater the conductance of the grid leak, the lower the frequency.

(*j*) The variation of frequency for a given change of C is greater with large grid conductances than it is with small grid conductances.

The experimental investigation has confirmed all the deductions made above, for each type of connection, with one exception. It has been found that addition of a grid leak of a suitable value may increase the amplitude of oscillations. The reason may be that the grid leak tends to keep the mean potential of the grid at the most favourable point on the characteristic curve of the valve.

This work was carried out under the auspices of the Radio Research Board, to whom thanks are due for permission to publish it. The author also wishes to thank Dr. D. W. Dye for his constant help and encouragement throughout the investigation.

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HIGH-FREQUENCY RESISTANCE MEASUREMENT BY THE USE OF A VARIABLE MUTUAL INDUCTANCE.*

By W. JACKSON, M.Sc., Student.

(*Paper first received* 20*th August, and in final form* 21*st October,* 1929.)

SUMMARY.

The paper deals with a method of high-frequency resistance measurement employing a variable mutual inductance. The sources and magnitude of the errors likely to occur are dealt with mathematically. The results of coil resistance measurements are given and compared with the calculated values of resistance and with the results obtained by the "resistance variation" method. The application to condenser resistance measurement is considered.

TABLE OF CONTENTS.

(1) Introduction.
(2) Theory of the method.
(3) Effect of direct induced voltage in the secondary coil.
(4) Effect of harmonics in the working current.
(5) Experimental results.
(6) Conclusions.
(7) Application to condenser resistance measurement.
Appendix.

(1) INTRODUCTION.

The subject of high-frequency resistance measurement has received considerable attention and it offers many difficulties. Of the several methods of coil resistance measurement which have been developed the "resistance variation" method has received most consistent application, mainly by virtue of its simplicity. The serious disadvantage of the method lies in the fact that the circuit resistance measured gives the combined resistance of the coil and the variable tuning condenser. If the coil resistance is to be accurately determined a condenser of known power factor is therefore a necessity. Since a variable condenser of known power factor at high frequency is not readily obtainable, the results are always liable to give a value of resistance in excess of the true coil resistance required.

The present paper deals with a method of high-frequency resistance measurement suggested by E. B. Moullin,† by which the coil resistance can be determined independently by use of a variable mutual inductance. A simple modification of the circuit connections provides a method of condenser resistance measurement. Although the procedure is different, this latter method closely resembles a bridge previously used by A. Campbell for measurements at acoustic frequencies and known as the "Campbell sifter." The method of coil resistance measurement is, however, quite distinct from that of the Campbell bridge, since the condenser employed is outside the measuring circuit and is used only for tuning purposes.

The early part of the paper consists of a theoretical discussion of the method of coil resistance measurement and of the sources of error which are liable to occur. The later part gives a description of the experimental work carried out, together with a statement of the results obtained, and closes with a brief consideration of the method of condenser resistance measurement.

(2) THEORY OF THE METHOD.

Consider the circuit shown in Fig. 1. L_1 represents a coil the resistance R_1 of which is to be measured. C is a variable condenser forming with L_1 a resonant circuit coupled to a source of continuous oscillations, generating a current of frequency $\omega/(2\pi)$, by means of the small coupling coil L_3. L_2 is a coil whose coupling to L_1 can be varied and which forms with L_1 a variable mutual inductance M, in which the self and mutual inductive effects are in opposition. R is a potentiometer of resistance wire in series with the L_1CL_3 circuit, while V is an indicator for measuring the potential between the points A and B.

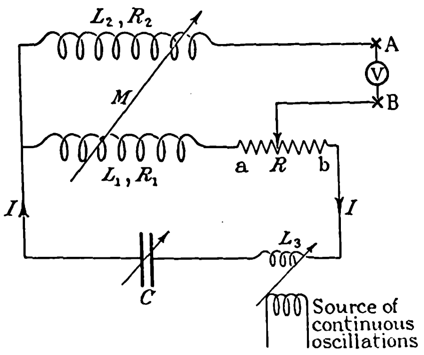

FIG. 1.

Let a current I of frequency $\omega/(2\pi)$ be caused to circulate in the circuit L_1CL_3 by tuning to the generator frequency. Provided that the indicator V has an infinite resistance, no current flows in the circuit L_2AB and the voltage between the points A and B may be written

$$V = \left\{R_1 + j(L_1 - M)\omega\right\}I$$

for the case in which the potentiometer tap is at "a."

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* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (excepting those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† "Radio-Frequency Measurements," p. 185.

As M is varied the voltage V passes through a minimum value V_1 for $M = L_1$, when

$$V_1 = R_1 I \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

For this value of M the insertion between the points "a" and B of a pure resistance R increases the voltmeter reading to a value V_2

where $$V_2 = (R + R_1)I \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Provided that I has been constant, equations (1) and (2) enable the unknown resistance R_1 to be determined in terms of V and R. It is preferable to vary R through a series of values and to plot a curve connecting V and the added resistance R. The curve ought to be a straight line, as in Fig. 2, having an intercept OR_1 along the R axis equal to the unknown resistance R_1. This reduces the error which a single reading might entail. If the current I is accurately known the value of R_1 may be checked as OV/I.

The application of this method to the determination of coil resistance at high frequency is, however, complicated by the self and mutual capacities which are always associated with mutual inductances. As the frequency rises these capacities become of increasing importance and seriously modify the simple expression for the minimum voltage given by equation (1).

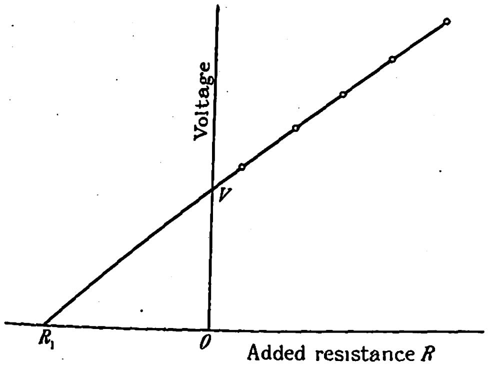

FIG. 2.

The self and mutual capacities of two coupled coils are distributed quantities the distribution of which varies with the nature of the individual coils and with their relative position. It is necessary, for simplicity, to represent these distributed quantities by lumped or concentrated capacities connected across the ends of the coils. While the current distribution in the various parts of the circuit to be considered may be seriously modified by earth capacity effects, it is difficult to allow for their effect since they are not so much a property of the circuit itself as of its position in relation to surrounding bodies and of its potential distribution. These effects, therefore, cannot be considered, but it is of importance to reduce them as much as possible by suitable circuit arrangement and careful earthing.

Representing the self-capacities of L_1 and L_2 by C_1 and C_2 and their mutual capacity by C_{12}, the circuit of Fig. 1 is given in diagrammatic form by Fig. 3.

The current I passing through the condenser C, and measured by the insertion of a thermo-ammeter in close proximity to C, is now the terminal current of L_1 and includes the current passing through C_1 and the other distributed capacities.

The required voltage between A and B, for a known input current I, may be derived as the vector sum of the voltages between AD and DB.

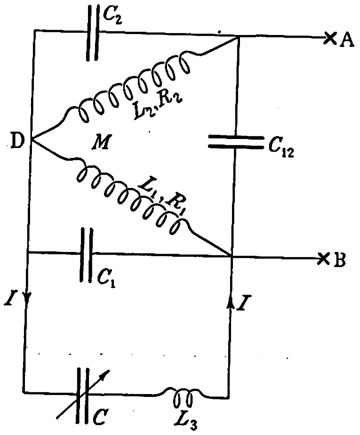

FIG. 3.

The potential difference existing between the terminals A and D of the secondary coil L_2 may be written

$$V_S' = (\sigma + jM'\omega)I \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where M' is the effective mutual inductance between L_1 and L_2, including the effects of self and mutual capacity, and σ an impurity term for which these capacities are responsible.

In an analysis of the capacity effects in standard mutuals Butterworth * has shown that for the case in which the mutual effect opposes the self-inductance, as applies in the present investigation, the circuit of Fig. 3 may be replaced by the simple circuit of Fig. 4, where R_1', R_2', L_1' and L_2' represent the effective resistances and inductances of the primary and secondary coils respectively.

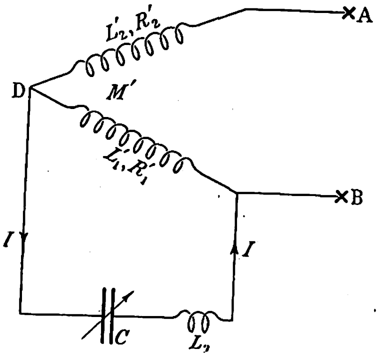

FIG. 4.

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* *Proceedings of the Physical Society of London*, 1921, vol. 33, p. 312.

R_1' and L_1' are given by the expressions

$$R_1' = R_1\left[1 + 2\omega^2\left\{C_1L_1 + C_{12}(L_1 - M)\right\}\right]$$

$$L_1' = \left[L_1 + \omega^2\left\{C_1L_1^2 + C_2M^2 + C_{12}(L_1 - M)^2\right\} - (C_1 + C_{12})R_1^2\right]$$

The effective mutual inductance M' and the impurity σ may be expressed thus:—

$$M' = M + C_{12}R_1R_2 + \omega^2\left\{C_1L_1M + C_2L_2M - C_{12}(L_1 - M)(L_2 - M)\right\}$$

$$\sigma = \omega^2\left[C_1R_1M + C_2R_2M - C_{12}\left\{R_1(L_2 - M) + R_2(L_1 - M)\right\}\right]$$

The general expression for the potential difference between the points A and B, due to the terminal current I, is therefore

$$\begin{aligned} V' = I\Big[&R_1\left\{1 + 2\omega^2\left\{C_1L_1 + C_{12}(L_1 - M)\right\}\right\} - \omega^2\left\{C_1R_1M + C_2R_2M - C_{12}\left\{R_1(L_2 - M) + R_2(L_1 - M)\right\}\right\}\Big] \\ &+ j\omega I\Big[L_1 + \omega^2\left\{C_1L_1^2 + C_2M^2 + C_{12}(L_1 - M)^2\right\} - (C_1 + C_{12})R_1^2 \\ &\quad - M - C_{12}R_1R_2 - \omega^2\left\{C_1L_1M + C_2L_2M - C_{12}(L_1 - M)(L_2 - M)\right\}\Big] \quad \ldots \quad (4) \\ = I&(a + jb) \quad \ldots \quad (5) \end{aligned}$$

The voltage indicated on a voltmeter of infinite resistance connected across AB is therefore

$$V = I\sqrt{(a^2 + b^2)}$$

This voltage will be a minimum with respect to variations in M when

$$\frac{d}{dM}(a^2 + b^2) = 0$$

Provided that the applied frequency $\omega/(2\pi)$ does not approach the natural frequency of the primary or secondary coils, the value of M, to the first order of small quantities, giving minimum value of $(a^2 + b^2)$, is

$$M = L_1(1 + L_1C_2\omega^2 - L_2C_2\omega^2)^* \quad . \quad . \quad . \quad (6)$$

which is also the condition that the reactive component b is zero.

On substituting this value of M in the expression (4) for V, we obtain

$$V_{min.} = IR_1\left\{1 + L_1C_1\omega^2 - (R_2/R_1)L_1C_2\omega^2 + (L_2 - L_1)C_{12}\omega^2\right\} \quad . \quad (7)$$

The effect of self-capacity in the primary coil L_1, of which the resistance R_1 is required, is thus to increase the apparent value of resistance indicated by the voltmeter reading; that of the secondary self-capacity to decrease it and that of the mutual capacity to increase it, since L_2 must of necessity be greater than L_1 in order to give a mutual inductance at least equal to L_1.

The effect of secondary self-capacity may be reduced by the use of a coil of low resistance R_2. Reduction of the secondary inductance L_2, in necessitating a closer coupling between the coils for provision of the required mutual inductance M, tends to increase the mutual capacity C_{12}.

(3) EFFECT OF DIRECT INDUCED VOLTAGE IN THE SECONDARY COIL.

In injecting an e.m.f. of the desired frequency $\omega/(2\pi)$ into the resonant circuit L_1CL_3, by coupling to the generator magnetically, care must be taken to avoid the injection of a direct induced voltage from the oscillator into the secondary coil L_2. If the circuit L_1CL_3 be tuned to the generator frequency, as will be the case in order to obtain as large a working current as possible, the current I will be in phase with the injected voltage, and therefore lagging 90° behind the generator current. The resistance-drop in L_1 is in antiphase with the current I and leads the oscillator current by 90°. An induced voltage in the secondary coil L_2, which will be approximately 90° out of phase with the generator current, will hence be in phase or in antiphase with the drop R_1I recorded on the voltmeter at the adjustment for minimum reading, depending on the relative directions of winding of the coils L_2 and L_3, and will thus cause the apparent resistance to be too high or too low. The presence of such a leakage e.m.f. may be detected by reversing the connections of the coupling coil so as to reverse its phase relative to the required drop R_1I.

This effect can be prevented only by completely screening the oscillator and the leads from the coupling coil L_3 to the measuring circuit.

By coupling the circuit to the oscillator by means of a resistance potential-divider, any leakage e.m.f. will be in phase quadrature with the intentional e.m.f. and will therefore be of very little importance.

(4) THE EFFECT OF HARMONICS IN THE WORKING CURRENT.

In the previous discussion it has been assumed that the current I was sinusoidal. The error introduced by the presence of harmonics may be investigated by representing the current by $I \sin \omega t + N \sin n\omega t$. This leads to serious mathematical complication unless it is accepted that minimum voltage occurs between A and B when the reactive component of the expression given in equation (5), after the effect of harmonics has been allowed for, is zero.

In this case the minimum voltage between A and B is given by the expression

$$\begin{aligned} V_{min.} &= \sqrt{\left[I^2R_1^2\left\{1 + L_1C_1\omega^2 - (R_2/R_1)L_1C_2\omega^2 + C_{12}\omega^2(L_2 - L_1)\right\}^2 + N^2R_1^2\left\{1 + n^2L_1C_1\omega^2 - n^2(R_2/R_1)L_1C_2\omega^2 + n^2C_{12}\omega^2(L_2 - L_1)\right\}^2\right]} \\ &= R_1\sqrt{(I^2 + N^2)}\left[1 + \left\{L_1C_1\omega^2 - \frac{R_2}{R_1}L_1C_2\omega^2 + C_{12}\omega^2(L_2 - L_1)\right\}\frac{I^2 + n^2N^2}{I^2 + N^2}\right] \\ &= R_1\sqrt{(I^2 + N^2)}\left[1 + \left\{L_1C_1\omega^2 - \frac{R_2}{R_1}L_1C_2\omega^2 + C_{12}\omega^2(L_2 - L_1)\right\}\left\{1 + (n^2 - 1)\frac{N^2}{I^2 + N^2}\right\}\right] \end{aligned}$$

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* See Appendix.

In order for a second harmonic to double the error due to self and mutual capacity, the ratio N/I would have to be $1/\sqrt{2}$ and for the nth harmonic $1/\sqrt{(n^2-2)}$.

From the above it would appear that the error due to harmonics is not likely to be serious in any case in which the circuit L_1CL_3 is tuned to the fundamental frequency of the oscillator.

(5) Experimental Results.

It is evident that unless care is taken in the construction of the mutual inductance, having as primary the coil of which the resistance is required, serious errors may be incurred. The provision of a suitable mutual inductance is a difficult matter, especially as very fine variation is necessary in order that there may be no difficulty in adjusting for minimum voltage between A and B (Fig. 1). The mutual inductance used consisted of two cylindrical single-layer coils wound on paxolin formers mounted coaxially end to end, the primary coil L_1 being fixed and the secondary L_2 movable. A coarse and a vernier adjustment were employed for varying the position of L_2 axially relative to L_1, while a clamping screw enabled the coil L_2 to be fixed when the final adjustment of M was completed. In order to reduce the mutual capacity between the coils the common point D was obtained by joining the adjacent ends of the coils, thus keeping the high-potential ends as far apart as possible.

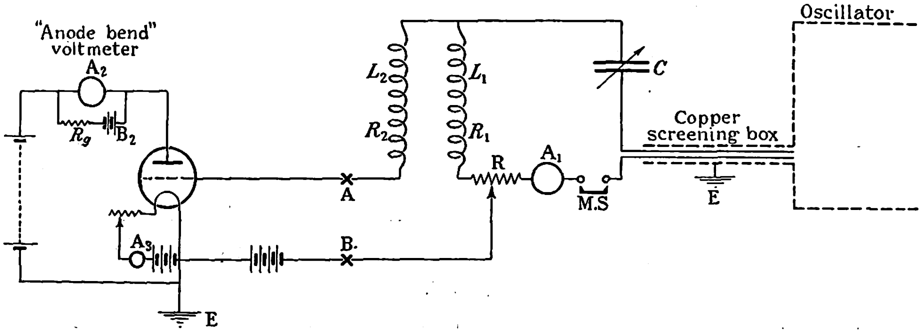

Fig. 5.

The most suitable voltage indicator for the purpose is the anode-rectification type of thermionic voltmeter, since, by the use of negative grid bias, grid current can be prevented for the range of voltage it is desired to measure, thus ensuring an infinite resistance between the points A and B. Such a voltmeter can readily be calibrated to measure high-frequency voltages accurately from 0·5 to 1·5 volts. If the resistance to be measured is of the order of 1 or 2 ohms the current I must be appreciable—up to 0·5 ampere—for accurate indication of the voltage, if the added complication of amplifiers is to be avoided. With such currents flowing, the voltage across L_1 will be considerable and, unless M is carefully adjusted, the indicating instrument may be damaged.

The provision of current outputs of the above order does not offer any difficulty with a valve oscillator, but it is important that the entire oscillator, together with the leads to the measuring circuit, be completely screened in order to prevent direct induced voltage into either the secondary of the mutual inductance or the voltmeter circuit. As previously mentioned, this could be checked by reversing the connections of the coupling coil and noting whether this produced an alteration in the apparent resistance of the coil L_1.

The oscillator was enclosed in a copper box having a lid with deep overlaps, while the leads to the measuring circuit were passed through a copper tube soldered into the side of the box. Currents up to 1·0 ampere were obtainable at resonance in the circuit L_1CL_3.

The potentiometer R was of Eureka resistance wire arranged non-inductively by bringing back the return lead close to the potentiometer wire, and was provided with 8 tappings in a total resistance of approximately 2·0 ohms.

The complete circuit connections showing the earthed points are given in Fig. 5. M.S. was a mercury cup switch for opening and closing the circuit L_1CL_3 when required; A_1 a thermo-ammeter for measuring the current in the L_1CL_3 circuit and A_2 a micro-ammeter in the voltmeter plate circuit, the zero deflection being balanced out by a small battery B_2 in series with a high resistance R_g round the micro-ammeter circuit.

Table 1.

	Primary coil	Secondary coil
Turns (closely wound)	25	93
Wire diameter..	0·037 cm	0·031 cm
Wire covering ..	Double cotton	Enamelled
Former diameter	13·3 cm	13·8 cm
D.C. resistance	1·66 ohms	9·03 ohms
Inductance ..	162 μH	1 800μH
Self-capacity ..	By direct measurement $C_1 = 4\cdot0\mu\mu$F	Natural wavelength when erected on base of mutual = 210 m $C_2 = 7\cdot0\ \mu\mu$F

In order to prevent hand-capacity effects during the measurements, an earthed electrostatic screen, consisting of a number of parallel wires joined together at one end, was erected between the observer and the measuring circuit. To enable the mutual inductance to be varied with the screen in position, the control rod of the mutual was made of considerable length and passed through the screen.

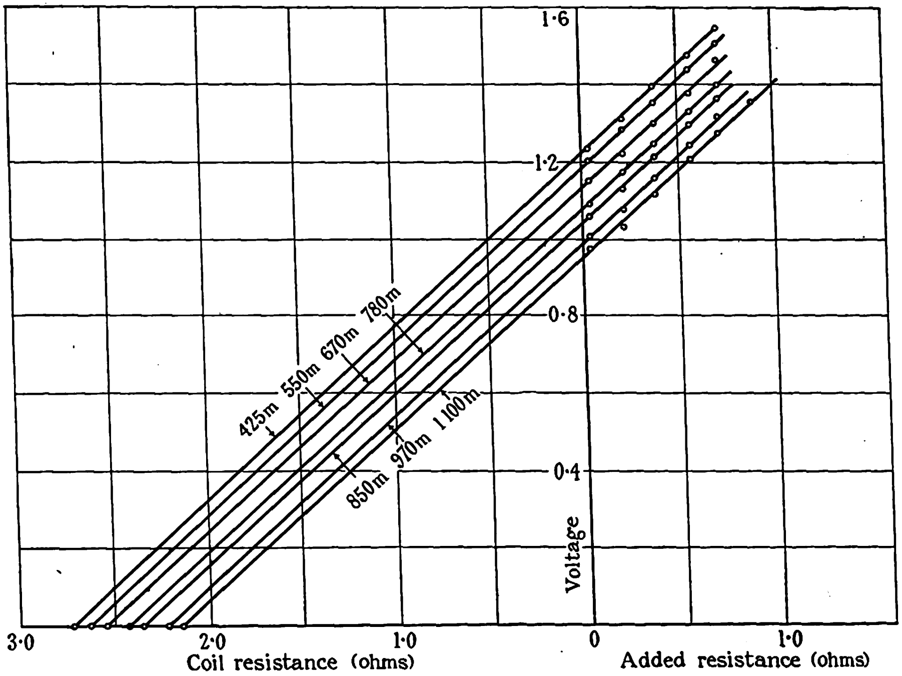

FIG. 6.

(A) The results of a series of measurements, taken over a wavelength range of 1 100 m to 425 m, using this mutual inductance are shown in Fig. 6. The curves connecting voltage between the points A and B, and added resistance R, when produced backwards to meet the resistance axis, give the apparent resistance R_1 of the primary coil L_1 at the several frequencies.

The constants of the primary and secondary coils of the mutual inductance, as measured independently, are shown in Table 1.

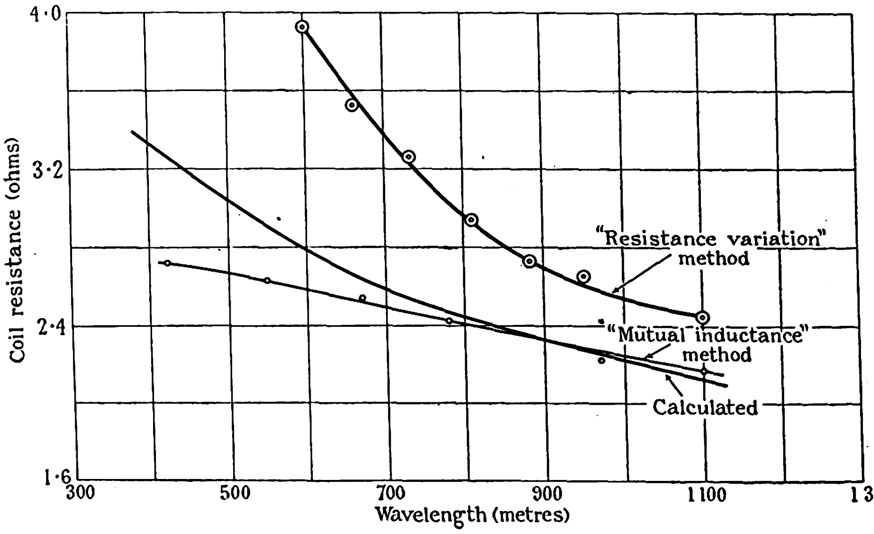

FIG. 7.

The large inductance of the secondary coil was necessary in order to provide the required value of mutual inductance without too close proximity between the primary and secondary coils. When adjusted to give a minimum voltmeter reading the ends of the coils L_1 and L_2 were approximately 1 cm apart. As the frequency was increased it was necessary, in providing the requisite value of M for minimum voltmeter reading, to reduce the coupling between the coils, indicating that capacity effects were present, an effect consistent with equation (6). This became pronounced in the region of 400 m.

Throughout the measurements the current I in the resonant circuit L_1CL_3 was adjusted to 0·43 ampere.

The apparent resistance R_1 deduced as OV/I (see Fig. 2) agrees to within a few per cent with the derived value OR_1.

A comparison of the above results with the calculated values of resistance using Butterworth's theoretical formula for short single-layer coils is obtained from the curves of Fig. 7. The theoretical formula mentioned is

$$R_f = R_0\left\{1 + F + uG\frac{d^2}{D^2}\right\}$$

where R_f is the resistance at frequency f cycles per second, R_0 is the resistance to direct current, $(1 + F) = \frac{1}{4}(\sqrt{2}z + 1)$, $G = \frac{1}{8}(\sqrt{2}z - 1)$, $z = \pi d\sqrt{(2f/\rho)}$, d is the wire diameter and D the pitch of the turns, each in centimetres. The factor $u = 3\cdot29 + b/a$, where b is the length of the coil and a its radius.

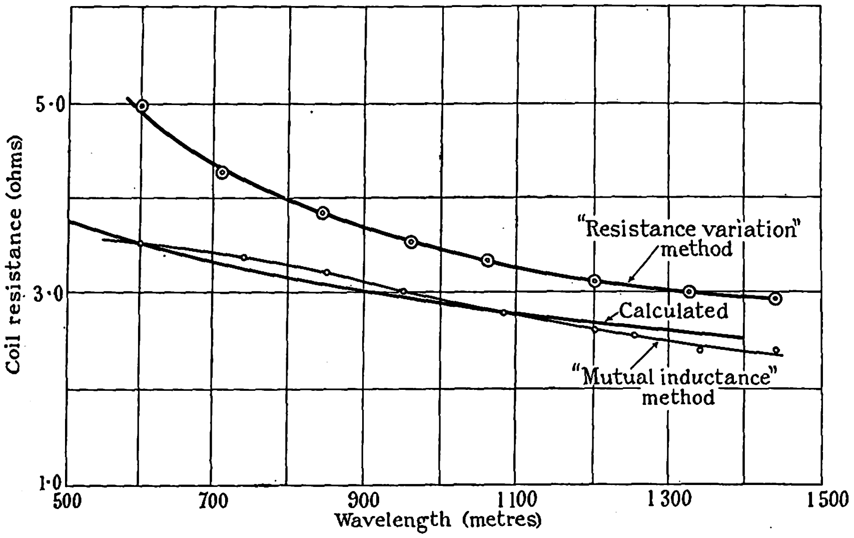

FIG. 8.

TABLE 2.

	Primary coil	Secondary coil
Turns closely wound	41	136
Wire diameter ..	0·045 cm	0·024 cm
Wire covering ..	Double cotton	Double silk
Paxolin former diameter ..	15·25 cm	15·25 cm
D.C. resistance	2·09 ohms	24·80 ohms
Inductance ..	370 μH	3 830 μH
Self-capacity ..	By direct measurement $C_1 = 4\cdot5\ \mu\mu F$	Natural wavelength when erected on base of mutual = 335 m $C_2 = 8\cdot2\ \mu\mu F$

At the longer wavelengths there is close agreement between the two resistance curves, with the value of resistance as measured by the mutual-inductance method slightly in excess of the calculated values. This is to be expected, since Butterworth's formula is based purely on a consideration of the eddy-current losses in the coil and does not include the effect on the apparent coil resistance of either the capacity between turns or the high-frequency dielectric losses in the coil former. At the shorter wavelengths, however, there is an increasing tendency for the mutual-inductance method to underestimate the coil resistance, indicating that capacity effects, in particular that due to secondary coil self-capacity, are becoming of importance in affecting the derived values of resistance. An estimate of the effect of the self-capacities C_1 and C_2 may be obtained from a consideration of equation (7). By use of the measured coil constants it can be shown that C_1 and C_2 may be expected to produce a net reduction in apparent coil resistance of 1·5 per cent at 1 000 m and 7·5 per cent at 400 m, although this does not take into consideration any compensating effect of mutual capacity, which would become of importance if C_{12} exceeded 2 μμF or 3 μμF.

The results of high-frequency resistance measurements on the primary coil L_1 when the resistance variation method is employed are also given in Fig. 7. The serious discrepancy between these resistance values and those obtained by the mutual-inductance method is, in part, due to this under-estimating effect. The correction is, however, much less than the difference to be accounted for, and it is therefore justifiable to account for this difference mainly by the unknown resistance of the condenser used in the resonant circuit of the resistance-variation method. This serves to show how important the condenser resistance, if unknown, may be as a source of error in the latter method.

(B) Table 2 gives the constants of a pair of coils wound to replace the primary and secondary of the previous mutual inductance for the purpose of further checking the accuracy of the method. The results of resistance measurements on the primary coil by the mutual inductance and resistance variation methods, together with the calculated values, are shown in Fig. 8.

The resistance values obtained by the mutual method are again in close agreement with the calculated values, but appreciably low compared with the resistance variation measurements. An estimation of the effect of primary and secondary coil self-capacities on the resistance values obtained by the mutual method shows them to be responsible for a net reduction in apparent resistance of 4·5 per cent at 1 500 m and 15·0 per cent at 700 m. It is worthy of note, however, that a mutual capacity of 6 $\mu\mu$F would be sufficient to compensate entirely for this 15 per cent reduction at 700 m by the introduction of an equal error of reverse sign. While such a high value of C_{12} is not to be expected in the coils of the mutual themselves, since at the setting for minimum voltmeter reading the adjacent ends of the coils L_1 and L_2 were more than 1 cm apart and these ends were joined, it may easily be provided in the input capacity of the voltmeter. This capacity would exist between the points A and B (Fig. 3), and although the valve used in the voltmeter was a V24 low-capacity valve it is unlikely that its capacity would be less than 5·0 $\mu\mu$F.

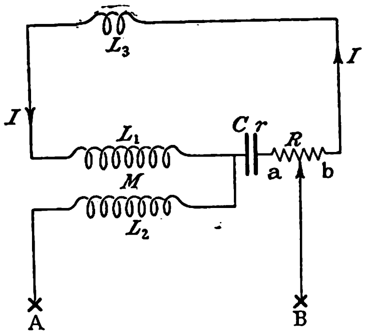

FIG. 9.

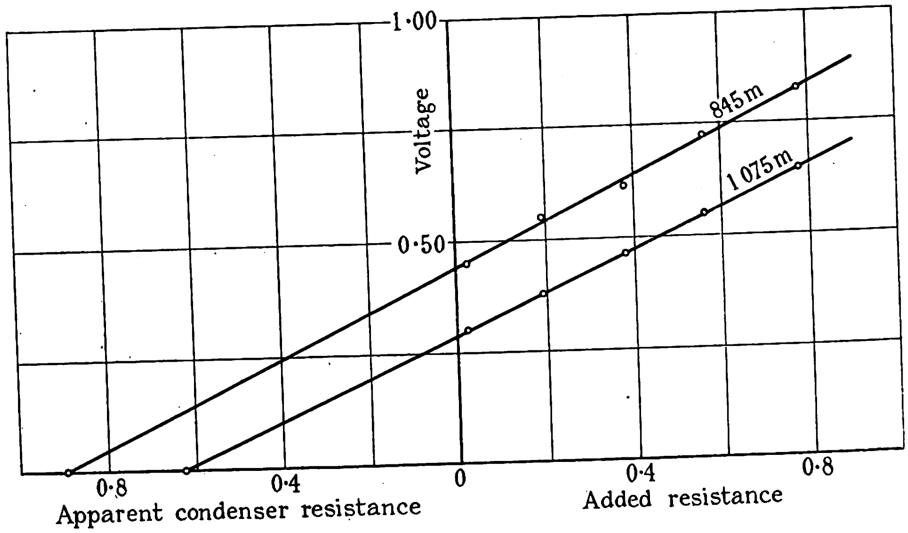

FIG. 10.

(6) CONCLUSIONS.

The recorded work serves to demonstrate that the method is capable of giving results which compare favourably with the calculated values of coil resistance at wavelengths well removed from the natural wavelength of the secondary coil. At wavelengths approaching this the small self and mutual capacities inherent in the mutual inductance are capable of introducing errors which, while to some extent compensating, may be far from inconsiderable. These errors may, however, be reduced by careful design of the mutual inductance and may be estimated with reasonable accuracy. As an offset to this disadvantage, the method possesses the advantages that no knowledge of the tuning condenser power factor is necessary, and there is no difficulty in manipulation or in indication of the balance condition.

(7) APPLICATION TO CONDENSER RESISTANCE MEASUREMENT.*

The system shown in Fig. 1 is readily adapted to the measurement of condenser resistance by a modification of the circuit connections to those of Fig. 9.

The condenser C, the resistance r of which is to be measured, is connected in series with the primary coil L_1 and a small coil L_3 coupled to the oscillation generator. The secondary coil L_2 has one end joined to the common point of L_1 and C, and the other to one terminal A of the voltmeter. The other voltmeter terminal B is taken to the potentiometer R connected in series with the L_1CL_3 circuit.

For a current I of frequency $\omega/(2\pi)$, caused to circulate round the circuit L_1CL_3 by tuning to the generator frequency, the voltage between the points A and B with the potentiometer tap at "a" may be written

$$V = I\left\{r + j\left(M\omega - \frac{1}{C\omega}\right)\right\}$$

As M is varied, the voltage V passes through a minimum value V_1 for $M\omega = 1/(C\omega)$, that is for $M = 1/(C\omega^2)$, when $$V_1 = rI \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

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* E. B. MOULLIN, *loc. cit.*, p. 145.

For this value of M the insertion of a pure resistance R between the points a and B increases the voltmeter reading to V_2, where

$$V_2 = (r + R)I \quad . \quad . \quad . \quad . \quad . \quad (9)$$

The unknown resistance r may be determined from equations (8) and (9) in terms of V and R, or from a curve connecting V and R obtained by varying R through a series of values.

The curves of Fig. 10 show the results obtained on a large variable air condenser using the mutual inductance, the constants of which are given in Table 1, at wavelengths of 1 075 and 845 m, both well removed from the natural wavelength of the secondary coil. The condenser resistances at these two wavelengths, and for condenser capacities of 1 980 and 1 220 $\mu\mu$F respectively, are thus found to be 0·62 and 0·89 ohm. These values of condenser resistance correspond to condenser power-factors of $2 \cdot 15 \times 10^{-3}$ and $2 \cdot 42 \times 10^{-3}$ respectively.

While it was expected that the power factor would be high, these values seem to be larger than one would justifiably expect in an air condenser.

Avoiding as it does the need for a standard condenser of known power factor, as is required in the comparison methods of condenser-resistance measurement, the method would appear to justify development.

The thanks of the author are due to the Governing Body of the Bradford Technical College for the facilities provided at the College for carrying out the recorded work, and also to Mr. E. B. Moullin, Associate Member, for his interest and for his help in scrutinizing the manuscript.

APPENDIX.

The general expression for the potential difference between the points A and B (Fig. 4), given by equation (4), may be written in the form

$$V = I(a + jb)$$

where

$$a = R_1\left[1 + 2\omega^2\left\{C_1L_1 + C_{12}(L_1 - M)\right\} - \omega^2\left\{C_1M + (R_2/R_1)C_2M - C_{12}\left\{(L_2 - M) + (R_2/R_1)(L_1 - M)\right\}\right\}\right]$$

and

$$b = \omega\left[L_1 + \omega^2\left\{C_1L_1^2 + C_2M^2 + C_{12}(L_1 - M)^2\right\} - (C_1 + C_{12})R_1^2 \right.$$
$$\left. - M - \omega^2\left\{C_1L_1M + C_2L_2M - C_{12}(L_1 - M)(L_2 - M)\right\} - C_{12}R_1R_2\right]$$

Since in the derivation of equation (1), when self and mutual capacities were not taken account of, it was shown that the voltage V was a minimum when M was equal to L_1, it is justifiable in the above, in which the effects of the small capacities C_1, C_2 and C_{12} are allowed for, to consider $(L_1 - M)$ as small compared with either L_1, L_2, M or $(L_2 - M)$, L_2 being necessarily much greater than L_1, and therefore M, in order to provide the required value of mutual inductance with reasonably loose coupling between L_1 and L_2. Hence as C_1, C_2 and C_{12} are of similar magnitude, $C_{12}(L_1 - M)$ may be neglected in comparison with C_1L_1, since $C_1L_1\omega^2$ is itself a small quantity compared with unity, provided that $\omega/(2\pi)$ does not approach the natural frequency of the primary coil. Also, since R_1 and R_2 need not be of sensibly different magnitude, $(R_2/R_1)(L_1 - M)$ may be neglected in comparison with $(L_2 - M)$. Similarly in the expression for b, $C_{12}(L_1 - M)^2$ can be considered to be negligible in comparison with $(C_1L_1^2 + C_2M^2)$, since under the previous condition $\omega^2(C_1L_1^2 + C_2M^2)$ is itself small compared with L_1. Also, provided that the natural frequency of the secondary coil is not approached, $C_{12}(L_1 - M)(L_2 - M)$ may be neglected in comparison with $(C_1L_1M + C_2L_2M)$.

The expressions for a and b therefore reduce to

$$a = R_1\left\{1 + 2\omega^2C_1L_1 - \omega^2C_1M - \omega^2(R_2/R_1)C_2M + \omega^2C_{12}(L_2 - M)\right\}$$
$$b = \omega\left\{L_1 + \omega^2(C_1L_1^2 + C_2M^2) - (C_1 + C_{12})R_1^2 - M - \omega^2(C_1L_1M + C_2L_2M) - C_{12}R_1R_2\right\}$$

that is

$$a = R_1(1 + 2\omega^2C_1L_1 + \omega^2C_{12}L_2) - M\left[R_1\omega^2\left\{C_1 + (R_2/R_1)C_2 + C_{12}\right\}\right]$$
$$b = \omega\left\{L_1 + \omega^2C_1L_1^2 - (C_1 + C_{12})R_1^2 - C_{12}R_1R_2\right\} - M\left[\omega\left\{1 + \omega^2(C_1L_1 + C_2L_2 - C_2M)\right\}\right]$$
$$= \omega\left\{L_1 + \omega^2C_1L_1^2 - (C_1 + C_{12})R_1^2 - C_{12}R_1R_2\right\} - M\left[\omega\left\{1 + \omega^2\left\{C_1L_1 + C_2(L_2 - L_1) + C_2(L_1 - M)\right\}\right\}\right]$$

In the expression for b, $(C_1 + C_{12})R_1^2$ and $C_{12}R_1R_2$ are negligible in comparison with $\omega^2C_1L_1^2$, R_1 and R_2 being small compared with $L_1\omega$. Further, $C_2(L_1 - M)$ is negligible compared with $C_1L_1 + C_2(L_2 - L_1)$.

Hence $$a = \alpha - M\beta \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

and $$b = \eta - M\gamma \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

where
$$\alpha = R_1\left\{1 + 2\omega^2C_1L_1 + \omega^2C_{12}L_2\right\}$$
$$\beta = R_1\omega^2\left\{C_1 + (R_2/R_1)C_2 + C_{12}\right\}$$
$$\eta = \omega L_1(1 + \omega^2C_1L_1)$$
$$\gamma = \omega\left\{1 + \omega^2C_1L_1 + \omega^2C_2(L_2 - L_1)\right\}$$

The voltage $V = I(a + jb)$ will be a minimum with respect to variations in M when

$$\frac{d(a^2 + b^2)}{dM} = 0$$

that is when $$M = \frac{\alpha\beta + \eta\gamma}{\beta^2 + \gamma^2}$$

On substitution for α, β, η and γ,

$$M = \frac{R_1^2\left\{C_1 + (R_2/R_1)C_2 + C_{12}\right\}(1 + 2\omega^2C_1L_1 + \omega^2C_{12}L_2) + L_1(1 + \omega^2C_1L_1)\left\{1 + \omega^2C_1L_1 + \omega^2C_2(L_2 - L_1)\right\}}{R_1^2\omega^2\left\{C_1 + (R_2/R_1)C_2 + C_{12}\right\}^2 + \left\{1 + \omega^2C_1L_1 + \omega^2C_2(L_2 - L_1)\right\}^2}$$

Expanding and neglecting terms of the second order of small quantities—to which

$$R_1^2\left\{C_1 + (R_2/R_1)C_2 + C_{12}\right\}(1 + 2\omega^2C_1L_1 + \omega^2C_{12}L_2)$$

and $$R_1^2\omega^2\left\{C_1 + (R_2/R_1)C_2 + C_{12}\right\}^2$$

in the numerator and denominator respectively belong —this required value of M reduces to

$$\begin{aligned} M &= \frac{L_1\left\{1 + 2\omega^2C_1L_1 + \omega^2C_2(L_2 - L_1)\right\}}{1 + 2\omega^2C_1L_1 + 2\omega^2C_2(L_2 - L_1)} \\ &= L_1\left\{1 - \omega^2C_2(L_2 - L_1)\right\} \\ &= L_1(1 + L_1C_2\omega^2 - L_2C_2\omega^2) \end{aligned}$$

to the first order of small quantities.

The minimum voltage between the points A and B (Fig. 4) is obtained by substituting this value of M in the expression

$$V = I\sqrt{(a^2 + b^2)}$$

Using equation (11) we obtain

$$\begin{aligned} b = \omega L_1(1 + \omega^2C_1L_1) - \omega L_1\Big\{1 &+ \omega^2C_1L_1 \\ &+ \omega^2C_2(L_2 - L_1)\Big\}\left\{1 - \omega^2C_2(L_2 - L_1)\right\} = 0 \end{aligned}$$

to the first order of small quantities.

Hence $V_{min.} = Ia$, where, by equation (10),

$$\begin{aligned} a = R_1(1 &+ 2\omega^2C_1L_1 + \omega^2C_{12}L_2) \\ &- R_1\omega^2\left\{C_1 + (R_2/R_1)C_2 + C_{12}\right\}L_1 \end{aligned}$$

to the first order of small quantities

$$= R_1\left\{1 + \omega^2C_1L_1 - (R_2/R_1)\omega^2C_2L_1 + \omega^2C_{12}(L_2 - L_1)\right\}$$

Hence, finally,

$$\begin{aligned} V_{min.} = IR_1\Big\{1 + L_1C_1\omega^2 &- (R_2/R_1)L_1C_2\omega^2 \\ &+ (L_2 - L_1)C_{12}\omega^2\Big\} \end{aligned}$$

A METHOD OF TESTING CURRENT TRANSFORMERS.*

By W. E. Bruges.

(*Paper first received 15th October, and in final form 19th December, 1929.*)

SUMMARY.

The author outlines a simple method of testing current transformers. The method is an absolute one and does not call for expensive apparatus or rely on the existence of a number of "standard" transformers.

There are two methods commonly in use at present by which current transformers are tested. There is the Silsbee method (Fig. 1) in which the transformer under test is placed in series with a previously calibrated transformer. The "spill" current is measured both in magnitude and in direction, and the error of the transformer under test can be roughly calculated. The spill current represents the vectorial difference between the errors of the two transformers.

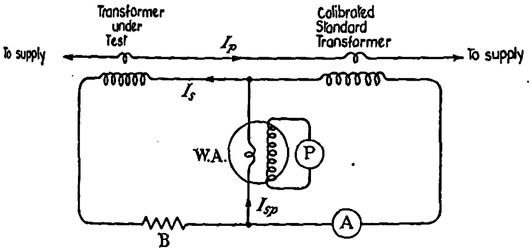

FIG. 1.—Silsbee (spill) method.

A = ammeter.
W.A. = wattmeter used as ammeter.
P = phase-shifter, excited from supply.
B = burden resistance.
I_p = primary current.
I_s = secondary current.
I_{sp} = spill current.
I_{ps} = phase-shifter current.

The other, the "bridge" method, is shown in Fig. 2. It relies on a calibrated condenser and resistances, and is comparatively expensive to arrange. Whilst this method is incapable of dealing with frequencies other than the fundamental, of which the error current may be composed, it possesses the very great advantage that the resistances and condenser may, if desired, be calibrated once and for all for a particular frequency. It is an absolute method. In order to avoid the use of very large shunts, a special transformer may be provided, as shown in Fig. 2. The secondary coil of this transformer should have a very low resistance, and the core should be made of high-permeability iron, such as mumetal, because if the error of this transformer has to be taken into consideration the method is scarcely an improvement on the Silsbee method. The vibration galvanometer will have comparatively large currents passing through it at other frequencies than the fundamental, harmonics, being exaggerated, of course, by the condenser.

The method to be described is shown in Fig. 3 in its simplest form. The transformer to be tested is placed in series with another current transformer having approximately the same ratio. The latter transformer the author proposes to call the balancing transformer, and its primary and secondary windings are placed in series with the primary and secondary windings, respectively, of the transformer under test. A phase-shifter is connected to the secondary terminals of the balancing transformer, or to a tapping, or to a separate winding round this transformer.

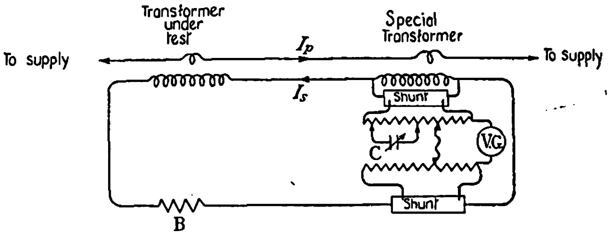

FIG. 2.—Bridge method.

V.G. = vibration galvanometer.
C = condenser.

The phase-shifter is adjusted until the flux in the balancing transformer is reduced to a negligible value, and the current delivered by the phase-shifter is then read. From the reading, the error of the transformer under test can either be directly stated or be very quickly calculated.† It may be shown that the error, referred to the primary, is:

$$\frac{k' - k}{k'} I_p + \frac{k}{k'} \cdot \frac{n}{N} I_{ps} \quad . \quad . \quad . \quad . \quad (1)$$

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* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (excepting those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† Let the error of the transformer under test, referred to the primary, be ϵ.

Then $$\epsilon = I_p - kI_s \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where I_p = primary current;
I_s = secondary current; and
k k', n, N are as given in the text.

When the flux of the balancing transformer has been reduced to zero, we have

$$(n/N)I_{ps} = I_p - k'I_s \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

whence $$I_s = (1/k')[I_p - (n/N)I_{ps}]$$

Substituting in (2), therefore,

$$\epsilon = I_p - (k/k')[I_p - (n/N)I_{ps}]$$
$$= [(k' - k)/k']I_p + (k/k')(n/N)I_{ps}$$

It must be borne in mind that ϵ, I_p, I_s and I_{ps} are all vector quantities.

where k = desired ratio (secondary to primary) of the transformer under test;
k' = turn ratio (secondary to primary) of the balancing transformer;
I_p = primary current;
I_{ps} = current delivered by the phase-shifter;
n = number of turns round the balancing transformer which are in series with the phase-shifter;
N = number of primary turns on the balancing transformer.

The two terms in the above formula must be added vectorially. It will be noticed that when $k = k'$ and $n/N = k$, the error becomes kI_{ps}. It will often be convenient to arrange for this to be the case, but it is not always possible, for instance when it is desired to operate a transformer in a protective circuit on a 3-phase line and the transformer has an odd ratio which is some multiple of $\sqrt{3}$.

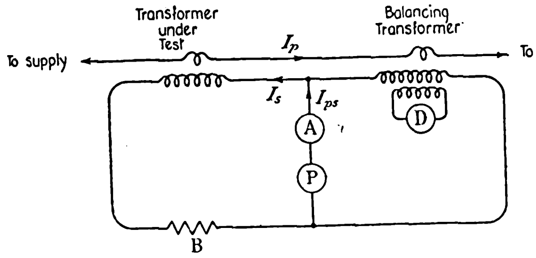

FIG. 3.

D = detector (milliammeter or galvanometer).

In order to ascertain when the flux in the core of the balancing transformer has been reduced to a negligible value, a detector—which may be a milliammeter or a galvanometer—is placed in series with a number of turns taken round the core of the balancing transformer. The phase-shifter is adjusted until the detector reads zero or a minimum value.‡

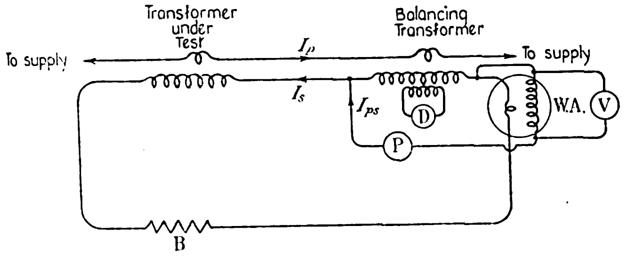

FIG. 4.

V = voltmeter.

The current delivered by the phase-shifter can be read by means of an ammeter placed in its output circuit; but generally it is desired to know both the magnitude and the direction of the current, and a wattmeter may then be used in conjunction with a voltmeter, as shown in Fig. 4, or in conjunction with an ammeter, as shown in Fig. 5. The ammeter reads the total current, and the wattmeter the component which is in phase with the secondary. This is shown vectorially in Fig. 6.

When the flux in the balancing transformer has been reduced, as described, the reactive effect of the balancing transformer will be negligible and the burden of the transformer under test may be calculated in the usual way, the windings of the balancing transformer being considered to be purely a resistance. When the burden is entirely resistive, it will usually be sufficient to multiply the secondary current by the total resistance of the secondary circuit, including that of the balancing transformer. This gives the voltage which has to be supplied by the transformer under test.

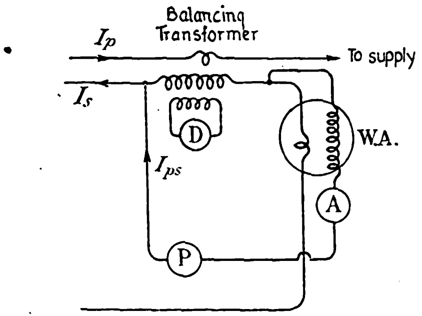

FIG. 5.

Further, since the effect—and therefore the sum—of the ampere-turns on the balancing transformer is a minimum, the current supplied by the phase-shifter will represent the difference between the primary and secondary ampere-turns of this transformer. As the windings of the balancing transformer are in series with the windings of the transformer under test, it follows that the current supplied by the phase-shifter also represents the difference between the primary and secondary ampere-turns on the latter transformer. An allowance must be made if the desired ratio of the transformer under test differs from the turn ratio of the balancing transformer, and this will be taken care of if the formula given above is used.

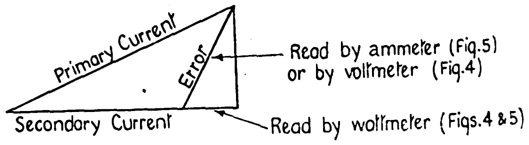
Primary Current
Error
Read by ammeter (Fig.5) or by voltmeter (Fig.4)
Secondary Current
Read by wattmeter (Figs.4 & 5)

FIG. 6.

It is occasionally advantageous to connect the phase-shifter to a separate tapping, or even to a separate winding on the balancing transformer. This may occur if it is desired to increase the current so that it may be more easily read by the instruments at one's disposal. A close coupling between the windings will then be advisable. Generally speaking, the test may be carried out with any current transformer having a known number of turns—the detector winding being wound round the outside. It would be more convenient to provide a tapped balancing transformer having a large core and low-resistance windings. One such transformer would be used for many

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‡ The number of turns in series with the detector for maximum sensitivity should be N_d, given by

$$N_d/N_b = \sqrt{R_d/R_b}$$

where N_b = number of secondary turns on the balancing transformer;
R_d = resistance of detector circuit; and
R_b = resistance of main secondary circuit of the two transformers = total burden resistance.

ratios and could be kept for the purpose. For accurate tests it will then be possible to make the first term in formula (1) as small as possible. If the resistance of the windings is made small, the burden can be more conveniently adjusted by an external resistance.

A very small error of the second order is introduced if a separate transformer is used to excite the wattmeter current coil, or if the current coil is not part of the burden itself. This error is usually negligible, but it can, where necessary, be calculated from a separate test. It is thought that it would generally be preferable not to include the wattmeter current-coil as part of the burden, and to short-circuit this coil while the detector reading is being reduced to zero; if this is not done, its reactance and resistance must be known.

It will be seen that although the wave-form of the phase-shifter is important, it is not necessary that it should possess a degree scale or be calibrated in any way.

It will generally be found impossible to reduce the detector reading absolutely to zero, owing to the harmonics in the magnetizing current of the transformer under test. These harmonics may be supplied separately by other phase-shifters. Whilst it is generally necessary to observe only the fundamental component of the error of a current transformer, nevertheless it is interesting to be able also to observe what differences occur due to harmonics. With well-made transformers these differences should be small. It should be mentioned that if the primary current is sinusoidal, the secondary current will be very nearly so, unless the magnetizing current is inordinately large; hence the voltage to be supplied by the transformer, which is usually the product of the current and the resistance of the circuit (the reactance being kept small), will also be nearly sinusoidal. Therefore the magnetizing current itself may be far from sinusoidal; its wave-form may be worked out approximately from flux curves, and the third harmonic will usually be seen to predominate.

It is worth noticing that the vector diagram of a current transformer may be drawn as ABCD in Fig. 7, where AB = secondary ampere-turns, CA = primary ampere-turns, and BC is the error in ampere-turns. Assuming a constant volt-ampere burden, BC will move, as the reactance or capacity of the secondary circuit is altered, on a circle with centre C. BCD is a right-angled triangle, CD representing the true magnetizing current and BD the iron losses. If AB is produced to E, DBE will represent the angle whose cosine is the power factor of the secondary circuit.

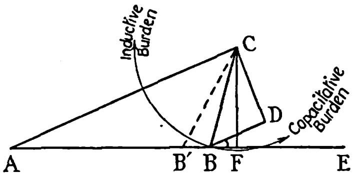

FIG. 7.

In formula (1) above, if $k = k'$, BC $= I_{ps}$, and BF is read from the wattmeter WA (see Figs. 4 and 5), where the point F is found by dropping a perpendicular CF on AE. If k is not equal to k', there will be another point B′ in AB. The wattmeter WA reads B′F, and B′C $= I_{ps}$. Generally we are able to arrange that the reactance in the burden circuit is negligible, at any rate for test purposes; then, of course, the angle DBE becomes zero and the point D lies in AB produced.

If the phase-shifter incorporates a degree scale, use may be made of this for checking results and for noticing the effect of reactance in the circuit.

DISCUSSION ON

"THE CONSTRUCTION OF THE 'GRID' TRANSMISSION SYSTEM IN GREAT BRITAIN." *

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 4TH NOVEMBER, 1929.

Mr. B. Welbourn: In designing the grid, the engineers of the Board have based it on the experience of the whole world. The extent of their inquiries is shown by the figures given in the paper. Whatever the experience lying behind the design and intended method of operation, each country has its own peculiar difficulties, and I venture to suggest how a few of these may be overcome on grid schemes which have not yet been completed. Valuable time and some expense would be saved if the preliminary surveys carried out by the Board could be done with such accuracy that the absolute positions of the towers could be determined and pegged out, thus avoiding a detailed re-survey by the contractors. Another difficulty which is commonly experienced by the Board, the Post Office, power companies, municipalities and others with overhead lines to erect, is that of obtaining wayleaves. In England we are individualists and do not like to interfere with the rights of property; but there comes a time when people cannot do absolutely what they like with their own property, because public utilities are being held up. There are two possible methods of dealing with the situation other than the persuasive method so far adopted by the Board. The Board have in their hands a weapon which might be used more freely than at present, in the right conferred on the Ministry of Transport to hold inquiries with a view to settling these questions. There has been a natural reluctance at the commencement of a new national scheme to make use of this power, but, when owners adopt the attitude that, although they are willing that a tower should be erected on their property, they will not allow its erection until they are forced, then it is time to adopt other methods, and I think that the Board might usefully consider arranging with the Ministry of Transport to hold monthly courts of inquiry in each grid area, so that all difficult cases could be brought before the court and disposed of in a regular way. My opinion is that this method would be so effective that there would be no need to resort to more drastic methods; but, should the proposed scheme be tried and prove a failure, then it would seem that the Government would have to ask Parliament to pass a one-clause Act giving the Board much more drastic powers in regard to wayleaves. The question of the life of steel-cored aluminium conductors under the climatic conditions existing in certain areas in this country has obviously considerably exercised the minds of the authors, and they have come to the conclusion that a life of 25 years can be depended upon. Strong evidence in support of this view is afforded by the behaviour of similar conductors in the worst industrial atmospheres in France and in and around Pittsburg in the United States. The case of Pittsburg was carefully examined about 18 months ago, with reassuring results. The examination showed that, with a galvanized-steel core and a single layer of aluminium wire surrounding it, the steel core was entirely protected against corrosion. On the grid the main conductors have two layers of aluminium surrounding the galvanized-steel centre while, in the case of the earth wire, the galvanized-steel core is compounded before the single layer of aluminium is laid on it, so that it is evident that, with the precautions taken and the experience gained elsewhere, there is no need to fear that the core will be attacked by the atmosphere, bad though it is in some districts. The authors do not indicate any way of dealing with vibration troubles with the conductors, if and when they arise. Our inquiries in the United States indicate that vibration trouble is confined to steel-cored aluminium lines where the area of the steel core is less than 40 per cent of that of the total conductor. There are three known methods of dealing with vibration at joints and points of suspension, viz. (i) that used with great success by the Electricity Commission of Victoria, Australia, on 132-kV lines; (ii) that used by the Hydro-Electric Power Commission of Ontario on their 220-kV lines; and (iii) the Varney method, patented by the Aluminium Corporation of America. The grid system is being carried out by British engineers with British or British Empire materials wherever these are available, and it is gratifying to note that, within the British Empire, there are at least two methods in use for dealing with vibration trouble if the need should arise. The successful operation of the grid will depend largely on the satisfactory operation of the transformers and, from this point of view, I inquired closely into the performance of large units when last in the United States. I was impressed by the regular weekly examination of the electric strength of the oil in the transformers, and the reconditioning of the oil if its strength fell below the prescribed standard; also by the large number of really high-voltage transformers that were insulated with paper. The British grid substations are being equipped with plant for the reconditioning of the transformer oil, but can the authors say whether the high-voltage transformers are also being insulated with paper? The authors quote the cost per mile of lines based on the Central Scotland contract. Since the paper was written further contracts for England have been let, and perhaps the authors would now give corresponding figures for the various areas concerned. The British practice is to use anti-climbing devices in order to prevent unauthorized persons from climbing the towers. A good deal of expense in first cost and subsequent maintenance is involved and it is doubtful whether, on 132-kV lines, the expense is warranted because, even if a mischievous boy climbed the pole and got right out to the end of a cross-arm, he still could not touch the live conductors without deliberately climbing down to the string of suspension insulators.

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* Paper by Messrs. JOHNSTONE WRIGHT and C. W. MARSHALL (see vol. 67, p. 685).

Mr. P. J. Robinson: The authors refer to the protective value of aluminium stranding against corrosion of the steel. Their statements would be perfectly correct provided that there have been no kinks or openings of the strand during erection, but it would appear that once a strand has been opened, and the steel is accessible to the weather, both corrosion and electrolytic action can take place in an acid or alkaline atmosphere. Has any attempt been made to coat the steel wire with bitumen previous to applying the aluminium conductors, and have any experiments been made of extruding a tube of aluminium over the steel core? I believe that this would be quite possible, and would certainly eliminate the defects I have mentioned. On page 695 (vol. 67) the authors mention arcing rings and horns on insulators; I am not clear whether they refer to bushings on circuit breakers and transformers, and they state that the use of arcing rings, etc., is by no means a standard practice. Has this view been modified since the paper was written, owing to the introduction of the one-piece stone insulator bushings which are being used so extensively on the Continent, where apparently they do not think it necessary to use arcing rings and bushings. I agree with the authors that all the propaganda that is being used against the erection of overhead lines is quite unjustified. When compared with the enormous mass of telegraph and telephone wires erected along main roads, the appearance of the overhead lines in connection with the grid becomes quite pleasing. In cases where it is necessary to put the lines underground in order not to interfere with the amenities of the district, is it proposed to step down the voltage for transmission by cable and to step up again on reverting to the overhead line, or is it proposed to operate cables at 132 000 volts? In either case, do the authors anticipate any trouble due to surges where lengths of cable connect sections of overhead lines? Fig. 8 shows a section of the line which is at present joined by isolating switches only and which has apparently been included as an emergency link. The two isolating switches are in series and are in very close proximity to each other, and I presume that the two switches have been put in with a view to enable the operator to work on one switch without one side being alive. At first glance this seems to be rather an expensive matter, and it is questionable whether it is warranted under the circumstances. A further disadvantage in this link, considering the interlocks referred to on page 703 (vol. 67), would appear to be that in the event of the emergency link having to be closed, assuming that the link controlled by the oil circuit-breaker is out of commission, the supply to both banks of transformers would have to be cut off; i.e. if both banks of transformers were on load, the circuit breaker on the healthy transformer would have to be opened until such time as the link had been closed, and the circuit breaker would then have to be closed again. In the meantime the supply would have to be discontinued. Do the authors rely on the galvanizing of the towers for preservation, or are the latter to be painted also? In many cases abroad they are painted, but I understand that this is rather a question of first cost, and that the operating engineers on the Continent would prefer to have the towers galvanized, as they find that painting is both expensive and difficult. Regarding oil circuit-breakers, have any tests been carried out on these to ensure that they have a rupturing capacity of 1 500 000 kVA? This is an extremely interesting point, as I understand that we have no testing plant in this country capable of testing up to such high rating, which seems to be rather discreditable in view of our large share in the construction of circuit breakers for the Dominions and elsewhere. The authors call for multiple-break oil circuit-breakers. I am rather under the impression that double break means the evolution of a double quantity of gas when the arc is undergoing rupture. Under these circumstances, is the multiple break warranted? Have the authors any views as regards the operation of these breakers, as to whether they should be operated by solenoid or centrifugal gear? Is it the intention of the Board to have an operator in these substations throughout the 24 hours? On page 710 (vol. 67) it is stated that there is a tripping circuit which operates the circuit breakers if the oil in the transformers rises to a certain predetermined temperature. Is any indication given in the control room as to why this circuit breaker has operated, i.e. whether it has opened under fault conditions or owing to high temperature? In Table 3 the weight of the transformers seems to diminish, in certain cases, with an increase of output. Is this an error? On the Continent it is a standard practice to erect towers in one piece, and haul them up by means of an anchor pole, using a caterpillar tractor for hauling purposes. I should imagine that mounting these towers on site would lead to rusty bolts and damaged galvanizing. No attempt seems to have been made to guard telephone or other wires which pass under the high-voltage lines. Is it the intention of the Board to ignore this matter entirely? Have the authors any information as to the trouble caused by salt-laden winds, which occasionally cover the insulators with a heavy coating of salt?

Mr. W. Fennell: I must confirm the remark which I made in the discussion at Manchester, namely that the cost per mile of the grid, particularly on the single-circuit line, is reasonable. A cost of £1 500 per mile for a single-circuit line of this description is, I think, a remarkable achievement. Of course, the negative profit of the contractors must be taken into account, but the result is extremely good. The paper does not state the method used when entering and leaving towns and cities. I should like to know how the 132-kV circuits of the grid will be led to the Clarence Dock at Liverpool. Warrington is to be a central switching point, and I imagine that the method of leading high-voltage lines in and out of the power-station yard will be a matter calling for a great deal of care on the part of the designers. The controversy over the Battersea power station turns upon the point of leading e.h.t. mains into and out of London. On one section of the secondary grid, not many miles from here, the line passes over the roofs of some suburban villas. It is inevitable that the lines shall pass above buildings, and I think further particulars in this connection would be useful. I think that the Board should make some tests in connection with the subject of local corrosion of line conductors. The question of aluminium and its power of resisting atmospheric impurities is very complicated. In South Staffordshire, with an acid atmosphere somewhat similar to that of Pittsburg, my experience indicates that only aluminium should be used. While brass lampholders failed in a year or two, aluminium holders seemed to last indefinitely. I erected a copper line in 1911 and it corroded at a rapid rate. An aluminium line which followed it was in good condition when I inquired two or three years ago. On the other hand, aluminium will not withstand an alkaline atmosphere. I am interested particularly in the secondary lines of the grid from the point of view of distribution, apart from the supply of power at existing power-station sites. The supply of rural areas does not seem to have been considered in great detail up to the present. Parts of the Western coast of England experienced a very bad brine-storm in November 1927, and high-voltage lines were affected for several hours. Steps should be taken to ensure that a sufficient factor of safety for insulators is provided in these areas. I do not say that the standard insulation will fail, but I think it would be better if it were reinforced. With regard to propaganda in relation to the preservation of rural England, I suggest that those who are concerned with obtaining wayleaves should not allow themselves to be induced to put lines underground simply to meet the views of local landowners regarding the appearance of overhead lines. Every such case is used to enforce further concessions.

Mr. E. M. Hollingsworth: I recently inspected some of the work carried out in connection with the Scottish Central section of the scheme, and was surprised at the speed at which the towers could be erected. I agree that these are pleasing in appearance and interfere very little with the landscape. A previous speaker mentioned the apparent difficulties of leading out the overhead lines from power stations in congested districts, but I question if there could be any more difficult example than that at Dalmarnock, where the overhead lines are already erected. On the question of corrosion of conductors and of the properties of insulators, I would point out that nearly three years ago, at the request of the Electrical Research Association, insulators of many kinds were exposed, in the Widnes district, to various chemical atmospheres, and also near the riverside in order to ascertain the effect of salt air. All the specimens are examined periodically, about once a month, and the condition of their surfaces as regards the formation of deposit, and the nature of the deposit, are recorded. We are assured by the Association that this co-operation is helpful in the investigation which they are carrying out in connection with the surface properties of insulators. I would mention that we are also co-operating in investigations as to the property of metals most suitable for use as overhead conductors, and for some time we have had placed in our works specimens of conductors of various kinds, some of these merely being exposed to the atmosphere, and others being, in addition, connected in circuit at various voltages.

Mr. F. V. L. Mathias: I was recently approached by a consumer of ours in Warrington, over whose works the Board propose to run overhead lines. These works generate a considerable number of gases: sulphurous acid, salicylic acid, ammonia and nitrous oxide. He asked my opinion as to how the conductors would be affected by these gases, as he did not want the risk of the lines falling on to his works. I must say that, in dealing with overhead gear on the tramways, it is our experience that galvanized steel is not particularly good; the wires have to be constantly renewed and constantly inspected. The inspection of a steel core enclosed in aluminium strands would be a rather difficult matter. It might be preferable to have the steel outside, so as to facilitate inspection, since it is practically impossible to detect any corrosion which may be taking place on the inside steel core. Even quite small areas of localized corrosion in the steel core would seriously affect the strength of the line.

Mr. H. Midgley: Can the authors give any details of the method to be adopted for protecting the transmission towers from corrosion? Painting is expensive and would entail a large and continuous labour charge. In addition the lines would have to be put out of commission during the painting process. Galvanizing, if adopted, is likely to suffer damage during erection, and the rapidity with which local corrosion, consequent upon such damage, becomes general is too well known to require further comment. The possibility of the metal spraying of completed towers appears to have much in its favour, as with such a method not only the tower members but also the nuts and bolts would receive a thorough protective coating. One aspect of the actual operation of the grid which appears to be fraught with considerable difficulty is that of paralleling two areas when, owing to a fault or some other cause, the interconnecting switches have tripped out and the two systems have become separated. Suppose, say, Liverpool and Manchester are normally running in synchronism, and that an exchange of load is being effected in one direction along the interconnecting line. If a separation occurs there will be a tendency for the frequency of the overloaded undertaking to fall slightly. The difficulty of re-establishing equal frequencies on two such large systems is obvious. Admittedly, this is probably the worst possible condition, but even if the frequencies of the two separated undertakings are identical the synchronizing current necessary to pull two complete areas into step might conceivably be quite sufficient repeatedly to trip the switches. An engineer who was associated with one of the interconnecting stations in this country some years ago had two sections of the system under his control, absolutely separated. They were both running, but not in phase, and owing to the very small breaking capacity of the switches the two halves could not be synchronized for about two hours, due to the tripping of the switches by the synchronizing-torque current. Admittedly, owing to the greatly increased breaking capacity of the switches being installed on the grid network, the possibility of such a situation arising is very remote, but at the same time it must be borne in mind that the size and number of the units interconnected by these switches have also greatly increased. I shall be glad to hear to what extent this aspect of the interconnection of large undertakings has been investigated.

Mr. H. R. S. Preston : It is stated that the general design of the lines complies with the Regulations of the Electricity Commissioners, but in and around Glasgow the lines are erected over railways, tramway equipment, telegraph wires and houses, without any special guarding arrangements and, although the factors of safety based on the specified loading conditions may be considered conservative, I think that some special means should be adopted to prevent damage in the event of a conductor breaking or falling, especially as it is recognized that trouble due to vibration may occur. Such an accident might cause much injury both to life and property, and might cause considerable public opposition to the scheme. It is stated on page 697 (vol. 67) that "The arcing horns and rings give a definite path for transient discharges and protect the insulators and conductors from power arcs." It is very necessary to protect the conductors from power arcs which might be caused by lightning and abrupt load-changes. In order that arcing should take place between the arcing horn and ring, the minimum distance specified between live metal and tower steelwork should not be less than the maximum distance between the arcing horn and ring of any insulator string. The specified minimum distance between live metal and tower is stated to be 42 in., whereas the distance between the ring and horn on the tension set is over 45 in. and, therefore, arc-overs are likely to occur between live metal and the towers. Is it the opinion of the authors that the arcing distance on the tension sets should be reduced to 42 in. or less? If so, then the only reason for increasing the number of discs in any insulator string should be bad atmospheric conditions, because whatever number of discs is added the distance between horn and ring should not be greater than that between live metal and tower.

Mr. L. Breach : The authors state that, owing to the change-over in frequency at Glasgow, it was found necessary to operate one circuit at 25 cycles per sec. and another circuit on the same tower at 50 cycles per sec. and, apparently, at a different voltage. I should like to ask, purely by way of interest, as I understand that this is only a temporary expedient, whether during the change-over any difficulty has been experienced owing to electrical swing due to the different frequencies and voltages at which the lines are operating. If so, what is the extent of this swing, and has it any definite period?

Dr. T. H. Turney : I am specially interested in the formulæ given for telephone interference, and although I have not seen how they are derived, it is interesting to note that Heaviside gives kindred formulæ for cylindrical waves of flux when electrostatic capacity is ignored. The authors mention that the formulæ become inaccurate at higher frequencies. Is this due to the omission of capacity effects? In other words, do the formulæ assume waves of diffusion, and not true electromagnetic waves? Some time ago two of our engineers were installing some telephone apparatus on a power system and, when they were making some connections on the telephone system, they noticed a series of sparks running along the tags of the telephone cable, owing to induction from a surge on the power system. It therefore appears that this question of interference due to surges has some importance. Can the authors give any information as to the way in which they propose to measure surges?

Messrs. Johnstone Wright and **C. W. Marshall** (*in reply*): Replying to Mr. Welbourn, delays in obtaining wayleaves have proved a serious obstacle to the construction of the "grid." The Central Electricity Board has, however, respected the rights of landowners and occupiers and has made appeals to the Ministry of Transport only in cases where all other methods of approach have failed. As for corrosion, the cases quoted by Mr. Welbourn regarding the behaviour of aluminium in industrial areas of France and the United States provide additional evidence of the soundness of the decision to use aluminium-steel conductors. The circumstance that vibration troubles have occurred only where the area of the steel core is less than 40 per cent of that of the whole conductor has already been noted. The "grid" conductors are not within the danger zone as defined in the above way, but the ratio of areas does not seem to be a very satisfactory criterion of safety from vibration; for example, one would hardly expect the addition of another layer of aluminium to make a conductor worse. Theoretical investigations are at present being made which will place the subject of vibration on a sounder basis. Some degree of vibration has been noted at isolated points on the "grid" lines, but no cases of a dangerous nature have yet been reported. The methods of overcoming vibration trouble mentioned by Mr. Welbourn have been supplemented by a new scheme, devised by engineers of the Electrical Research Association, which appears to have definite advantages. As regards transformers, it is obvious that oil maintenance is a matter of great importance, and it may be that the weekly oil inspection and testing are justified. Permanent oil-filtration plant is provided at all 132-kV "grid" substations, so that very frequent oil treatment may be resorted to at low cost. Paper is largely used as an insulating material in the "grid" transformers. The contract prices for lines in other areas have been somewhat lower than those for Scotland. The provision of anti-climbing devices is dictated by legal and political requirements, and there is at present little hope of it becoming possible to omit them in Britain, although in other countries only the oldest lines have any anti-climbing devices on their towers.

Turning to Mr. Robinson's remarks, the danger of corrosion being started by wires becoming kinked during erection is not negligible, but the line conductors, where there are two layers of aluminium, are not likely to give trouble. The earth wire has only one layer of aluminium. The steel core is bitumenized (in the manner mentioned by Mr. Robinson) before the aluminium is laid over it. Conductors in which an aluminium coating is extended over steel have not been considered for the "grid" up to the present. The scheme has, however, possibilities, and if wires of this type become available their properties and cases will be investigated as an alternative to the present construction. It does not by any means follow that the extruding system would be better than ordinary stranding; as the different coefficients of expansion are elastic, the electric and magnetic properties of aluminium and steel make it difficult to be sure that no trouble would occur when these metals are closely allied in the form of a tube and core. Arcing horns or rings are used on circuit-breaker and transformer bushings. The stoneware bushings referred to by Mr. Robinson are, so far as we are aware, used only in Germany. They make a useful alternative to porcelain or steatite and are said to be much cheaper. In some cases they are used without arcing horns, but this omission is by no means universal. From an æsthetic point of view, it is generally agreed that the "grid" lines compare favourably with telegraph and telephone lines. Only in a few cases has it been necessary to depart from the use of overhead lines for 132-kV working. In these cases 132-kV cable is being used. Joining up lengths of cable with overhead lines introduces an electrical discontinuity, which changes the form of any impulse passing along the lines. Experience on lower-voltage systems has proved that the cables are of value in protecting inductive apparatus from potential surges, and it is expected that similar results will be obtained on the 132-kV system. The two isolating switches shown in Fig. 8 are necessary to enable maintenance work to be carried out safely. The standard method of protection for the tower material is galvanizing. Painting will be adopted in one scheme where special steel towers are being used. Our own experience of Continental practice indicates that the maintenance engineers prefer galvanizing, although this method of protection is rarely used in France and Germany. No tests of the rupturing capacity of 132-kV circuit breakers have been made in Great Britain. Reliance has been placed on tests made on lower-voltage switches, and on information obtained from America, to ensure that the rupturing capacity will reach the required standard. Circuit-breaker failures have as a rule occurred on comparatively low-voltage systems. While it is possible that this is merely a result of the law of averages, combined with the fact that many switches which have failed were of poor design and construction, the thermal and mechanical stresses which arise from very large currents are undoubtedly less severe on very high-voltage breakers. The creation of a British testing plant, where such matters could be settled, is very desirable. There has been no attempt to standardize the type of circuit breaker to be used on the "grid," and both 2-break explosion-pot and multiple-break types will be used. Solenoid operation is usual: its chief disadvantage is the large power required for closing purposes. No centrifugally-operated breakers have yet been ordered. It is not anticipated that special operators will be required throughout the 24 hours at all "grid" substations. Tripping of circuit breakers caused by protective relays is definitely indicated on the relays involved. Maximum pointers are provided on temperature indicators. Table 3 in the paper as printed in the *Journal* contains the weights of transformers as given in the contracts between the Board and the manufacturers. The method of tower erection used extensively on the Continent, whereby the complete tower is pulled up into position by a winch or tractor, is generally applied to narrow-base riveted towers. The bolted wide-base towers used on the "grid" are erected vertically. Careful inspections are made to ensure that the galvanizing is kept as nearly intact as possible. The subject of guarding of lines at crossings has been closely studied. The Regulations of the Electricity Commissioners and the requirements of the Post Office are fully complied with, although in some instances the form of protection afforded differs from that usually adopted. The engineers of the Board have made a careful investigation of the effects of salt-laden winds. The lines have been kept as far inland as possible. Special insulators are being tried with a view to overcoming the troubles due to conducting deposits,.

Mr. Fennell refers to the difficulties of bringing 132-kV lines into cities. These difficulties are considerable, and the costs of the lines are greatly increased thereby. Special constructions are being considered whereby lines can be brought in over and along canals or railways. Double transformation and the use of lower-voltage cables will only be resorted to where the above methods cannot be applied. If it had been absolutely forbidden to take high-voltage lines over buildings, the cost of the "grid" would have been increased to a very serious extent. Great care is taken with the construction in order to eliminate the possibility of trouble occurring, and special samples of aluminium and galvanized steel wires and fittings are mounted in the worst districts so as to give the maintenance engineers convenient and timely warning of any corrosion which may occur. The evidence regarding relative rates of corrosion on brass, copper and aluminium in Mr. Fennell's district is interesting. Consideration of the subject of supplies to rural areas does not come within the scope of the paper and has not been mentioned. The matter has, however, not been neglected by the Board. With reference to brine storms, the determination of the amount which can justifiably be spent to ensure trouble-free operation in all line sections is very difficult. The insulation provided on the lines is adequate for the great majority of the sections in all ordinary conditions met with in Britain. It is expected that certain lines will have to be specially insulated. Provision has been made on the towers so that anti-fog insulators can be fitted where required. In no circumstances are lines being cabled merely to meet the views of local landowners regarding the appearance of overhead lines. On the other hand, the best available advice has been taken to ensure that lines will not be unsightly.

We are pleased to note that Mr. Hollingsworth has remarked on the speed of erection of the towers. We hope and believe that the British contractors will show themselves to be capable of attaining the highest standard in this respect. So far as we are aware, no more difficult work in overhead line construction than the Glasgow section of the "grid" exists in the world. The Widnes experience regarding the effects of chemical- and salt-laden atmosphere should be of great value, and details of the results obtained are awaited with interest.

In reply to Mr. Mathias, the effects of sulphurous acid, salicylic acid, ammonia and nitrous oxide on overhead lines are obviously dependent on the degree of concentration of these chemicals in the atmosphere. Presumably, the degree of concentration does not exceed that usual in the neighbourhood of modern chemical factories. In that case, the effects can be overcome by painting of towers and conductors and washing of insulators. The proposal that the rôle of steel and aluminium should be reversed does not commend itself to us. Ease of inspection of the steel is, in our opinion, more than counterbalanced by the higher rate of corrosion of steel relative to aluminium and the greater impedance and eddy-current losses. Experience has also shown that the degree of protection afforded by aluminium is very high, and that there is little fear from internal corrosion.

Mr. Midgley mentions metal spraying as a method of preventing corrosion. This suggestion opens up great possibilities, but, so far as we are aware, the method has not been developed to such an extent as to make it possible to use it on the "grid" towers. In the circumstances foreseen by Mr. Midgley, where two large sections of the "grid" which normally operate in parallel become disconnected, re-paralleling will generally be done on the lower-voltage switches joining the grid transformers to undertakings. Provision, in the form of condenser tappings on the circuit-breaker bushings, is also being made whereby sections can be paralleled on the 132-kV side. The particular instance mentioned by Mr. Midgley would be made much more useful if he would state definitely the capacities of the two interconnected systems and of the interconnecting link.

We note from his reference to crossings that Mr. Preston is of the opinion that some special means should be adopted to prevent damage in the event of a conductor breaking or falling. All precautions which are economically possible have been taken to this end. Mr. Preston should note that the minimum distance between live metal and towers occurs only when a conductor is in its position of maximum displacement from normal. The probability of an arc-over taking place between live metal and towers, relatively to the arc taking its normal path between arcing points, is very small. The arcing distance on tension sets has deliberately been set above that on suspension sets in order to prevent still further the possibility of damage to highly-stressed tension insulators. Increasing the numbers of discs per string, in addition to adding to the insulating value of the strings, also definitely reduces the electro-mechanical stresses on the individual units.

Replying to Mr. Breach, no untoward experience has so far been encountered on the lines in Glasgow where two circuits working at different frequencies are carried on the same towers. The open-circuit induced voltages on neighbouring lines are fairly high, but the energy transfer is small, and for this reason the temporary use of the lines in the manner described is considered to be sound practice. If Mr. Breach will state more precisely the nature of his difficulty we shall be glad to investigate the subject more closely.

The formulæ given for inductive interference are briefly dealt with in the "Directives" of the Comité Consultatif International, and definite references to the original work of Rudenberg are provided which will enable Dr. Turney to correlate the formulæ quoted with those of Heaviside. The reason for the discrepancy between values deduced from formulæ and those determined by experiment has not yet been elucidated. The experience quoted by Dr. Turney, in which sparks running along tags of telephone cable were observed, is of interest. We should be glad to have information regarding relative displacements of the power lines and communication lines figuring in this experience. It is frequently considered that the erection of the "grid" lines will add appreciably to the damage arising from induced voltages, but it should be remembered that, although the short-circuit currents on the "grid" lines will be larger than on existing power lines, in many instances communication lines are erected on the same towers as power lines and with a very small separation. In such cases communication work can be conducted without serious trouble due to inductive effects. It is therefore anticipated that the comparatively large displacements which exist between the "grid" lines and the communication lines will effectively prevent the occurrence of serious trouble.

NOTES ON THE 3-SWITCH TYPE OF SUBSTATION.

The following notes are based on Fig. 6 (vol. 67, p. 699):—

In normal operation the cross-over connection is open. When one transformer only is in use it is closed.

In the case of a line failure, the fault current is broken on the line switch and the corresponding transformer switch in parallel. One transformer is thus temporarily disconnected, but can be re-connected after opening the line isolator.

A faulty transformer is cut out of circuit on both high- and low-tension sides.

All possible faults on any part of the substation gear are cleared by one or other of the above cases.

A section switch can be taken out of service for overhaul, and a supply taken through both transformers with the cross-over connection in use, in emergencies. When both transformers are in use it is possible to reclose after a line has been disconnected by means of the transformer circuit breaker, thus having the reactance of both transformers in circuit.

When the station is to be used for working with one transformer only, the three circuit breakers are kept in use and the cross-over connection is closed. The transformer which is out of use is disconnected by means of its isolator switch and low-tension circuit breaker.

In the case of line failures, the section circuit breaker, and the transformer circuit breaker adjacent to it, operate, leaving the transformer connected to the sound line through the remaining circuit breaker.

In the case of a transformer failure, both 132-kV transformer circuit breakers and the transformer lower-voltage circuit breaker open.

INSTITUTION NOTES.

Honorary Member.

At the Ordinary Meeting of the Institution on the 9th January the President announced that the Council had that day elected Sir Richard Glazebrook, K.C.B., D.Sc., F.R.S., an Honorary Member of the Institution.

Local Hon. Secretary for Italy.

Mr. L. Emanueli has been appointed by the Council as the Local Hon. Secretary of the Institution for Italy, to fill the vacancy caused by the death of Mr. Semenza.

Subscriptions of Retired Members.

The Council have amended the Rule (see *Journal*, 1927, vol. 65, p. 93) in regard to the subscriptions of Corporate Members of long standing who have retired from the profession. The revised Rule now reads as follows:—

> "Any Corporate Member who has reached the age of 60 and has retired from the practice of his profession or business, may apply to the Council to remit his future annual subscriptions, provided that his membership of the Institution has been continuous for at least 25 years. If he desires to have the publications of the Institution he will receive them on payment of £1 1s. 0d. per annum."

Graduateship Examination Results: November, 1929.

*Passed.**

Baldwin, C. S. S. (Manchester).
Bates, H. O. (London).
Batley, H. (London).
Bevan, P. A. T. (Abertillery).
Boydell, N. (Southport).
Brockbank, J. B. (Wolverhampton).
Brown, W. J. (Altrincham).
Buckley, C. F. (Malta).
Butterworth, H. (Manchester).
Capp, P. F. (Luton).
Castellan, G. E. (Rugby).
Charlton, T. H. (Manchester).
Clift, R. C. (Plymouth).
Cowlishaw, A. (Sheffield).
Daines, S. A. (Bedford).
Deason, J. N. (London).
Ellwood, P. (Rugby).
Evans, T. (Ebbw Vale).
Ferris, G. T. (Plymouth).
Fielding, A. L. (London).
Flint, E. F. (London).
Gartside, A. (Bromsgrove).
Gent, A. (Accrington).
Godden, F. W. (Cheltenham).
Goodyer, K. S. (Coventry).
Haldane, H. R. (London).
Hall, W. G. E. (Erith).
Hawken, J. J. (Plymouth).
Heath, F. E. (London).
Hegan, A. (Lancaster).
Helm, L. R. D. (Skipton).
Hollingworth, J. E. R. (London).
Holroyd, B. N. (Manchester).
Isterling, J. (Liverpool).
Just, E. J. (Norton-on-Tees).
Lewis, G. E. H. (Bakewell).
Lloyd, J. L. (Heswall).
Loveluck, J. H. N. (Ingol).
Lund, G. (St. Helens).

Passed—continued.

Lusty, H. H. (Ashton-upon Mersey).
Mare, A. J. (London).
Marshall, H. F. (Leamore, Walsall).
Maxwell, R. G. (Dublin).
Meyer, L. W. (London).
Mittra, M. G. (Stafford).
Morley, C. G. L. (London).
Morris, C. H. (Birmingham).
Moss, J. L. (Barking).
Palmer, E. B. (Smethwick).
Parsonage, S. H. (London).
Philip, M. (London).
Phillips, J. D. N. (Hayes, Middx.).
Platt, L. K. (Blackpool).
Raybould, S. (Birmingham).
Spruce, A. M. (Walsall).
Stahl, H. C. (Manchester).
Swinney, J. (Manchester).
Thomson, M. F. (London).
Tudball, F. C. (Manchester).
Vickers, H. E. (Hull).
Vine, H. A. E. (Manchester).
Walters, F. (Burton-on-Trent).
Ward, E. (Farington).
Watts, J. L. (Birmingham).
Wilkinson, A. B. (Leigh, Lancs.).
Withers, A. S. (Dewsbury).
Woodcock, V. (Birmingham).
Woodroffe, D. N. (Castle Bromwich).
Yardley, A. A. R. (Edinburgh).

Passed Part I only.

Allen, R. G. (Manchester).
Billson, F. W. (Wolverhampton).
Cole, F. J. (London).
Fernando, E. A. (London).
Geach, E. A. (Chichester).
Halstead, F. J. (Chesterfield).
Lash, A. R. (Carnarvon).
Martin, A. J. (Eynsford).
Matthews, T. F. (Tredegar).
Palmer, E. H. K. (Harrow).
Ridler, P. H. (Darwen).
Saville, J. (Dresden, Stoke-on-Trent).

Passed Part II only.

Galloway, J. (London).
Mullane, A. J. (Cardiff).
Snelling, C. A. (Ystrad Mynach).
Viant, J. R. (Southampton).

Further results, relating to candidates who sat for the Examination abroad, will be published later.

Proceedings of the International Conference on Large Electric High-Tension Systems.

The Secretary has been requested to call the special attention of the members to the subscription form enclosed with this issue of the *Journal*, for copies of an English translation of the Proceedings of the Fifth Session of the above Conference held in 1929. The Proceedings will contain the 100 papers presented at the Session and full reports of the discussions, and, in order to justify the cost of publishing an English translation, at least 300 subscriptions will be necessary.

Of the papers presented, 30 deal with the design and manufacture of generating and transforming plant,

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* This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

38 with overhead lines and cables, and 32 with parallel operation, earthing the neutral, protection against surges, metering h.t. energy, etc. They contain recent information in regard to developments since the last meeting of the Conference and were written by experts from 15 different countries. Members wishing to subscribe should fill in the form and return it with a remittance of the appropriate amount to the Secretary, The International Conference on Large Electric High-Tension Systems, Boulevard Malesherbes 25, Paris.

American Society of Mechanical Engineers.

The American Society of Mechanical Engineers will celebrate its Fiftieth Anniversary in April 1930, at Washington. The principal event will be a convocation in that city, starting on April 7th, but this will be preceded by a reception to the delegates at the home of the Society in New York on April 5th, and a pageant depicting the first meeting of the Society. Members of The Institution of Electrical Engineers who may be in the United States at the time are cordially invited to participate in the meetings. Full particulars can be obtained from the Secretary of the American Society of Mechanical Engineers.

The Benevolent Fund.

The Committee of Management desire to draw the attention of the members to the appeal for funds which will be found on the last page of the cover of this issue of the *Journal.*

Membership Transfers.

The following transfers have been effected by the Council in accordance with the provisions of Bye-Laws 14, 15 and 18:—

From Companion to Associate.

Ryan, William Albert, B.A., B.L.

From Associate to Companion.

Adlard, Howard T.
Alabaster, Geoffrey Hubert.
Alabaster, H.
Anderson, Frederick William M.
Atherton, Arthur.
Atkinson, George Alexander S.
Barker, Arthur Henry, B.A., B.Sc.
Barr, Thomas Hall.
Barrett, Harry George.
Beatty, Andrew Henry.
Bigge, Denys Leighton S.
Bishop, Walter Frederick.
Blackwood, John A.
Blundell, J. Wagstaff.
Booth, Lancelot Henry, M.A., LL.M.
Boyd, William Robert E.
Brooks, Emile.
Burbury, Henry Herbert T.
Burnham, Walter Witt.
Byng, Ernest Gustav.
Cameron, Sir Maurice Alexander, Major, K.C.M.G., late R.E.
Challoner, William.
Clough, William Thomas.
Cohen, Jacob Whaley, Lieut.-Col., C.M.G., C.B.E., D.S.O., T.D.
De Roemer, Charles William.
Ditmas, Francis I. L., Lieut.-Col., D.S.O., M.C.
Dunlop, Daniel Nicol.
Eastick, John Clare N.
Evans, Bertram Charles.
Falmouth, The Rt. Hon. the Viscount.
Faning, Vyvyan Eaton.
Faraker, Frederick Cecil.
Ferguson, Harry Edmund.
Fleming, Albert Arnold.

From Associate to Companion—continued.

French, Sir Somerset Richard, K.C.M.G.
Gill, Hubert Alexander.
Goodyer, Thomas Boyce, O.B.E.
Graves, Thomas.
Gray, James.
Green, Arthur Leonard.
Griffiths, Martin.
Henderson, Charles Joseph.
Henderson, John Francis.
Herbert, George.
Hider, George Ernest.
Hobbs, William Edward.
Hosgood, Octavius Sidney.
Hoyle, Harry.
Hughman, Sir Ernest Montague.
Hughman, Robert William.
Hussey, William Clive, Major, C.V.O., R.E.
Ince, John Oscar.
Ingram, John, B.Sc.
Irwin-Packington, Philip.
Jameson, Charles Godfrey.
Jennings, Ernest John.
Jones, Francis Henry.
Kahn, Henry Joseph.
Lees, Charles H., D.Sc., F.R.S.
Leete, Ernest.
Le Tall, F. W.
Lloyd, Daniel William, B.Sc.
Lloyd, George Christopher.
Lloyd, Harold R.
Lockhart, James.
Lord, F. A. B.
Lucas, William, M.A.
MacIntyre, Hugh McCallum.
Mackenzie, Thomas Brown.
Mackinnon, Lachlan.
Maclean, James Borrowman, C.B.E.
Macmillan, Robert.
Macnaughton, Duncan James.
Maling, Frederick T.
Mallins, Charles W.
Malpas, Douglas Duncan, M.R.C.S., L.R.C.P.
Martin, William, M.D.
Maunsell, M.C., Major, R.A.
Merriman, Will H.
Metcalf, Rev. Francis William R., M.A., R.N.
Michie, Arthur Cumming.
Morris, Robert John.
Murray, William.
Napier-Whittingham, Duncan.
Nash, Sir Philip A. M., K.C.M.G., C.B.
Nickless, John Ernest.
Norman, The Rt. Hon. Sir Henry, Bart., P.C., M.P.
Owles, Archibald Bewick.
Parsons, Charles Sidney, B.Sc.(Eng.).
Pearman, William Arthur.
Pirelli, Alberto.
Pirelli, Piero.
Prance, Henry Waymouth, Major.
Quennell, William Alec, Lieut.-Col., R.A.O.C.
Raworth, John Ernest.
Renfree, Tom Rolls.
Renwick, Sir Harry Benedetto, Bart., K.B.E.
Rickie, James Hepburn.
Ridsdale, John Langford D.
Rowell, Percy Fitzpatrick.
Roy, Charles Smart, Ph.D.
Ryan, William Albert.
Sandberg, Oscar Fridolf A., O.B.E.
Scott, Sir Buchanan, Colonel, K.C.I.E., R.E.
Scott, William Albert.
Sear, Abraham James.
Sergeant, J. Charles.
Shepperd, Alfred H.
Simpson, Lightly S., Col., C.B.E., D.S.O., R.E.
Skerrett, Henry Norton.
Smail, James C., O.B.E.
Stanley, Stanley Herbert.
Stevenson, Charles A., F.R.S.E.
Sutcliffe, James Anderton.
Swain, John Henry S.
Tansley, George Edward.
Thomson, Octavius Baynes.
Tuckett, Philip Debell.
Upsdell, Rev. George Edgar S., M.A.
Vickerman, Montague Harold.
Walker, William Peto.
Ward, Basil Kendall.
Wiggins, Harold Percy.
Wilson, Christopher.
Wilson, Ernest.
Wilson, William Henry.
Wisely, George A. K., Capt., R.E.
Woodcock, William Edwin.
Worsdell, Frederick Ernest.
Wright, Harold Charles.
Wyllie, Colin Campbell.
Yarrow, Harold Edgar.

From Associate to Graduate.

Bramwell, Eric Benjamin.
Chakravarti, Narendra Nath.
Geernaert, Sidney Glorieux.
Hartland, Sydney.
Qadri, Noorul Hoda.
Stapleton, Stanley John.

From Associate to Student.

Easton, Harold.
Jeffery, Clifton Adin K.
McKay, Hugh Stewart.

From Student to Graduate.

Adams, Henry Frederick T., B.A.
Aikman, Robert Alexander.
Ainger, Christopher George, B.Sc.
Anderson, James Richard, B.Sc.(Eng.).
Bailey, Herbert Bolton, B.Sc.
Bamford, William, B.Sc.
Beddoe, George Neville, B.Sc.(Eng.).
Bennett, Norbury Anderson, B.Sc.(Eng.).
Best, William Bernard, B.Sc.(Eng.).
Bhalla, Kanwar Lall.
Bhasin, Om Parkash.
Birtwell, John Tempest.
Bishop, Geoffrey, B.Sc.
Bishop, William Russell.
Bligh, Norman Richard, B.Sc.(Eng.).
Blumlein, Alan Dower.
Bowker, Henry Charles, B.Sc.(Eng.), Ph.D.
Bramley, Lionel Napier, B.Sc.(Eng.).
Briggs, Charles Stanley, B.Sc.(Eng.).
Buckhurst, John Charles V., B.Sc.
Burdes, Leonard.
Butler, John Henley.
Caldecott, Walter Donald.
Campbell, Ian Drummond, B.Sc.(Eng.).
Canning, Horace Reginald.
Carter, John Alfred V., B.Sc.(Eng.).
Chalmers, George Herbert, B.Sc.
Chapman, Geoffrey Tancock.
Child, Thomas William.
Ching, Edgar Alexander.
Chisholm, Alexander David.
Clement, John, B.Sc.
Cobb, Kenneth, B.Sc.(Eng.).
Coke, Robert Alexander.
Connon, Edward William, B.Sc.
Cook, Harold Foden, B.Sc.(Eng.).
Cowan, James Allan.
Cross, Leonard Jack, B.Sc.(Eng.).
Crutch, Leslie Spicer, B.Sc.(Eng.).
Cutmore, Reginald Richard.
Dickinson, Herbert George B.
Drakeford, Louis Samuel F., B.Sc.(Eng.).
Drummond, Charles Walter B.
Drury, George John S.
Dumeresque, John Sibley D.
Dyson, Edgar Veary.
Earle, James Bendyshe.
England, Philip Cuthbert, B.Sc.(Eng.).
Evitt, Frank Beresford, B.Sc.(Eng.).
Fairlie, Archibald, B.Sc.
Fernando, Edmund Clement.
Field, Albert William, B.Sc.(Eng.).
Ford, Wallace, B.Sc.(Eng.).
Forgan, Albert George, B.Sc.(Eng.).
Fowler, Geoffrey, B.Sc. Tech.
Fricke, Henry Moger.
Gale, Arthur Richard N.
Gaughan, Martin, B.Eng.
Ghose, Satyendra Chandra, B.Sc.(Eng.).
Gillespie, Colin Arthur.
Ginger, John Edward W.
Gosling, Arthur John G.
Gould, Leslie Spencer, B.Sc.(Eng.).
Graham, David, M.Sc.
Graham, Harry.
Grant, Roderick Morison, B.Sc.
Greig, James, B.Sc.
Groves, William Byers G., B.Sc.
Haigh, Daniel Grenfell.

From Student to Graduate—continued.

Hall, Frederic Philip W.
Harris, Richard Norman.
Harris, Robert William L., B.Sc.
Harwood, Edward Holroyde, M.Sc.
Hawke, Christopher.
Hogg, Thomas Mylne, B.Sc.
Hypher, Patrick Basil, B.Sc.(Eng.).
Ingamells, George Harry, B.Sc.(Eng.).
Ingham, Frank.
Iyengar, Komandur R. N., B.Sc.
Johnson, Guy Winter, B.Sc.(Eng.).
Johnston, Eric F., B.Sc.
Kendall, William George S.
Kiew, Kon Fatt, B.Sc.
Kilshaw, John Booth.
King, Stanley George.
Kishan, Kewal.
Knight, Arthur William.
Knight, Sidney Alfred, B.Sc.(Eng.).
Kulkarni, Heramba Suryanarayan.
Lambert, Douglas Edward, B.Sc.(Eng.).
Langbein, William.
Lanyon, George William, B.Sc.(Eng.).
Lawry, Arthur Vivian.
Lawson, Robert.
Leitch, John Muir, B.Sc.
Leith, Allan Ramsay.
Lemon, Eric Oscar, B.Sc. (Eng.).
Lingard, Harold.
Manser, Harold Walter.
Mason, Thomas Frederick V.
Mather, Frank.
Matthews, Albert Dent.
Matthewson-Dick, Tom.
Miles, Philip Pierpoint.
Moffatt, Joseph Walton.
Moolgaokar, Sumantrao.
Morgan, Guy William.
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VOLTAGE CONTROL OF LARGE ALTERNATORS.

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SUMMARY.

The voltage control of large alternators is considered, with special reference to large high-speed machines now being installed in capital stations.

With a view to stimulating discussion the treatment is descriptive and is dealt with under the following headings:—

Exciter stability.
Exciter response.
Alternator stability.
Alternator response.
Combined response of alternator and exciter.

INTRODUCTION.

The problem of maintaining constant voltage on a generator when large loads are frequently thrown on and off is still met with in some mills and factories which, for good reasons, still generate their own power.

With power supply from capital stations, and with increasing size of systems, incidental variations in legitimate load have become relatively small and only system faults constitute changes of load which require adjustment of the machine excitation.

As systems expand they are sectionalized, with interconnecting reactors between sections. When a severe fault occurs close to the generating machinery in one section, it is unlikely that any practical design or mode of operation can maintain full voltage. Indeed, there is a difference of opinion among operating engineers as to whether the excitation of the machines should be allowed to increase appreciably under these conditions. When, however, a fault occurs at a distant point or in an adjacent section, it is usually desired that the excitation on the generators be increased quickly to the limit of the exciter capacity, so as to maintain the supply voltage as near to normal as possible, at any rate on those sections of the system which are not local to the fault.

Side by side with increase in size of system, there is also a tendency to increased sizes of generating units. The magnet systems of these machines require larger stores of electromagnetic energy, which tends to a longer time in responding to changes in the excitation circuits intended to maintain normal voltage after sudden load-changes.

The study of the machine voltage control requires consideration of "stability" and "speed of response," both separately and in combination. Stability determines whether the drop or rise in voltage becomes cumulative after certain load-changes, and response determines the quickness with which, by a change in the excitation circuits, voltage can be restored when temporarily disturbed by load-changes. In some cases when a change of load tends towards instability a quick response can restore stability before the machine voltage has become unduly depressed.

Voltage control is nowadays required to be automatic within a few per cent of normal value. As direct manipulation of the alternator field circuit is not practicable, the control of the generator voltage is effected by changes in the exciter field circuit, so that it is necessary to consider the stability and response of the alternator and its exciter in combination. However, the consideration of the subject is simplified by discussing, firstly, the exciter alone, secondly, the generator alone, and finally the two in combination as a generating unit.

EXCITER STABILITY.

Two kinds of instability of the exciter may occur; these may be designated "load instability" and "inherent instability."

Exciter Load Instability.—This is caused by the load current in the armature overpowering the field excitation. Assuming that no alternator field rheostat is used, so that the exciter is loaded simply upon the alternator field windings, the exciter load current and voltage will increase or decrease together except in so far as a higher load causes an increase in resistance due to the temperature of the alternator field coils. This increase may be more than 33 per cent above the cold resistance when the unit is put into service. This feature, together with the saturation which occurs, helps to make the exciter stable at heavy loads, but some attention to design details is necessary to guard against exciter instability at light loads. It is suggested that the air-gap should be such that at low exciter voltages the field ampere-turns are greater than the corresponding armature reaction with the alternator field cold. In addition to this precaution, equalizing connections should be provided on the armatures where lap windings are used.

A further aspect of exciter load instability which requires consideration is that, when load is thrown on to the alternator, its excitation tends by virtue of the inertia of its magnet system to assume, temporarily, the new and larger value of excitation required for maintaining constant voltage under the new load conditions. Thus the armature may be loaded before its field circuit is adjusted and its field current brought up permanently for the new condition. This effect will usually be taken care of by the proportions of design just proposed; but when the load change is abnormal, and automatic means of causing the exciter field circuit to respond quickly are not in use, a shunt exciter may lose its voltage altogether and then build up with reversed polarity. In the meantime the supply is subjected to a surge as the alternator slips a pole and re-synchronizes with other generators on the system whose exciters have not been so affected. Separate excitation of the exciter field is a preventive against complete reversal.

It has been suggested that a certain amount of series winding on the main poles is helpful in regard to the load instability of a shunt machine, but when the series ampere-turns are suddenly increased the shunt ampere-turns decrease correspondingly because of the inertia of the exciter magnet system, so that the net excitation is not immediately affected. Inasmuch as load instability arises from the cross-magnetizing action of the armature current, a pole-face, or, as it is usually called, a compensating winding, affords a cure, and a damping winding, consisting of a set of short-circuited bars, affords a partial remedy.

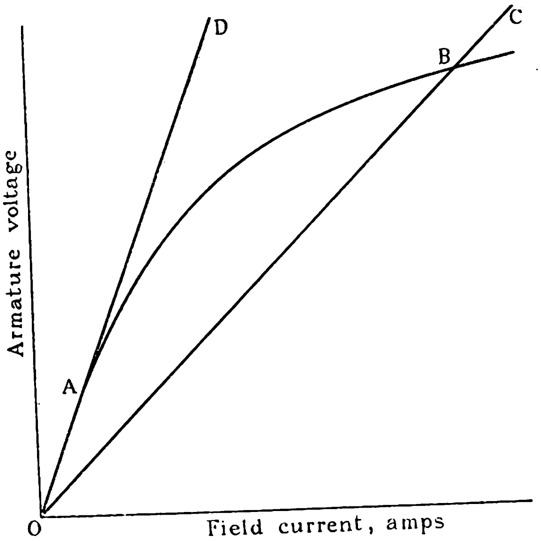

Fig. 1.

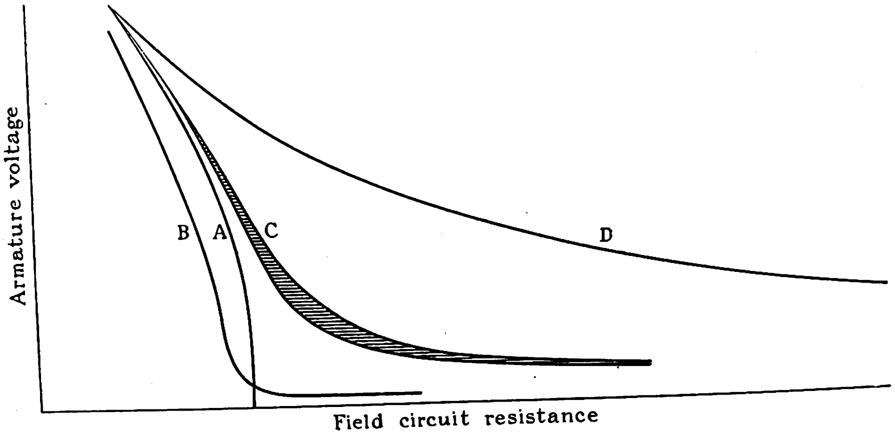

Fig. 2.—Curves illustrating grading of rheostats for different types of exciters.

Inherent Instability of Exciters.—In order that a shunt exciter may be stable at a given voltage, it is necessary that a straight line drawn through the origin of the saturation curve should cut the curve at this point. For instance, if OAB in Fig. 1 represents a load saturation curve connecting field current and armature voltage, then as a straight line drawn through the origin definitely cuts the saturation curve at B, the voltage is inherently stable at this point.

The slope of the straight line OB gives the resistance in the exciter field circuit for this voltage. As further resistance is introduced into the exciter field circuit, the line representing it becomes steeper and ultimately a certain value of resistance, represented by, say, OD, corresponds to the initial shape of the saturation curve, which, unless some precaution is taken, may be very nearly a straight line through the origin up to an appreciable proportion of the maximum exciter voltage. With resistance corresponding to OD, the exciter voltage will settle down to a value corresponding to A, but if the resistance be further increased the exciter voltage will disappear, the exciter having become inherently unstable. However, shunt exciters are not so inherently unstable as indicated by the saturation curve in Fig. 1, because they must have a small remanent magnetism in order to build up, and the saturation curve therefore does not pass exactly through the origin.

The instability of the shunt machine presents itself to the designer as a difficulty in suitably grading the shunt rheostat in order to obtain uniform increments in voltage. For this purpose it is convenient to exhibit exciter stability by a curve connecting field circuit resistance and armature voltage, and a curve corresponding to the saturation curve shown in Fig. 1 is shown as curve A in Fig. 2. The difficulty in grading a rheostat for equal increments of exciter voltage will be obvious.

Various attempts have been made to stabilize the shunt machine at lower voltages. Some of these consist in introducing premature saturation in some short length of the magnetic circuit, while others attempt to provide an initial voltage which is independent of the shunt field circuit.

Two means of effecting the first method are shown in Figs. 3(*a*) and 3(*b*). The former shows the pole cut so that for a short length it becomes prematurely saturated, while the latter shows a shim used between the pole core and the frame. The shim is perforated with holes and so produces local saturation as flux passes from the pole core and into the frame. The use of a cast-iron magnet frame in preference to one of steel helps the stability of a shunt machine, but any method of producing initial saturation must of necessity limit the maximum voltage. A curve for studying rheostat grading corresponding to a small amount of initial saturation is shown as B in Fig. 2. This shows easier conditions as regards rheostat grading than curve A, but some difficulty still remains owing to the field-coil resistance varying with temperature. A different setting of the field rheostat is therefore possible for the same load, according to whether the loads previously carried were high or low. This necessitates a fine grading over a relatively large portion of the rheostat.

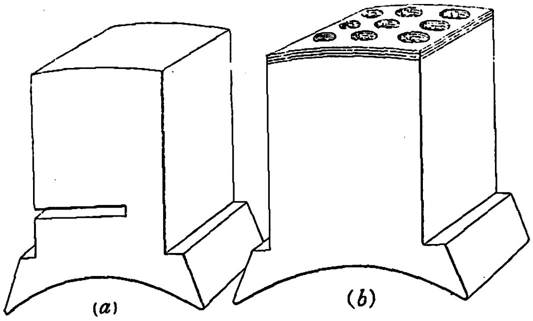

Fig. 3.

Methods of providing a small initial voltage consist of making either a part or the whole of the magnetic pole cores of some hard magnetic material or, alternatively, of providing a small coil in addition to the shunt winding, which can receive a trickle current from a battery. Curves corresponding to these methods are shown as C in Fig. 2, but the use of hard magnetic material is attended with some disadvantage in that the rising magnetization curve of such material differs from the falling one, especially at low flux densities. The possibility of a rise or a fall in voltage at any time in this region of curve C in Fig. 2 is shown by shading.

The use of a small amount of initial excitation is a step towards completely separate excitation. This ensures inherent stability. A curve corresponding to this condition of excitation is shown as D in Fig. 2. In many stations, however, a continuous source of supply for the full excitation of the exciter is not available, for even when a battery is installed many engineers are reluctant to allow the operation of the unit to depend ultimately upon it. In order to make separate excitation of the exciter acceptable the practice has been initiated of building, as an integral part of the machine, a small service exciter which operates at constant voltage with a saturated magnetic circuit and which, therefore, is perfectly stable for exciting the main exciter. A neat arrangement consists of combining the service exciter in the same frame as the main exciter, as shown in Fig. 4.

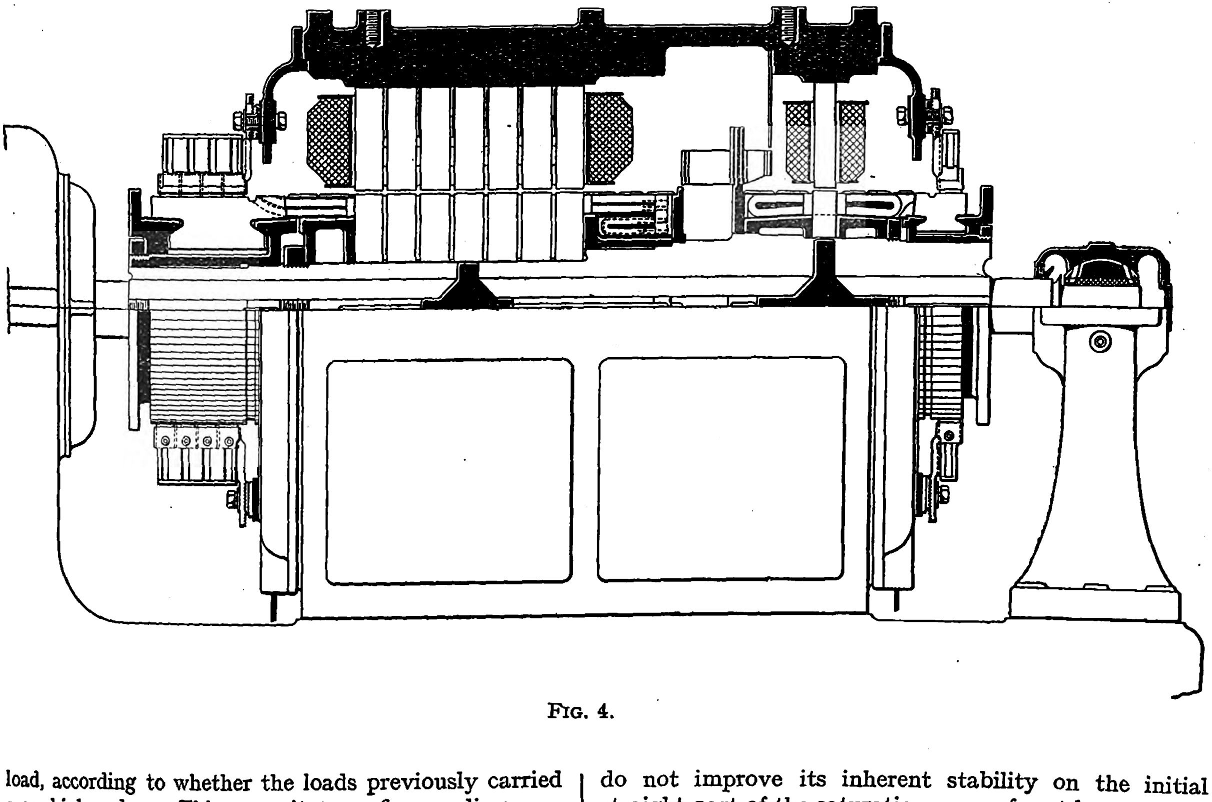

Fig. 4.

Series windings on the main poles of a shunt exciter do not improve its inherent stability on the initial straight part of the saturation curve, for at low voltages a pure series machine has the same range of instability as a shunt machine.

Exciter Response.

Definition.—The response of an exciter may be defined as the rate at which its voltage increases per second when the resistance in its field circuit is changed. Ultimately, in studying the complete alternator unit the response in exciter voltage must be translated into a response in alternator voltage.

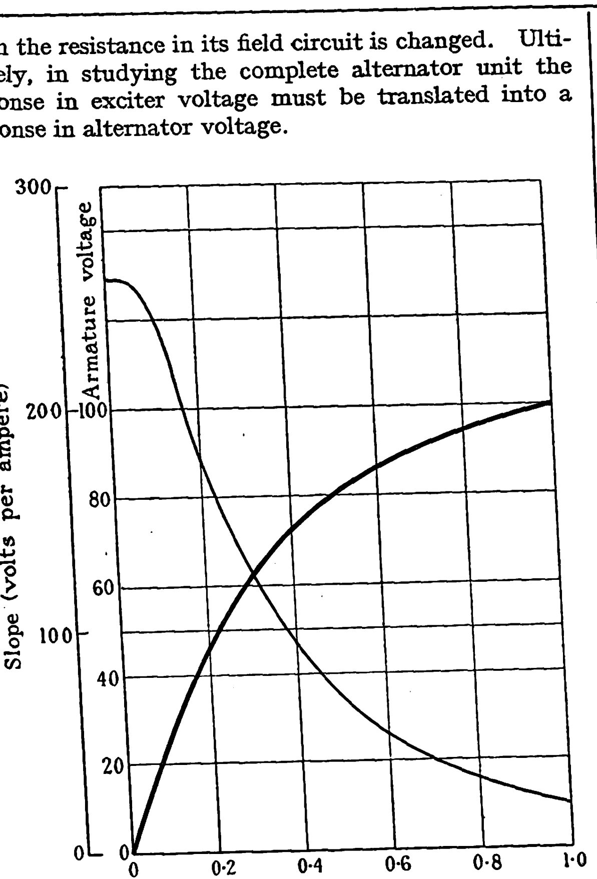

FIG. 5.—Typical exciter saturation curve.

The definition applies to the removal or the addition of resistance corresponding to rising or falling voltage, but, because the exciter voltage can be made to fall much more quickly than it can be made to rise, exciter response is considered throughout the paper with particular reference to the condition when all the exciter rheostat is short-circuited and the exciter voltage increases to the maximum possible value.

The response figure at any voltage is calculated by dividing the ultimate increase in exciter voltage by the time-constant of the exciter, the time-constant being defined as the time in seconds which the voltage would take to reach its final value if it continued to grow at the same rate at which it commenced to grow from the voltage in question. When saturation is present, the ultimate voltage in this definition is that which would be reached if the degree of saturation remained unchanged.

For a separately-excited exciter, the time-constant is calculated in seconds by dividing the self-induction of the exciter coils in henrys by the resistance in the exciter field circuit, a certain small time being added to allow for mutual circuits in the exciter field system, as explained later in the paper.

Comparison between Shunt-excited and Separately-excited Exciter.—In order to make the discussion general and the deduction applicable to all cases, a typical saturation curve is shown in Fig. 5, which gives a maximum voltage of 100 with an excitation of 1 ampere. Saturation curves, of course, vary in detail and designers may at times be tempted to run to a higher degree of saturation at the expense of an excessive field current, but this curve may be taken as representative if, for any actual case, a particular exciter voltage is reduced to a percentage of the maximum and the corresponding field current is reduced to a fractional part of its maximum. Fig. 5 also indicates degree of saturation at any excitation by giving a separate curve for volts per ampere. But for saturation such an exciter would give 260 volts at maximum excitation.

Again for the sake of generality in discussion, the time-constant of a typical exciter when working separately excited and unsaturated is taken as 1 sec.

Curve (a) in Fig. 6 shows the growth of voltage in this typical machine separately excited, when the field rheostat is changed to increase the voltage from 15 to the maximum value. If saturation were not present the exponential law would be followed, but because of saturation this curve is distorted at high voltages. The growth to the maximum from any other voltage may be obtained by moving the vertical axis to give zero time at that voltage.

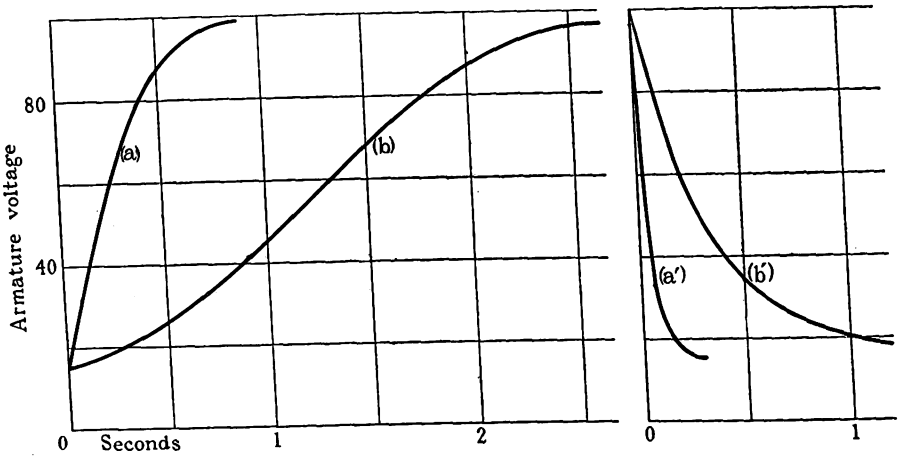

FIG. 6.—Growth and decay of voltage with shunt-excited and separately-excited exciters (exciter time-constant = 1 sec.).

The shunt exciter is slower than the separately excited machine in voltage growth and response as it depends for its exciting current upon its own voltage, which, at time of light load, is of relatively low value, whereas the separately excited machine has always a high, steady voltage with which to effect changes in exciter excitation.

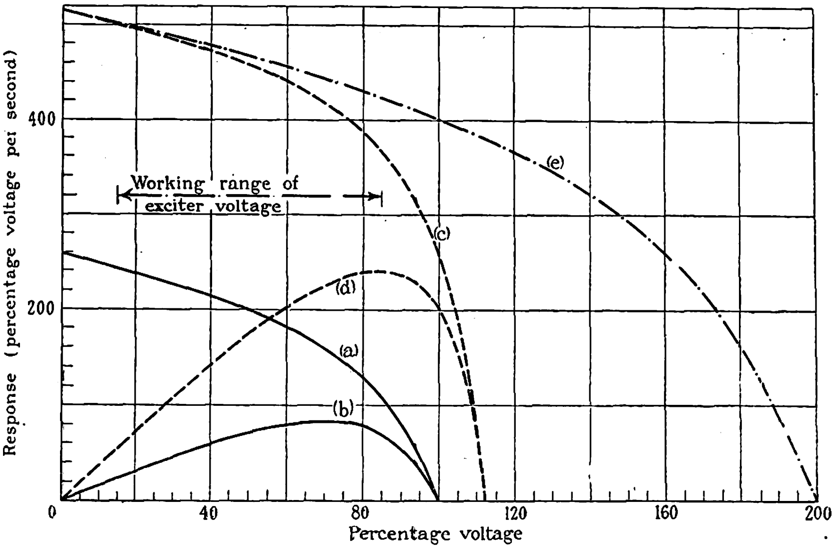

Fig. 7.—Voltage response of shunt-excited and separately-excited exciters (exciter time-constant = 1 sec.).

The growth of voltage from 15 per cent to maximum for the same typical exciter used as a shunt machine is shown as (b) in Fig. 6.

Curves (a′) and (b′) in Fig. 6 show the fall from maximum voltage when exciter field resistance corresponding to about 70 per cent of open-circuit alternator voltage is inserted. The exciter voltage falls away so quickly that a rise in alternator voltage after a reduction in load is easily prevented, and in the remainder of the paper only the response for an increase in load will be considered.

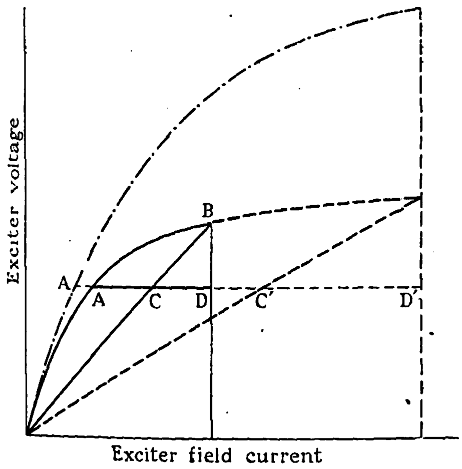

Fig. 8.—Graphical representation of exciter response.

The response curve at different voltages for the separately-excited exciter has been plotted in curve (a) in Fig. 7 from curve (a) in Fig. 6. At high voltages the total change in voltage is smaller, so that the response falls off as maximum voltage is approached. It is therefore desirable that the maximum available exciter voltage should be at least 15 per cent greater than that required for maximum excitation of the generator. The response for the same exciter when shunt-excited is plotted as curve (b) in Fig. 7.

It is interesting to show on a typical saturation curve how the responses for the two types of machine are related to one another. In Fig. 8, if B is the maximum possible voltage in both types of machine and A is any selected voltage, AC represents the response for a shunt machine and AD that for a separately-excited machine at this voltage.

Use of Curves for a Particular Exciter.—The growth and response curves in Figs. 6 and 7 have been based upon an exciter time-constant of 1 sec. for the unsaturated range of voltage and when the exciter is separately excited.

The time-constant of any exciter under these conditions can be calculated with fair accuracy from design data, so that values taken from Figs. 6 and 7 can be corrected for a longer or shorter time-constant as required. For instance, if the time-constant is 0·5 sec., a given voltage is reached in half the time shown in Fig. 6, and the response figures in Fig. 7 are twice as fast. From a machine-design point of view, the time-constant of an exciter is lower the higher the speed, but apart from this it seems to depend only upon the amount of loss which can be allowed in the field coils. As diameters become larger, it becomes more difficult to remove the heat from the more bulky field coils, although with turbo-alternator exciters the ventilation is very efficient. However, without exceeding a reasonable internal temperature in the centre of the cotton-insulated spool, a time-constant, as already defined, of 2·5 sec. can be obtained on the exciter for a 100 000-kW turbo-alternator running at 1 500 r.p.m., and 1·0 sec. for a 50 000-kW turbo-alternator running at 3 000 r.p.m.

Effect of Solid Poles, etc., upon Exciter Time-constant.—As metallic spool bodies and solid poles and magnet frame act as mutual circuits to the field spools and so may add appreciably to the time-constant calculated from the spools alone, it is well at this stage to review briefly the theory of mutual circuits in so far as it applies to the present discussion.

With a single self-inductive circuit, the flux grows simultaneously with the current in this circuit, but when a secondary circuit, although not in perfect mutual relation, is present, the flux grows in accordance with the sum of the currents in the two circuits, and in general its growth is retarded.

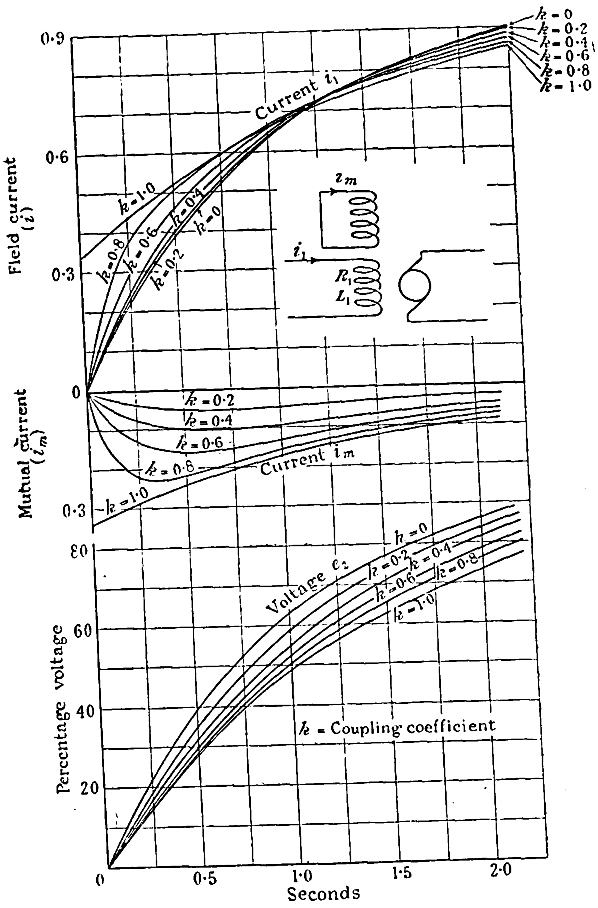

FIG. 9.—Growth of current and voltage in separately-excited exciter with a mutual field circuit.

When the secondary mutual circuit is short-circuited upon itself, a sudden initial growth of current will occur in the main circuit. However, this is a false current as regards generation of flux, as it will be opposed by a sudden growth of transient current in the secondary circuit.

The time-constant of the secondary circuit can be calculated in the same manner as the time-constant of the primary, and when the coupling between the two circuits is perfect the time-constant which determines the growth of the resultant flux is the sum of the time-constants of the two separate circuits.

When the coupling between the circuits is imperfect some intermediate rate of flux growth results. The growth is not truly exponential but is so nearly so that a time-constant sufficiently accurate for present calculations can be measured from an oscillograph record by taking 0·632 of the total growth of the exciter voltage over the unsaturated range.

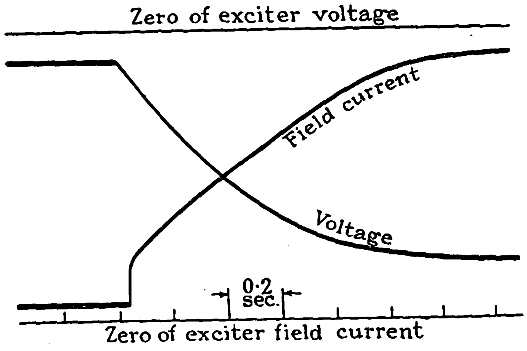

FIG. 10.

In order to illustrate this point, a set of curves has been plotted in Fig. 9 for a primary time-constant of 1 sec., a secondary time-constant of 0·5 sec. and for different coupling coefficients 0, 0·2, 0·4, 0·6, 0·8 and 1·0. Primary and secondary currents and resultant voltage growth are shown.

When the circuits are perfectly mutual, the initial opposed transient currents in both primary and secondary appear without any appreciable period of growth. This condition is found to exist between the mutual circuits of an exciter field system, and oscillograph records of growth of field current afford a means of discovering experimentally the relative importance of the mutual circuits or, alternatively, of checking calculations.

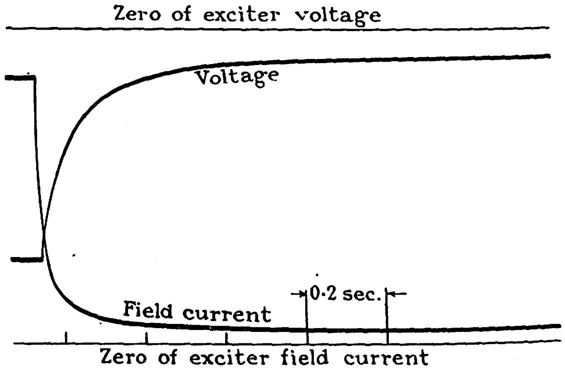

FIG. 11.

For instance, Fig. 10 shows oscillograph records of the rising field current and armature voltage of an exciter which, when the rheostat was short-circuited, showed a sudden change in exciter field current of 19 per cent of the total ultimate change, thus indicating an addition of 23·5 per cent to the time-constant for the field coils alone. Fig. 11 shows the falling curves when the rheostat is again connected in circuit. The field circuit then has a shorter time-constant, so that the mutual circuit which does not change becomes relatively greater. The sudden initial change of exciter field current is about 63 per cent of the ultimate change. Such curves as these are useful in determining how far mutual circuits have been eliminated from the design.

Another method of experimentally determining the values of time-constants of the main and the mutual circuits is to take two records of rising armature voltage, using a different resistance in the field circuit. This changes the time-constant of the field coils in inverse proportion to the total resistance of the circuit, the time-constant of the mutual circuit being included as a constant figure in each of the observations.

In the exciter for the 100 000-kW turbo-alternator already mentioned, a solid magnet frame would add 0·15 sec. to the time-constant, and solid poles would add another 0·15 sec.

To get the very best response from the exciter, having regard to magnetic dimensions to give its rating, it would be desirable to dispense with metallic supports upon which to mount the spools, and to laminate both the pole cores and the magnet frame.

Super-excitation.—By super-excitation is meant some means of securing quicker response than by converting to separate excitation the standard self-excited shunt machine, which has a margin of 15 per cent between the maximum voltage available and that required for maximum load on the alternator. The first step is to use a larger section of conductor with a correspondingly smaller number of turns for the field spools, or to provide a higher voltage for separate excitation so that a highly saturated condition will be reached in the exciter magnetic circuit when all the field resistance is removed. This procedure does not alter the time-constant of the exciter, but it increases the possible voltage-change. If, with the same field spools, the constant voltage for the exciter excitation is double its previous value, the response is double at the lowest voltage, and a constant value is added to the response at all other voltages within the working range. This condition of excitation as an extension of that previously considered is indicated by broken lines in Fig. 8, and at voltage corresponding to A on the saturation curve response for separate excitation is represented by AD′, and for shunt excitation by AC′. Response characteristics for both conditions are shown in Fig. 7, (c) and (d). This step in super-excitation is satisfactory if quicker response is desired without the necessity of over-exciting the alternator when heavy faults occur. A further step is to re-design the exciter so that in addition to providing excessive excitation in the field spools the magnetic circuit remains unsaturated at the voltage required for maximum alternating rating. This procedure will usually involve some sacrifice in the time-constant of the exciter, so that the response may be slightly less at low voltages, but it is higher at higher voltages and, in addition, it provides for a higher maximum voltage in an emergency.

In addition to the previously mentioned curves in Fig. 8, a saturation curve of an exciter is shown which has the same degree of saturation throughout its range as in a normal machine, but which has a maximum voltage of double the previous value with an excitation for this voltage which is also double the previous value in order to ensure the same degree of load stability.

Assuming, for the sake of standardizing the curves for future reference, that the time-constant of the re-designed exciter is still 1 sec., response is now indicated in Fig. 8 by A′D′ and the curve for response over the whole range of voltage has been added to Fig. 7 as curve (e).

It is not considered necessary to add a curve for a shunt machine to this design, in view of the poor inherent stability at the lowest voltage required for alternator excitation.

ALTERNATOR STABILITY.

Inherent Instability of Alternator.—If an alternator is connected to a circuit which consists largely of capacity, e.g. unloaded long overhead lines or underground cables, it may be self-exciting owing to leading current in the stator windings acting as a magnetizing current upon the magnetic circuit. The alternator will be inherently unstable in that the voltage may rise to a value which will be limited only by saturation.

A case sometimes occurs in high-potential testing when a smaller alternator is used to provide current for testing a large stator. On commercial circuits the effect has been noticed in some installations abroad. It is not likely to be as troublesome in England as, even when the country is linked together in one distribution network, the charging current will be small compared with the load current, which will contain a lagging as well as a power component. However, it is suggested that operating engineers, in specifying power factor for their machines, should include the capacity current required in distribution, and that manufacturers should base the stator dimensions upon kW rather than kVA rating and should use longer air-gaps when high power factors are specified.

In the same way that it is possible to say at what value of field resistance the shunt exciter will become inherently unstable, so is it possible to say at what value of external capacitance the alternator will commence to build up. In Fig. 12 an alternator saturation curve for the machine chosen later to represent typical present-day turbo-alternator practice is drawn to show, vertically, stator voltage as a percentage, and, horizontally, excitation in terms of stator current, as a percentage of the full-load value, having regard to the effectiveness of the armature windings carrying leading current. On a tangent drawn through the initial part of the saturation curve the excitation for 100 per cent voltage corresponds to 53 per cent full-load current. A capacity corresponding to this current and voltage is the limiting value which will cause self-magnetization, and the voltage would then rise to about 65 per cent of normal. Fig. 12 also shows that if the line capacity corresponds to full-load current at normal voltage, the alternator will self-magnetize itself to 36 per cent above normal value.

Load Instability of Alternator.—When capacity is absent or negligible, and with a constant excitation, load conditions produce a drop in voltage and, according to the nature of this load, the alternator may be unstable. If the load is of such a character that the drop in voltage is followed by a corresponding drop in load current, as may occur with a purely lighting load, a steady but reduced voltage will result. On the other hand, if the kVA demand remains the same with falling voltage as, for instance, with an induction-motor load, it may be that an additional load cannot be sustained and the alternator voltage falls to zero if the excitation of the alternator is not adjusted, preferably by automatic means, as soon as the changed load conditions affect the alternator voltage. The usual condition of service is probably intermediate between these two, corresponding approximately to a synchronous-motor load in which there is a constant power demand but in which the wattless demand diminishes somewhat with falling voltage.

Trend in Turbo-alternator Design.—An alternator is often judged in regard to its stability either by the ratio of the armature reaction expressed in ampere-turns at full load to the field ampere-turns at no load, or by the ratio of field current required for normal stator voltage with the terminals open-circuited to the field current to produce steady full-load current with the stator windings short-circuited. The former method classifies the machine from the point of view of the designer, who includes in his consideration the percentage reactance as well as the percentage armature reaction, while the latter method is more suitable from the operator's point of view and gives what is termed the "synchronous reactance" of the alternator, 100 per cent synchronous reactance meaning that the same excitation is required for normal voltage on open circuit as for full-load current on steady short-circuit.

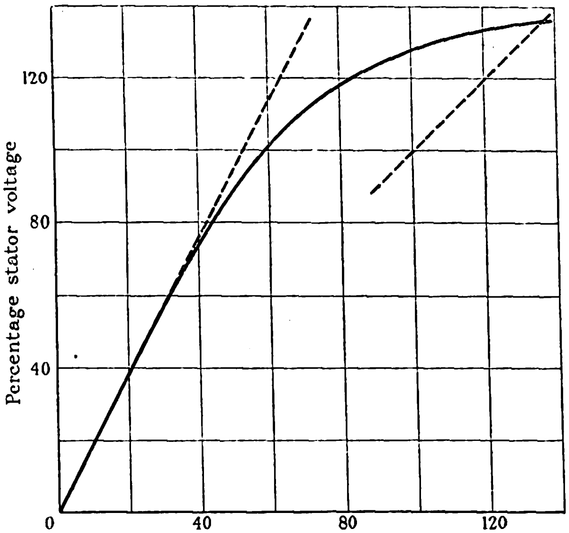

FIG. 12.—Building-up of stator voltage with capacity load.

When turbines came into use about 25 years ago the design characteristics of the alternator which they drove were the same as those of salient-pole machines as then built. Such machines had a reactance of 8 per cent and an armature reaction of 65 per cent, and gave on test a synchronous impedance of, say, 73 per cent. The tendency in turbo-alternator design, however, has been to design with higher armature reactions, and nowadays typical figures for machines built in England and on the continent of Europe are reactance 16 per cent and armature reaction 160 per cent, giving a synchronous reactance of 176 per cent. These characteristic figures apply to machines designed to work at 0·8 power factor.

In America, designs have not such high percentages of armature reaction, but some machines with figures even in excess of these have been in successful operation for some years on large systems in England. The evolution has taken place gradually over the whole period of turbine development, partly as the result of a search for a design which will be cheaper per unit of rating, and partly in keeping pace with the art of turbine design, for the large ratings now being built at the higher speeds would be impossible for mechanical reasons if the electrical design characteristics of even 10 years ago had to be used.

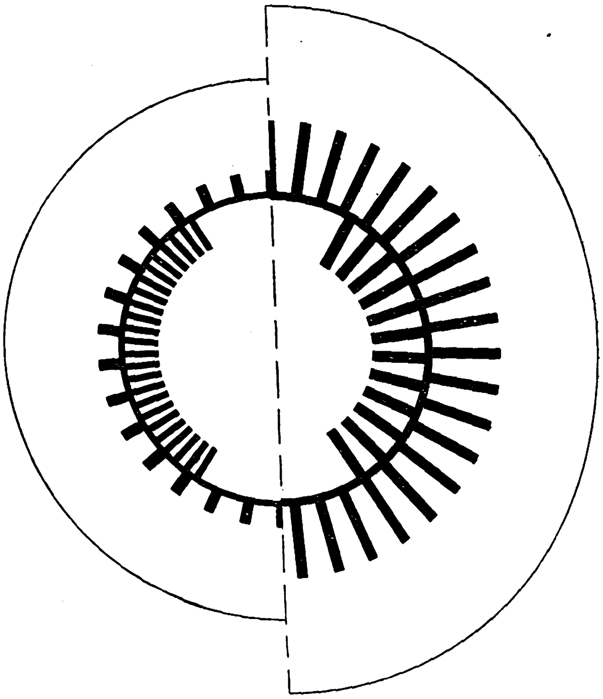

FIG. 13.—Two-pole designs dated 1908 (left) and 1928 (right).

In design language, the turbo-alternator has become more a "copper" machine and less an "iron" machine, and a comparison of the two diagrammatic cross-sections of slots and cores in Figs. 13 and 14 will show what is meant by this statement. For the purpose of comparison, old and up-to-date designs for both 2 and 4 poles have been chosen, the comparative sections having been so drawn as to have the same stator-face diameter. Fig. 13 shows a modern 2-pole design, in comparison with one from which machines were built in 1908. Again, Fig. 14 shows a modern 4-pole design and a design in use in 1910. In both cases the up-to-date design shows deeper slots and, therefore, contains a larger cross-section of copper, the result of which appears as a higher rating for the same length of core.

Performance Characteristics of a Modern Turbo-alternator.—Curves of excitation for open circuit (saturation), short-circuit (impedance) and load at unity and 0·8 (lagging) power factors on a machine which has been taken as a design typical of the present time are shown in Fig. 15, normal voltage, maximum load current and excitation for normal voltage on open circuit all being taken for the sake of generality as 100.

It will be seen that maximum load at 0·8 power factor requires 2·63 times the excitation for open-circuit normal voltage, and if we assume a temperature-rise of 90 deg. C. on the rotor-winding copper as measured by resistance between no load and full load, the exciter will need to be stable over a range of 1 : 3·5. With a margin of 15 per cent between the maximum excitation voltage required and maximum exciter voltage available, it appears that a shunt exciter must be stable at 24 per cent of its maximum voltage.

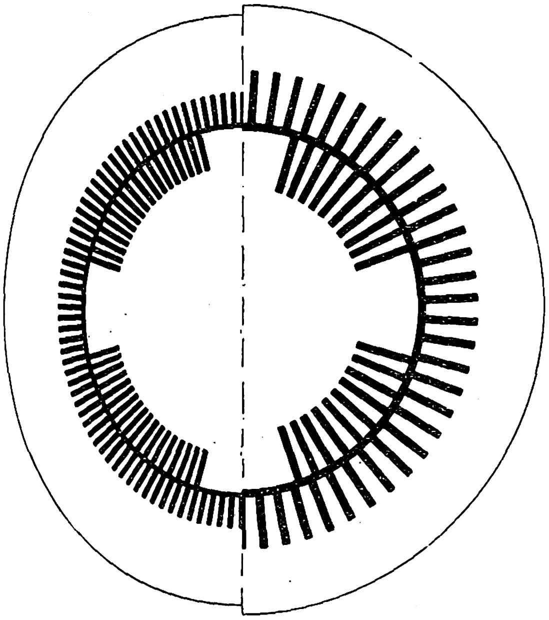

FIG. 14.—Four-pole designs dated 1910 (left) and 1928 (right).

The inherent voltage regulation of an alternator is defined as the voltage-rise which will occur when full load is thrown off, excitation remaining constant at full-load value. With the older type of machine, for a power factor of 0·8 this was usually guaranteed to be not more than 22 per cent, but with the present-day machine this figure has risen to approximately 45 per cent. The corresponding figures of voltage-drop, when the full-load circuit is suddenly connected to the alternator terminals, are about 30 per cent with the older machines and about 60 per cent with the present-day machines. In either case the voltage variations between no load and full load, and vice versa, are altogether too wide for satisfactory service without automatic regulation, but, on the other hand, full load is never thrown on or off, and, as pointed out in the introduction, incidental variations of load are becoming smaller in relation to the capacity of the machines.

The performance characteristics of the modern turbo-alternator are further developed in a family of load saturation curves at 0·8 lagging power factor for $\frac{1}{5}$, $\frac{2}{5}$, $\frac{3}{5}$, $\frac{4}{5}$ and full load at normal voltage in Fig. 16. From these, a family of volt-ampere curves, each for a constant excitation, corresponding to one of the loads calculated for Fig. 16, can be derived as in Fig. 17.

In this form, characteristic curves are useful in determining the change in voltage which would follow a change in load. The positions on the various curves corresponding to normal voltage are shown as dots, and through these radial lines are drawn from the origin. Each of these radial lines represents an impedance corresponding to the particular fractional load for which it is drawn at normal voltage, so that if the machine is working at, say, 40 per cent load and another 20 per cent load is thrown on, then the voltage will fall along the volt-ampere characteristic for 40 per cent load excitation until this curve cuts the radially drawn impedance line for 60 per cent load, provided the load is such that the impedance does not change with voltage. This occurs at 87 per cent normal voltage and 52·2 per cent normal current. If, still without changing the excitation, the load circuit is changed to correspond to another 20 per cent rise in load, the voltage will fall, still along the same volt-ampere characteristic, until it meets the next radial line drawn in the diagram. The voltage will then become steady at 75·5 per cent of normal voltage and the current which is being carried will be 60·5 per cent of full-load value.

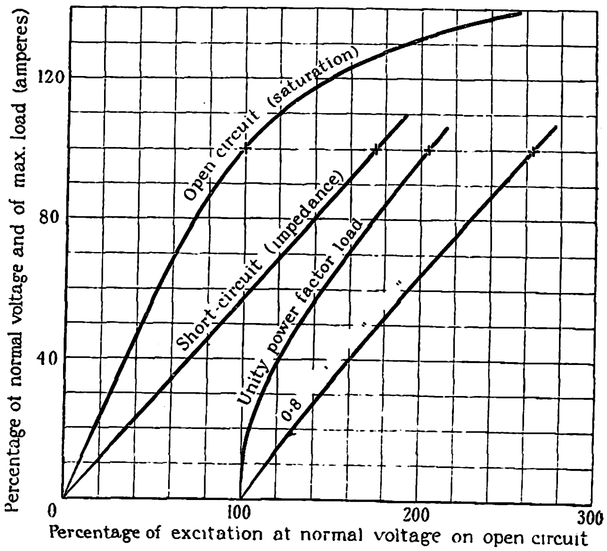

FIG. 15.—Characteristic curves of typical turbo-alternator.

When the load circuit is changed to a much lower impedance, say one corresponding to 40 per cent above the maximum rated load, the voltage will still settle down to a steady but lower value, namely, 51·5 per cent of normal, the current being 72 per cent of maximum load value. It is therefore apparent that, under this condition of loading, the machine is stable and that it does not entirely lose its voltage until the terminals become short-circuited.

In order to illustrate the performance for the other extreme condition of loading, i.e. when the kVA remain constant in spite of falling voltage, rectangular hyperbolæ have been drawn in Fig. 17. The first curve of this kind, drawn through a point representing 20 per cent load at normal voltage, just touches the volt-ampere characteristic for no-load excitation, and from this we conclude that, under these conditions of load, if 20 per cent load is thrown on with the machine at no-load excitation, a steady voltage will be reached where the two curves touch one another, viz. at 64 per cent voltage and 31·5 per cent current. If, however, the circuit is changed to correspond to a higher load at normal voltage, the excitation still remaining constant as for normal voltage on open circuit, the corresponding constant kVA curve will not touch or cut the volt-ampere curve for no-load excitation, so that the alternator will completely lose its voltage and, therefore, may be said to be unstable when load of this character beyond a certain value is thrown on.

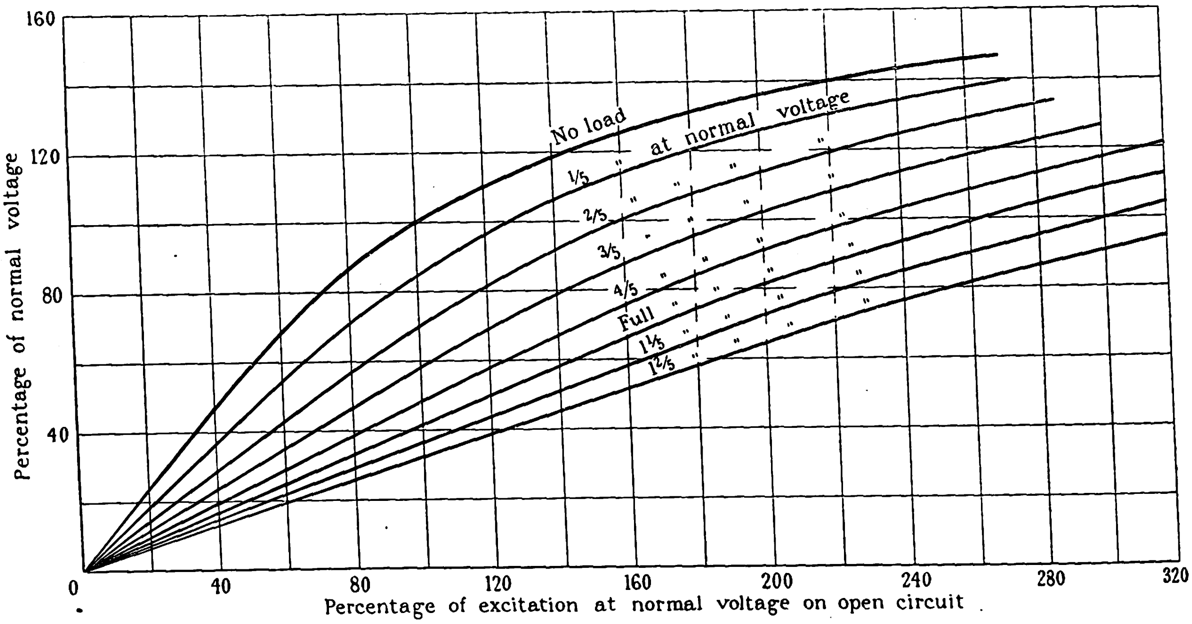

FIG. 16.—Load saturation curves at 0·8 power factor.

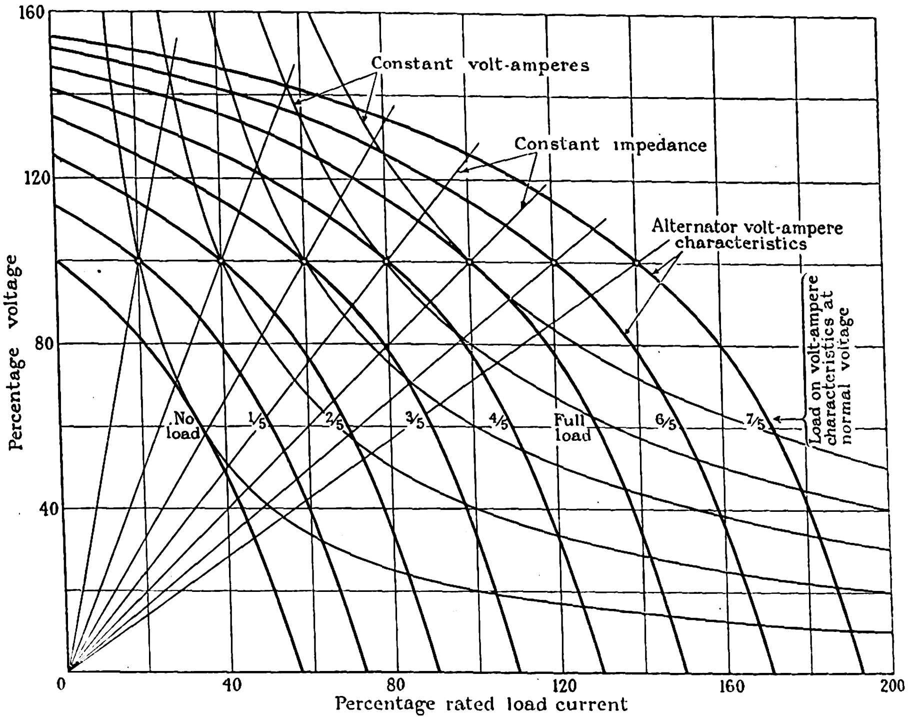

FIG. 17.—Volt-ampere characteristics of alternator for various constant excitations (0·8 power factor).

An inspection of the other curves will show that the capacity for higher loads of this character becomes less and less as the alternator voltage is brought back to normal after each change in load. At maximum load, as the two types of curves are practically tangential to one another at normal voltage, there is no margin for further loading of this character unless the excitation is increased. However, there is no doubt that, with falling voltage, load does not follow constant kVA but rather constant kW with a wattless component of current proportional to the voltage. Moreover, the inertia of the alternator magnet-system prevents the voltage from falling unduly before the excitation circuits can be changed, so that an alternator may be said to be stable conditionally upon an adjustment being made in the excitation circuit.

ALTERNATOR RESPONSE.

Alternator Reactance and Armature Reaction.—The voltage-drop in the alternator voltage when load is thrown on is calculated in two steps.

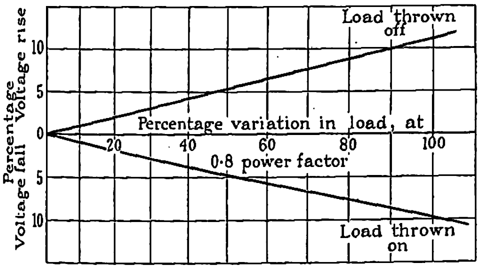

FIG. 18.—Reactance voltage-change at different loads.

The first involves the reactance of the stator windings and assumes that constant voltage is available for this reactance in series with an impedance corresponding to the load, and the calculation consists in determining the different percentage voltage absorbed in the stator reactance before and after the load-change.

The reactance voltage-rise or fall, as the case may be, for percentage changes of 0·8 power-factor load for a machine with 16 per cent reactance is shown in Fig. 18. When full load is thrown off, the voltage-rise due to this cause is 11 per cent; or if full load is thrown on when the machine is on open circuit the voltage-drop is 9·8 per cent. As the time-constant of a load circuit of normal power factor is very small, the change in load current, and therefore the change in voltage at the alternator terminals due to reactance, occur very quickly, in fact practically simultaneously with the change in the load-circuit conditions.

The second part of the calculation takes account of the magnetizing effects of the opposing stator and rotor currents, and each change in load produces a change in the main flux of the machine and therefore in the machine voltage.

The main flux of the machine has an appreciable time-constant, so that this change in voltage takes place slowly. Without any change in the excitation circuit, a change in rotor current occurs simultaneously with a change in the stator load current. Thus the flux is maintained at the instant the load-change takes place. The rotor current then gradually returns to its former value as the new stator current becomes effective in changing the main flux of the machine.

A fraction of the total voltage-change, therefore, is in evidence as soon as the load conditions change, but the remaining portion of the voltage-change takes an appreciable time, and with a quickly responsive exciter this time is long enough, especially if an automatic regulator is used to change the excitation-circuit conditions to allow the exciting current to be adjusted to the new value required for the new load. The voltage variation in the transient period during which it is being restored to normal value after a change in load, is considered in the section dealing with "Combined response of alternator and exciter."

An interesting example of the transient variation in field current when a change in load conditions causes a change in flux is shown in Fig. 19. This is an oscillograph showing the stator voltage and the exciting current of an alternator from the instant of the opening of a switch which was short-circuiting the stator windings. At this instant, a voltage corresponding to the voltage previously absorbed by current flowing through the reactance of the short-circuited windings suddenly appears at the stator terminals, and at the same time the exciting current drops to that corresponding to this voltage, although the exciter voltage remains constant. The fall in exciting current is not so sharp as the rise in

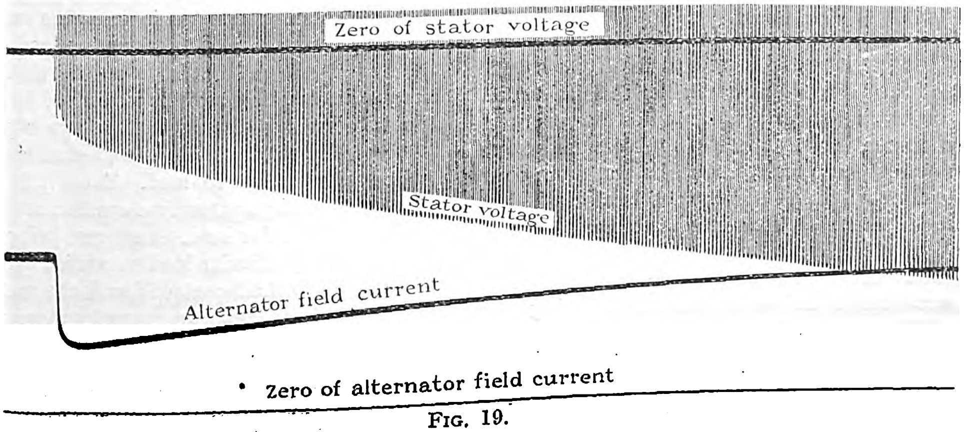

FIG. 19.

voltage, because of the presence of mutual circuits, but after a few cycles both rotor current and armature voltage rise together, the former to its previous value and the latter to a voltage corresponding to the rotor current when the stator is on open circuit.

Alternator Time-constants on Open Circuit.—If excitation corresponding to 25 per cent in excess of normal voltage were suddenly switched on, the form of curve for the growth of alternator voltage would be similar in shape to that given in curve (a) in Fig. 6 for a separately excited exciter. The actual time of growth of the voltage to the maximum value would be longer, in fact probably about 10 times as long, because the time-constant of the alternator would be longer than for the exciter. The growth for large alternators would be slower than for small alternators.

From a design point of view the time-constant of turbo-alternators with characteristics as previously described depends principally upon the diameter and the number of poles, and is almost independent of the length of core. As the maximum permissible rotor diameters as determined by the mechanical properties of the steels at present available seem to have been nearly reached, larger outputs are being obtained by lengthening the active core of the machine. The time-constants for the large sizes of turbo-alternators thus seem to have assumed a uniform value, and for both 3 000-r.p.m. and 1 500-r.p.m. 50-cycle machines, designed with the characteristics already described, the time-constant with the magnetic circuit unsaturated and based upon conductive material in the rotor windings alone is about 10 sec.

However, the rotors of all 3 000-r.p.m. machines and of many 1 500-r.p.m. machines are made from a single forging, and this adds a considerable section of mutual current-carrying material which becomes effective when a flux change is taking place. Thus the solid mass of the rotor core adds about 4 sec. to the time-constant of a 1 500-r.p.m. machine, and about 2 sec. to that of a 3 000-r.p.m. machine. In the alternative 1 500-r.p.m. construction, in which separate plates about 3 inches in thickness are mounted on a central shaft, the additional time-constant due to this cause is negligible. The importance of the solid conducting section of steel in the solid rotor body may be judged by observing the relative sections of copper and steel in Figs. 13 and 14, it being remembered that the conductivity of the steel is only 20 per cent of that of the copper.

The coupling coefficient between the coils and core of a solid 3 000-r.p.m. rotor was investigated by associating the oscillograph test referred to in Fig. 19 with a set of calculations as plotted in Fig. 9. The difference between the observed rise in voltage and the observed change in field current represents the equivalent current in the mutual circuit. A calculation of the time-constants of the exciter windings and the solid rotor enabled a set of curves of secondary or mutual currents to be calculated and plotted for different degrees of coupling. The curve which corresponded in shape to the experimentally deduced curve indicated that the coupling was of the order of 75 per cent.

The adjustment of flux in the alternator at different loads does not take place, as in the exciter, over the wide range between practically zero value and the highest point of the saturation curve, and for this reason it is only necessary to consider the time-constant of the alternator at normal voltage.

The partial saturation of the magnetic circuit of the alternator at normal voltage and on open circuit will be found to give a slope to the saturation curve at this point, expressed as volts per ampere, of about 60 per cent of that for the unsaturated portion. In making response calculations on no load, e.g. when all load on the machine is thrown off, the time-constants for large 50-cycle turbo-alternators may therefore be taken as 7·2 sec. for 3 000-r.p.m. machines, 6 sec. for 1 500-r.p.m. machines of the plate-rotor construction, and 8·4 sec. for 1 500-r.p.m. machines of the solid-rotor construction.

Alternator Time-constants on Load.—The flux-changes from one load to another being relatively small, adjustments of field current, of which a wide range is required in modern turbo-alternators, are concerned chiefly in counterbalancing changes in armature reaction due to the varying load. With increasing load, for instance, the stator current tends to reduce the flux, and an increase in exciting current is required to bring it back to a value which gives normal voltage at the terminals. In effect, this changes the time-constant of the alternator with every change in load. Thus, it is necessary to determine the alternator time-constant at normal voltage for each particular load, due regard being given to the slope of the particular load saturation curve at normal voltage and to the increased flux in the machine required at this load to maintain normal voltage at the stator terminals.

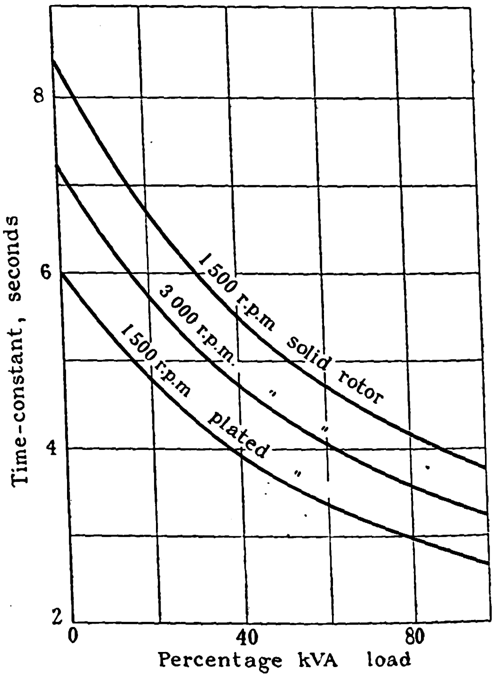

FIG. 20.—Alternator time-constants at different loads (0·8 power factor).

The curves in Fig. 20 show the time-constants on load for the different types of machines when working at 0·8 power factor. An allowance has been made for the higher temperature of the rotor coils at higher loads and for increased leakage at the higher excitations.

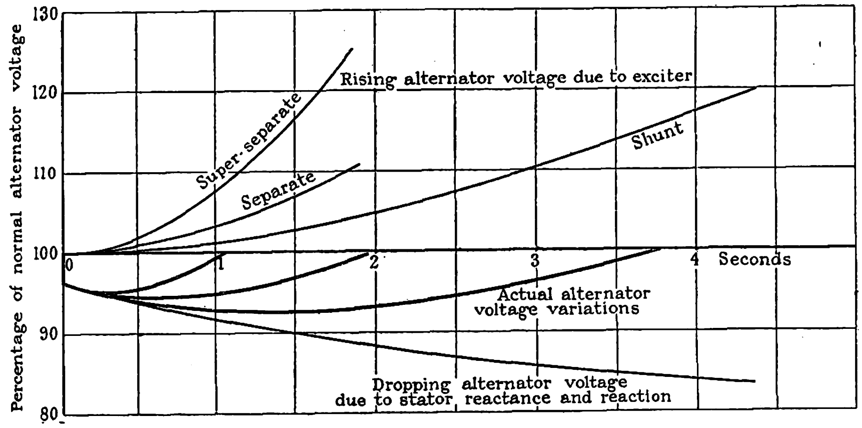

FIG. 21.—Restoration of voltage after increasing load suddenly from 40 per cent to 80 per cent (power factor 0·8) with different methods of exciter excitation.

Alternator Response.—A knowledge of the time-constant and the regulation of the alternator on load allows a curve to be drawn of falling voltage when load is thrown on. As already pointed out, such a curve consists of an initial sudden drop due to the reactance (see Fig. 18), followed by a gradual change to a value which may be determined from Fig. 17. It is sufficiently accurate for present purposes to assume an exponential variation during the latter change corresponding to the time-constant given for the new condition of load in Fig. 20; and the character of the voltage-drop of a solid-type 1 500-r.p.m. turbo-alternator, already carrying 40 per cent load, when another 40 per cent load is suddenly thrown on is shown in Fig. 21. This curve represents the response of the alternator alone, i.e. if the excitation circuits are not adjusted. The assumption has been made that the load-circuit impedance does not change with falling voltage and, even if this assumption is not strictly true, the combined response of alternator and exciter as studied in the next section will not be much affected, as the voltage variation from normal is then relatively small.

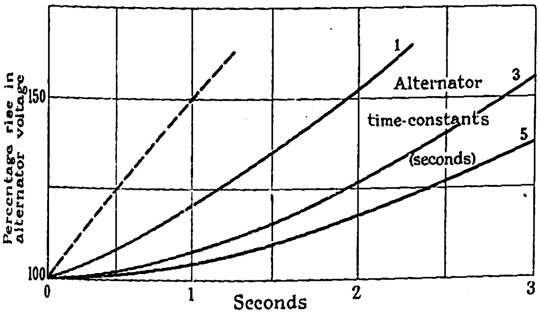

FIG. 22.—Delay in growth in alternator voltage after exciter response.

COMBINED RESPONSE OF ALTERNATOR AND EXCITER.

Voltage regulators operate upon the exciter field circuit rather than directly upon the alternator field circuit, because it is not practicable to manipulate contacts carrying the large exciting currents of the latter. As soon as an increase in load causes an appreciable voltage-drop the regulator should short-circuit the exciter field rheostat and continue to do so until normal alternator voltage is restored. In combination, the response of the alternator waits upon the response of the exciter, and an accumulative delay occurs in the restoration of the normal alternator voltage. For instance, suppose that under certain conditions the exciter voltage responds at a rate which corresponds to an increase in the alternator voltage at the rate of 50 per cent per second, as indicated by a dotted line in Fig. 22; then if the alternator has a time-constant of 5 sec. the actual

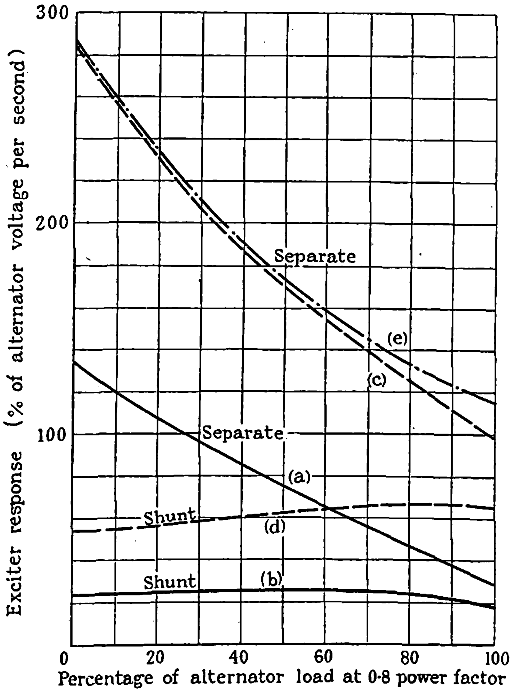

FIG. 23.—Exciter response in terms of alternator load and voltage (exciter time-constant = 1 sec.).

growth of alternator voltage is shown by the full line in the figure.

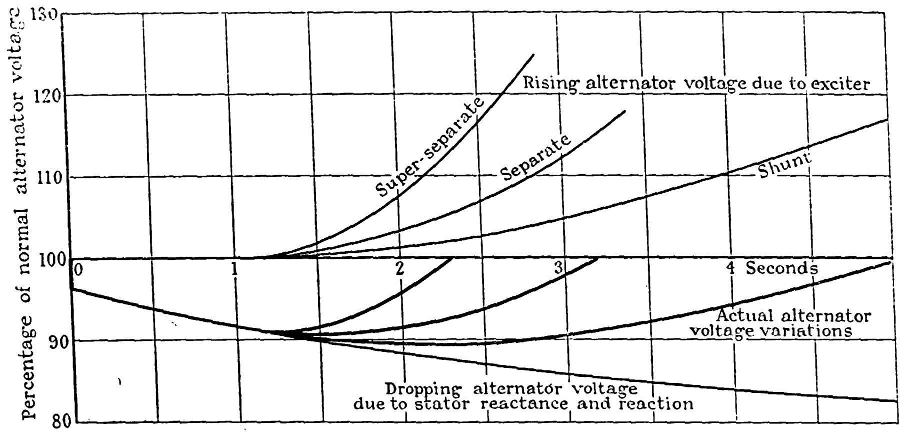

FIG. 24.—As Fig. 21, but with action of regulator delayed by 1 sec.

In order to make calculations of the combined response of exciter and alternator, it is convenient to convert the curves in Fig. 6, which show exciter response in percentage exciter voltage per second at any given exciter voltage, into the corresponding percentage alternator voltage per second at any given alternator load. Thus the abscissæ of Fig. 7 shown as percentage exciter voltage can, by reference to the abscissæ of Fig. 16, be converted into percentage alternator load, and, assuming full alternator load to correspond to 85 per cent of exciter voltage, and taking account of increased temperature of rotor windings on load, the ordinates in Fig. 7 can be converted into percentage of alternator voltage per second having regard to the slope of the particular load saturation curve of Fig. 16 which applies. The result is shown as Fig. 23, the ordinates, however, requiring correction, as did those of Fig. 7, for the particular exciter time-constant.

In calculating the combined response of alternator and exciter it is sufficiently accurate to take from Fig. 23 the average exciter response in terms of alternator voltage in the given change in load, and to associate this with the alternator time-constant for the new load as obtained from Fig. 20. By this means, upon a change in load and with the exciter rheostat short-circuited, a curve of rising voltage can be plotted in Fig. 21 on the supposition that the increased alternator reaction for the new load is not effective.

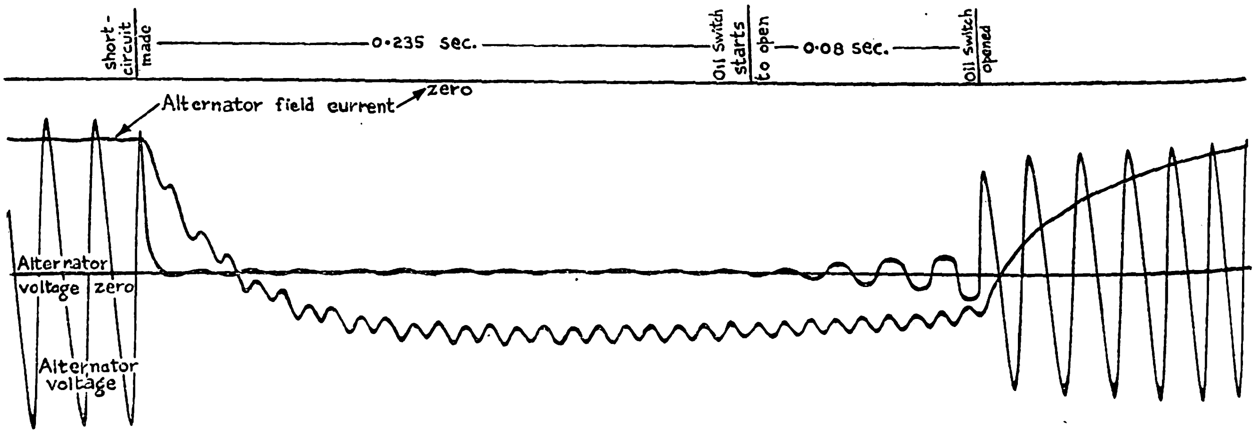

FIG. 25.—Sudden single-phase short-circuit on 4 000-kVA turbo-alternator.

Three such curves are given in Fig. 21 for the change of load conditions already considered for alternator response alone. One curve is for a shunt exciter, the second is for the same exciter separately excited, while the third is for super-excitation of the same machine at twice the exciter voltage.

We have now calculated (1) the drop in voltage due to armature reaction when the exciter does not respond, and (2) the rise in alternator voltage due to the exciter if armature reaction were not effective.

We assume that the actual cycle of voltage variation after a change in load is the addition of the rise on the one curve to the fall on the other. Such average curves have been drawn as thick lines in Fig. 21 and show a maximum voltage-drop of 8 per cent and a time of 3·8 sec. to restore the voltage completely to normal again in the case of the shunt exciter. For separate excitation the figures are 5·5 per cent voltage-drop and 1·8 sec. for restoration, and for super-excitation 4·5 per cent drop and 1·0 sec.

The vibrating-contact type of regulator provides for different exciter voltage at different loads by allowing its contacts to remain closed for a relatively long time at high loads and a relatively short time at low loads. For such a gradual increase in load as does not cause much alternator voltage variation the change in the character of the beat, that is to a longer period of junction of the contacts with a shorter time of break between periods of contact, is also gradual and the average value of alternator field current increases with the load. With sudden increase in load and wider variation in voltage it is necessary, in order that the middle curves in Fig. 21 may be obtained, that the regulator should short-circuit the exciter field rheostat as soon as possible after load is thrown on. This is effected in the vibrating-contact type by a cessation in the beating of the contacts. Any hesitation in the regulator in doing this will appreciably lengthen the time before voltage is restored and appreciably increase the maximum voltage-drop which will occur during this period. In effect, the upper curves of Fig. 21 will be displaced a certain distance to the right. If the delay is, say, 1 sec., the curves of Fig. 21 take the form shown in Fig. 24.

Again, because of the lagging of the alternator response behind the exciter response, the exciter voltage will temporarily overshoot the value required for the new load, but as soon as alternator voltage is restored the regulator should commence beating in a suitable manner for the new load.

Another type of sudden load application is a short-circuit on the machine. If this is in the neighbourhood of the busbars, while the short-circuit lasts it will cause the alternator voltage to disappear completely. The usual protective devices installed to disconnect the lines associated with a fault are expected to remove the short-circuit in a fraction of a second. Upon removal, a large fraction of the alternator voltage, corresponding approximately to the extent to which the high initial current associated with a sudden short-circuit has fallen, will reappear. This point is illustrated in Fig. 25, which is drawn from the oscillograph record of stator voltage and field current on a 40 000-kVA turbo-alternator before, during and after a sudden single-phase short-circuit. When the short-circuit is removed after approximately 0·3 sec. the voltage reappears at 70 per cent of its full value.

The time-constant of a large turbo-alternator under short-circuit conditions is approximately 1 sec., and Fig. 26 shows the percentage reappearance of voltage after various durations of short-circuit. The curves have been drawn truly exponential, but a consideration of tests such as shown in Fig. 19 indicates that rather larger voltages than indicated appear after short-circuits of comparatively long duration.

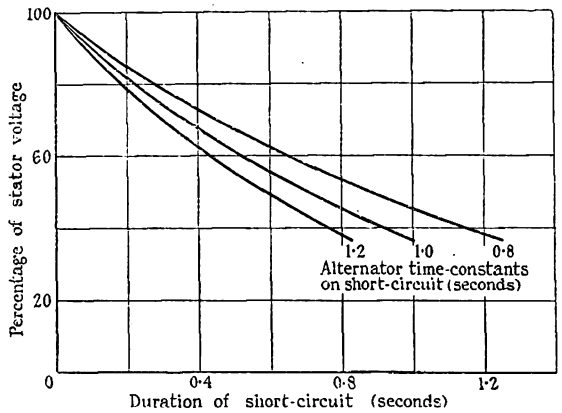

Fig. 26.—Reappearance of stator voltage upon removal of short-circuit.

Reverting to Fig. 25, the presence of the mutual circuits in the alternator rotor body is indicated by a relatively slow adjustment of rotor current at short-circuit and after the short-circuit is cleared.

The author desires to thank his colleagues on the engineering staff of the British Thomson-Houston Co. for helpful criticism and suggestions.

Discussion before The Institution, 28th November, 1929.

Mr. J. A. Kuyser: I should like to support the proposal to use what the author calls the "service exciter." By means of this exciter it is possible to obtain greater stability than by any other means. In many cases generators have to operate by themselves, and small variations in the contact between the brushes and the commutator may cause voltage fluctuations. In other cases exciters are operated at very low voltages, due to the fact that the alternator is operated at a higher power factor than that for which it was designed. In all these cases a service exciter would be of great assistance. Another suitable application is where a house alternator is used which supplies current to the auxiliary motors. These motors are often large compared with the generators, so that when a motor is started up there will be a large voltage-drop and other motors will be tripped. A service exciter in connection with an automatic voltage regulator will give the necessary quick response and will help to maintain the voltage. In connection with the design of the service exciter, we have been using a type of exciter of somewhat different mechanical construction. The first point of difference is in the field system. This is made throughout of cobalt steel, which gives the advantage of a constant flux and also eliminates the fine-wire field-winding. Another modification is that the service exciter is run at a low speed of about 750 r.p.m., and is driven from the governor of the steam turbine. The lower speed results in increased reliability. In order to obtain the maximum possible stability from the service exciter, it is of advantage to introduce some magnet steel in the magnetic circuit of the main exciter. We have been using a cobalt-steel plate placed between the poles and the yoke, which is proportioned to give from 10 to 12 per cent residual voltage. With reference to the arrangement shown in Fig. B, by the use of a short saturated path reasonably good results can be obtained if the magnetic section is reduced to about 15 or 20 per cent of the pole section, and the length of this path is made about 2 or 3 times the length of the air-gap. Fairly good stability is obtainable by this method, but the disadvantage is that a very large number of ampere-turns are required in the field coils.

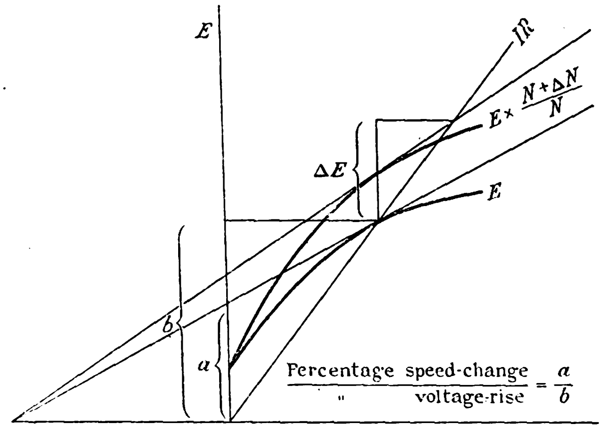
E
IR
E× $\frac{N+\Delta N}{N}$
ΔE
E
b
a
I
Percentage speed-change / " voltage-rise = $\frac{a}{b}$

Fig. A.

It is also necessary in this case to use a small series winding to prevent reversal of the exciter polarity. This series winding is not necessary if the magnet-steel plate is used. In connection with the general problem of stability, exciter stability has not to my knowledge been properly defined. I would propose that stability be defined as the ratio between the change in speed and the corresponding change in voltage. If we accept this as a definition, the stability can be easily determined from the saturation curve. It can be shown that by drawing a tangent at the saturation curve and prolonging this to meet the vertical axis (see Fig. A), the ratio a/b is equal to the exciter stability. I have plotted some curves on this basis; they give the stabilities of the different arrangements of exciters (see Fig. B). The horizontal line at the top represents 100 per cent stability, which can be obtained by energizing the exciters from a battery. It is interesting to note that the service exciter in combination with a normal main exciter gives, at low voltages, less stability than the self-energized exciter containing a magnet-steel plate.

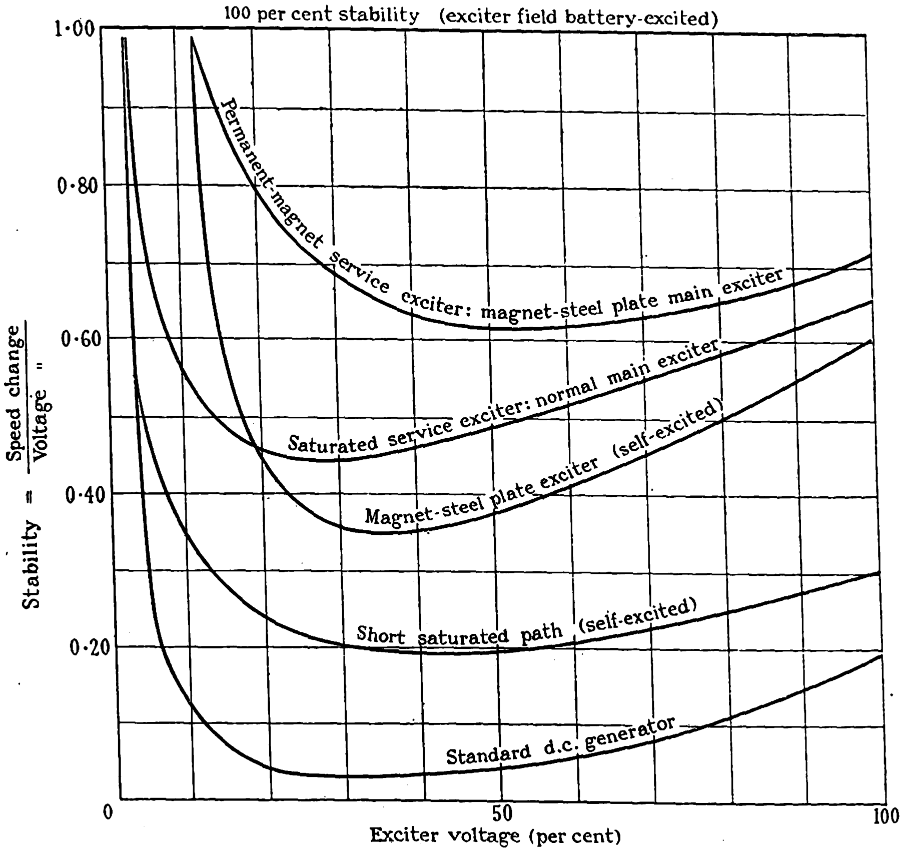

Fig. B.

Mr. J. D. Peattie: This paper is very welcome, coming as it does at a time when preparations are being made for linking up generating and distribution systems on a much larger scale than in the past. In this country the location of stations is close to the load centres, and our problems will differ from those which have arisen in other countries where heavy lines transmit power over long distances. On page 317 the author refers to the fact that magnet systems of larger machines require larger stores of electromagnetic energy, and therefore a longer time of response. I suggest that this statement requires amplification. It is not so much a matter of the actual amount of energy stored, as of the relation between that amount and the dimensions of the exciter, which is required to generate and maintain the energy in the magnet system. In considering transient phenomena such as those described by the author, it is of great assistance to keep in mind the energy aspect, rather than other quantities such as current and voltage which appear in intermediate calculations. Before it can be used to transmit energy from the turbine shafts to the ultimate consuming devices, any electrical system must be raised to a definite potential. I use " potential " in its original meaning as the amount of energy required to bring the system from rest to a given state. This energy is being drawn off continually at the consuming devices, and replenished by an equal flow at the turbine shafts. The energy content of a 3-phase system is in a state of continual circulation between the magnetic and electrostatic fields of the three phases. The exciter acts rather like a strut which helps to keep the system propped up to that potential. In the case referred to on page 323 of the paper, it may, if reverse excitation is used, act like a tension rod and keep the system down to the working potential. Any disturbance in the conditions immediately involves a redistribution of the internal stored energy. The rate of adjustment depends on the electrical dimensions of the system. The author's suggestions will be of assistance in determining the parts played by the alternator and exciter in such a readjustment, and in forming conclusions regarding the behaviour of the system as a whole. In the two main divisions of his argument, stability and response, the author deals with phenomena which occur, for example, in times greater than 1 sec., and between $\frac{1}{5}$ and 1 sec. I hope he will add a few remarks on voltage regulation within one cycle, that is in times less than $\frac{1}{50}$ sec. Alternators are specified to give sine waves of pressure on open circuit with a load of which the resistance, inductance and capacity are independent of voltage. In practice a considerable proportion of loads do not obey this simple rule, and a sine wave of pressure does not necessarily give a sine wave of current. It would be of great interest to know how much distortion can be introduced into the current wave of a modern alternator without distorting its voltage wave.

Mr. F. de la C. Chard : At the foot of page 318 the author states that: " The use of a cast-iron magnet frame in preference to one of steel helps the stability of a shunt machine." It seems to me that any means of producing initial saturation must have an adverse effect on the exciter response at higher exciter voltages, and more especially such a means as this of employing a material having the magnetic characteristics of cast iron. As there are other means of obtaining stability, which do not affect the response of the exciter, such as the method of inserting a material having high retentivity in the magnetic circuit, it would seem preferable to adopt them. The remarks of the author on the subject of old and present-day design, and the comparison of the two designs, are particularly interesting. He attributes the evolution of this design to two causes, one being the relative cheapness per unit of rating, and the other the mechanical considerations involved. I think that there is at least one other cause which should be included, namely, that of changed outlook. The perfection of the automatic voltage regulator has altered the relative value of alternator characteristics. Regulation figures, which were formerly kept as low as possible by minimizing the reactance of the alternator, are nowadays comparatively unimportant, while the large outputs that are usual to-day make a high figure for reactance essential as a means of protection in limiting the initial value of fault currents.

Mr. A. R. Everest: I think that one of the most interesting points brought out in the paper is the difference between the modern turbo-alternator and the machines of 25 years ago. Those who had occasion to deal with those early machines will remember that they were specified to have very close inherent regulation, and consequently only a small armature reaction was allowed in proportion to the field. It did not take very long to show that the design was entirely wrong for this class of machine. One was necessarily restricting the output for a given machine, and perhaps only rating the machines at a small fraction of their possible capacity. Moreover, there was the question of the behaviour of the machine under sudden short-circuits. Practice was gradually modified, and machines are now designed so as to have a much heavier armature reaction in proportion to field. As a result it has been possible for the size of machines to increase up to their present dimensions—for example, the 160 000-kW machine now in service in the United States. An output of 200 000 kW has been named as the probable upper limit of size according to present knowledge. A discussion has been taking place in France, recorded in the *Bulletin* of the Société Française des Ingénieurs Électriciens, on a subject very similar to that discussed by the author, namely, the question of the stability of the large turbo-alternator, and the method whereby it can best be excited. It appears that those who have taken part are divided into three groups: (1) Those who claim that on a short-circuit a machine should lose its flux very quickly, for the protection of apparatus generally; (2) those who claim that it should maintain its flux at full value; and (3) those who claim that the machine should maintain its flux, but that there should be a certain amount of flexibility, and associated with it a need for rapid recovery and therefore quick response of excitation. It is the last-named class who seem to have had the last word. The author has shown that with modern designs of turbo-alternators the exciter is required to operate with a stable voltage over a voltage range of about 4 to 1, and has indicated various constructional means which are alternatively employed to produce the required result. Of these, the method preferred by the author, namely, the provision of a separately energized exciter, appears worthy of general support.

[The author's reply to this discussion will be found on page 337.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 11TH NOVEMBER, 1929.

Mr. L. H. L. Badham: On page 323 the author considers alternator load stability with constant excitation on the basis that the alternator under discussion is the only machine supplying the load, but one machine generally constitutes a fraction of the total generator capacity supplying a network. Under these conditions the alternator, if left with a constant excitation, does not operate at the power factor of the increasing load but at constant voltage with an improved power factor, thus drawing excitation, by way of the stator windings, from the magnetizing power of the rest of the machines. In this way the limiting load which can be carried by the machine is increased, and it is interesting to determine what these limits are for a machine with the characteristics shown in Fig. 15. In Fig. C, excitation curves at normal voltage have been drawn for a range of power factors from zero (leading) to zero (lagging). For any given value of excitation the percentage rated current and corresponding power factor for each value of excitation chosen are shown in Fig. D. From these last curves it is observed that, with constant excitation, the load increases and the power factor improves up to a certain maximum kilowatt output. When this stage is passed, the alternator will fall out of step with the system. The curves show, however, that the machine has a considerable margin above the load for which excitation has been set. For instance, with excitation for 40 per cent load at rated power factor, the machine has a maximum capacity of about 10 per cent above its rated kilowatt load. The results are expressed in another way in Fig. E, in which the loads at which instability commences are plotted against the corresponding excitation. It is seen that the pull-out kW load occurs only after the power factor has become

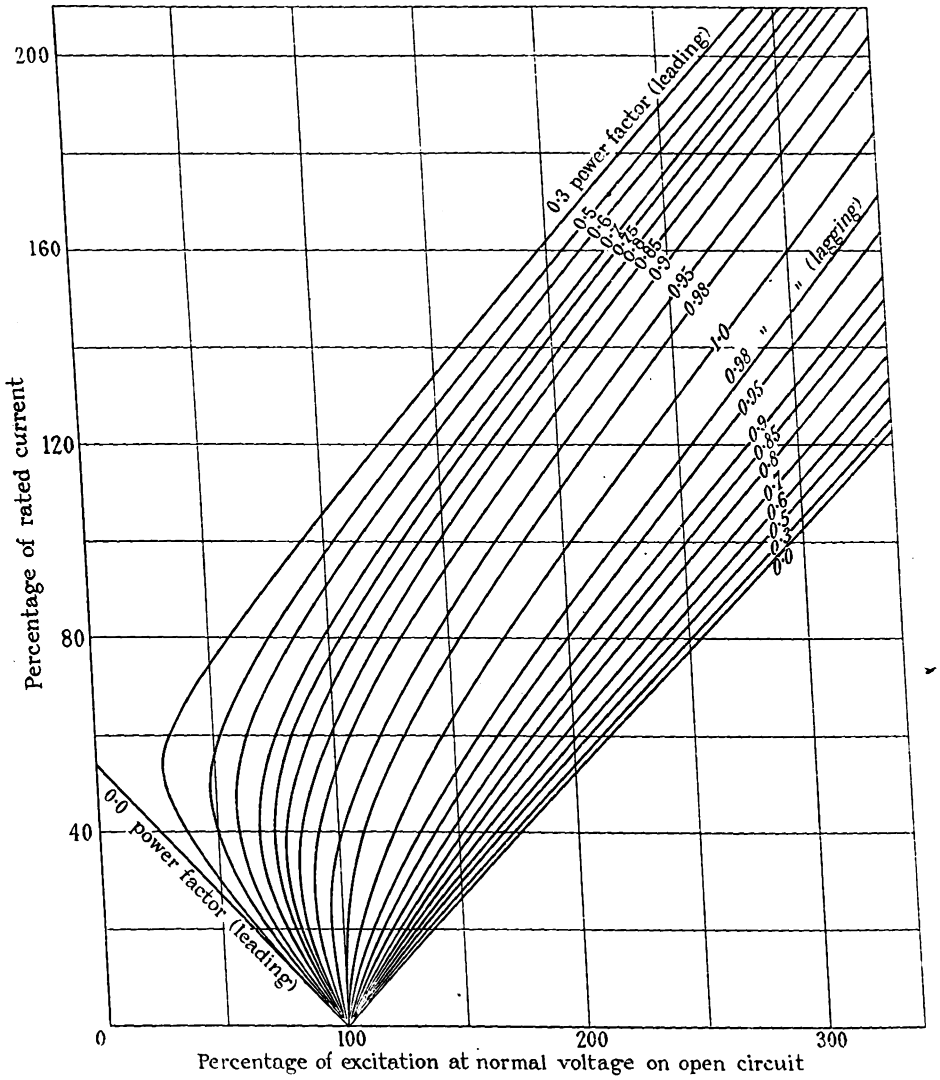

FIG. C.—Load excitation characteristics at normal voltage.

appreciably leading, and is directly proportional to the excitation. These results apply to steady condition of operation, but under momentary varying loads the maximum load which may be carried without falling out of step is greater than these owing to the effect of the armature transient on the field system, which augments the excitation and is a function of the time-constant of the alternator response (see that section of the paper which deals with alternator response alone).

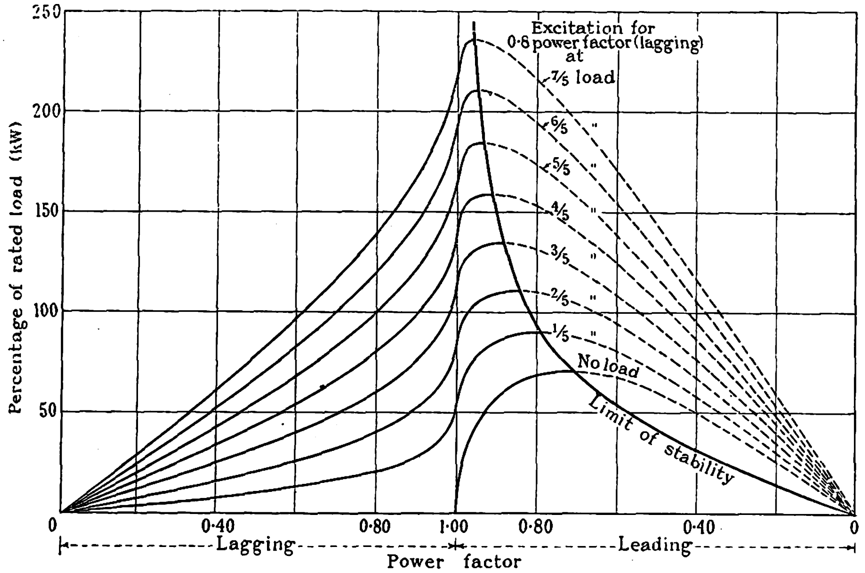

FIG. D.—Kilowatt/power-factor characteristics of alternator for various constant excitations when paralleled on a large system.

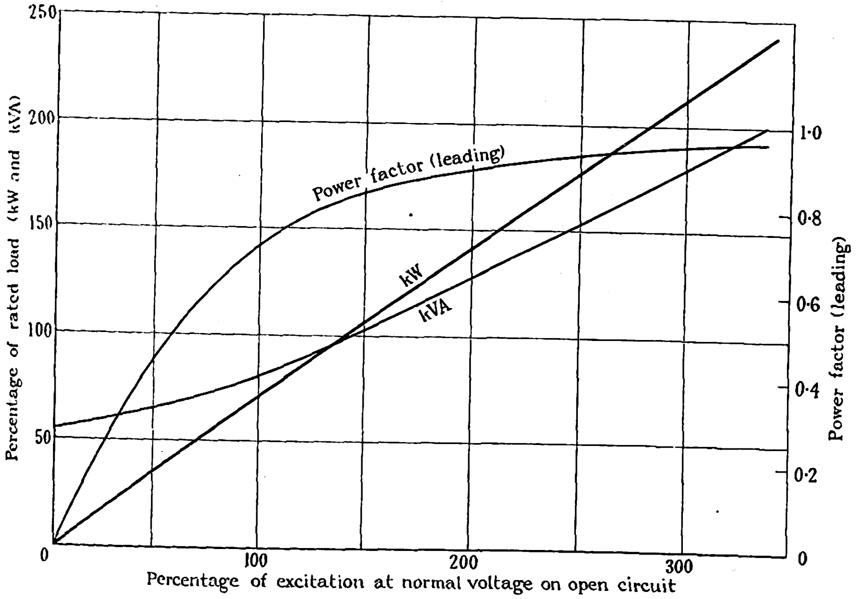

FIG. E.—Alternator characteristics at limit of stability when paralleled on large system at constant excitation.

Dr. R. G. Jakeman: It is well known that the separately-excited exciter for large turbo-alternators solves the problem of exciter instability, and the author's paper gives a very clear comparison of this type of excitation with the ordinary self-excited exciter. It does not appear, however, that the disadvantage of the properly designed self-excited exciter is very marked, especially in view of the fact that a very large number of such exciters are in satisfactory operation. The disadvantages of exciting the main exciter from a small direct-coupled machine are increased cost, increased length of set and the fact that there is another commutator to look after. The author states that to compound an exciter does not improve the load stability, but in my experience it does definitely do so. The series field compensates to a certain extent for the distortion caused by the armature reaction. I should like to ask what the author's experience is of the surge caused by slipping a pole. I understand that tests have been carried out on this point without any disturbance being detected. Finally, it is not quite clear to me what is the effect of the lack of equalizing connections on a lap winding.

Mr. F. C. Hall: It seems to me that in order to obtain a ready response in both the exciter and alternator field circuits a low time-constant in each of these circuits is most desirable, and as the resistance of the field coils is an important function of the time-constant it plays a big part in the satisfactory regulation obtainable. Curiously enough, the usual method of obtaining a ready response is to cut out or cut in external resistance in the exciter field circuit, the former to raise and the latter to lower the voltage. In the case of raising the voltage this action opposes the object to be achieved, because the more resistance there is in the exciter field circuit the lower will be the time-constant. If we refer to Fig. 6 the above arguments appear to be borne out by actual tests taken by the author. It will be seen that the time required to raise the voltage is appreciably greater than that required to lower it. Curves (b) illustrate this point best, and curves (a) show that the difficulty is largely overcome by means of separate excitation of the exciter fields. It seems that if some method of improved ventilation of the exciter field coils could be found to enable more heat to be dissipated in the coils, they might be made of wire of a higher resistance than copper so as to leave more internal resistance in the circuit when cutting out the external resistance by means of the regulator. This result can, of course, be achieved by retaining an equivalent amount of external resistance, and there would naturally be consequent losses in either case. If there are other difficulties I should be glad if the author would mention them in his reply.

Mr. G. R. J. Parkinson: Although the paper deals chiefly with the design of exciters and alternators, the author has thrown light on a number of phenomena which I have experienced as an operating engineer. I am particularly interested in Fig. 12. The company with which I am connected has had to deal with an industrial load, chiefly induction motors, at a very poor power factor, sometimes as low as 0·65 lagging. A number of static condensers have been connected, and although many are fixed in substations, and switched off as required, others, connected directly to consumers' transformers, are not switched off at week-ends and holidays, the result being that on Sunday mornings, and at times of very light load, the power factor of the system is about 0·4 leading. On these occasions, with one generator running, the voltage is extremely unstable, the smallest movement of the exciter rheostat causing the voltage to vary between 50 and 150 per cent of the normal. Steps have now been taken to see that these condensers are disconnected at times of very light load. The author refers to the necessity of maintaining full voltage in the event of a short-circuit on the system, and although I recognize the importance of maintaining an uninterrupted supply there are occasions when a serious drop in voltage is the lesser of two evils. Most supply engineers have found it extremely difficult to keep their switchgear quite up-to-date: their undertakings have grown so rapidly that the rupturing capacity of their switchgear has not kept pace with the growth of their generating plant, and in the event of a serious short-circuit a drop in voltage may prevent the burn-out of a switch panel and a complete shut-down. The author mentions the advisability of engineers operating their generators at the power factor for which the machines were designed. Although I can sympathize with him as a designer, I must point out the difficulties from an operating engineer's point of view. In a public supply the power factor varies tremendously at different times of the day and week, and I have found it advisable to order machines to give their full kilowatt output at the lowest power factor that is ever likely to be experienced. It may be that if such a machine be used generally at a higher power factor the instability and response may be somewhat worse, but on the other hand the high overload capacity on higher power factors may prove very useful. Referring to the reversal of an exciter, following a short-circuit on the alternator, I have found that this is more likely to occur when the exciter is provided with laminated pole-pieces, rather than in one with solid poles, and I should like to ask the author whether he can explain this difference.

Dr. M. L. Kahn (*communicated*): The paper is of particular importance at the present moment, as the problems arising in the voltage control of large alternators are so intimately connected with the question of system stability which is bound to come under consideration in connection with the grid scheme. On page 324 the author reminds us that in the United States large turbo-alternators have generally lower percentages of armature reaction than some machines which have been in successful operation for a number of years on large systems in this country. I am not sure that this experience can be relied upon in the future in this country, with the growth of the supply system approaching the conditions which are to be found in the United States, more especially in view of the conditions which the interconnection of supply systems will introduce. On the other hand, as the author points out in his following remarks, a large percentage of armature reaction is unavoidable if machines of large output are to be built for a speed of 3 000 r.p.m. It will, therefore, be necessary to find a safeguard which will ensure system stability on large power systems even though the percentage armature reaction of the turbo-alternator is high. The solution of these problems is a combination of extremely quick-acting voltage regulators in conjunction with quick-response exciters. The author has given actual data to compare the various systems of excitation which are possible from this point of view. A point in connection with quick response of the excitation which has not been specifically mentioned in the paper is the fact that, if the voltage of a system is allowed to drop, the motors connected to the system take more current and some may even fall out of step. This may increase the current to such an extent that the alternator voltage falls more quickly than the excitation can be raised, in the event of the voltage control not taking effect immediately. On the other hand, with quick-response regulators and exciters the drop in voltage can be stayed in time, so that the unstable condition just described will not arise and the voltage of the alternator can be brought back to its normal value. From this it is evident that for large turbo-alternators it is essential to adopt the system of excitation which gives the quickest response. From Figs. 21 and 24 it can be clearly seen that this is the system of an exciter which is separately excited and has, in addition, a very large voltage margin above the maximum voltage required for normal excitation. The additional expense involved by the adoption of this system will be well repaid by the increased stability of the power supply. An exciter possessing these features is shown in Fig. 4. I take it that this represents an exciter direct-coupled to a large turbo-alternator running at 1 500 r.p.m. For this speed the combination of two exciters on one shaft is quite practicable. On the other hand, for large turbo-alternators running at 3 000 r.p.m. such a combination would probably involve considerable mechanical difficulties and be less reliable than separately-driven exciters. Such exciters could, for example, be connected to condensing-plant pumps. In the development of the scheme for the calculation of response of the various field systems, the author frequently refers to a "time-constant." This expression is derived from the corresponding feature of a general circuit with a given reactance and resistance. Whilst for this general circuit this factor—the reactance divided by the resistance—is a constant, the factor becomes variable if used in the way the author applies it for exciters and turbo-alternators, and it is rather bewildering to find in Fig. 20 that this time-constant will vary so much for a given alternator. It would, therefore, be preferable to call this feature the "time-factor," especially as the variation with the load shown in Fig. 20 does not occur in the time-constant of the general circuit, from which the expression is taken. It is not quite clear from the paper why this time-factor is affected so much by the load, and a further explanation would be of great interest. The definition of the response figure given on page 320 is also somewhat difficult to understand on first reading it. Would it not be better to define the response figure as the voltage growth per second, or as the rate of voltage growth? That is what I understand the author to intend it to mean. For the straight part of the curves (a) and (b) in Fig. 6, the response is constant and can be read directly from these curves. I am particularly interested in Fig. 17, from which the voltage-drop of the alternator for constant impedance can be calculated for any load variation. In his figures for the voltage-drop on page 325 the author has given this drop for constant impedance, so far as I understand his meaning which is expressed in the words "when the full-load circuit is suddenly connected to the alternator terminals." It would be just as well if such a definition for the voltage-drop of an alternator were generally agreed upon, as the usual requirement in specifications, i.e. to state the voltage-drop if full load is switched on the alternator, is somewhat ambiguous. This is quite clear from the explanation of the conditions which arise when load is switched on to an alternator, and which are given at the top of page 324. Such expressions as "full-load circuit" or "full-load impedance" should always be introduced in specifying voltage-drops, so that one should say "if full-load impedance is switched on to the alternator," in preference to "if full load is switched on to the alternator." I cannot quite understand why the author states on page 323 that the time-factor of an exciter is not reduced if a large field conductor is used, or if the exciter field voltage is increased materially in case of separate excitation. Surely both alterations involve additional resistance in the exciter circuit with a corresponding reduction in the time-constant. Another point on which I cannot follow the author's reasoning is the effect of the series winding on the exciter with reference to reversal of polarity. An increase in series ampere-turns due to the sudden rise of current in the alternator field circuit can only affect the current in the shunt coils of the exciter in so far as it tends to change the flux. It is, therefore, essential to consider the sum of all the magnetomotive forces acting on the magnetic circuit, including the armature ampere-turns. If the series ampere-turns are correctly dimensioned so as to counterbalance the armature ampere-turns, an increase in current will affect the series ampere-turns and armature ampere-turns equally, so that no material change in the magnetomotive force takes place and the shunt cannot be affected. Compounding is, therefore, if properly applied, quite effective in preventing the demagnetization of the exciter in case of a sudden increase of field current due, for example, to a short-circuit on the alternator.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON AND BIRMINGHAM.

Mr. H. W. Taylor (*in reply*): Mr. Kuyser has suggested a definition for exciter stability which gives all types of exciters the same merit at the lowest voltage, and for this reason I would rather refer to Fig. 2 and define exciter stability as the rate of increase of voltage in regard to field-circuit resistance.

The mechanical analogies suggested by Mr. Peattie are very interesting. His reference to voltage regulation within one cycle refers not so much to operation with change of load but to alternator wave-form with continuous load. The larger the alternator the less likely is a bad wave-form of current to distort the wave-form of voltage.

I think Mr. de la Chard has taken our statement "The use of a cast-iron magnet frame in preference to one of steel helps the stability of the shunt machine" as a recommendation as regards policy for best stability and response. A general recommendation, however, is given on page 323 and is to the effect that the exciter should be separately excited and the poles and magnet frames laminated, and that no metallic support should be used for the field spools.

Mr. Everest has contributed some interesting notes on the development of the modern machine. With regard to the discussion between the French engineers, we agree with the middle course they seem to have adopted, namely, not to attempt to maintain the flux under extreme conditions but to provide for its rapid recovery as soon as normal conditions are restored.

Mr. Badham has taken the characteristics of a modern turbo-alternator as given in the paper and has developed some interesting curves showing that when this machine is allowed to trail it has a satisfactory margin of overload, provided the excitation is set at a reasonable value. In order, however, to have full advantage, in the case of faults, of all the excitation available on all machines, it is recommended that each machine should always be in operation with its own regulator.

Dr. Jakeman and other speakers have referred to the use of compound field windings on exciters and to the reversal of exciter voltage. The arguments for and against their use may be summarized as follows: As mentioned on page 319, series windings do not improve the inherent instability of a shunt machine; again, series windings do not improve the response because the time-constant of the exciter is inversely proportional to the total section of conductive material on the field spool; series windings do not have an immediate effect in overcoming load instability, because they act at right angles to the armature reaction and the latter is quicker in depressing the armature voltage than current on the field coils is in raising it; when, however, a shunt exciter is designed with a relatively short air-gap as an ordinary direct-current machine, exciter voltage oscillation and even reversal may occur with large changes in load on the alternator, and a small amount of series winding will prevent this; the same result, however, can be obtained without the series field winding if the air-gap is proportioned as indicated on page 317. With a separately-excited machine, reversal of voltage with changes in alternator load will not occur. The station voltage can remain undisturbed when, due to instability, one of the exciters reverses its voltage and its alternator slips a pole, if other machines running in parallel are controlled by regulators and excited with exciters which can, for the time being, supply the necessary extra excitation. All lap-wound exciter armatures should have equalizing connections. If these are not provided, there is a tendency at low voltage for an inequality in the poles to cause the machine to build up as a 2-pole machine, under which condition connections between brush arms which, for 4-pole operation, are of the same polarity, become short-circuiting connections between brushes of opposite polarity. This effect has been noticed even with the shunt exciter on open circuit and therefore without current round the commutating poles, but is not likely to occur with the air-gap proportions indicated on page 317.

In reply to Mr. Hall, it is not possible to cause the exciter voltage to rise as quickly as it can be made to fall in the same machine. His suggestion to improve the response of the machine by improved ventilation of the field coils is, in fact, the procedure which is adopted by the designers, but there is no advantage in using material other than copper on a field spool having a given heat-dissipating capacity. The use of an external resistance with correspondingly higher excitation voltage for the exciter would improve its time-constant, but its response could be still further increased by using the higher excitation voltage without the resistance.

Mr. Parkinson's experiences with the operation of machines over a wide range of power factor and the consequent instability at low power factors are of interest and there is no doubt that the stabilized exciter proposed in the paper is particularly useful under these conditions. Referring to Mr. Parkinson's experience that exciter voltage-reversal is more likely to occur with one provided with laminated pole-pieces than with one having solid pole-pieces, I think this is due to the fact that the latter machine would have a slightly longer time-constant and therefore would be slower in losing its voltage with a sudden excessive amount of armature reaction.

In reply to Dr. Kahn, the constant volt-ampere curves in Fig. 7 were intended to indicate the case of motors taking more current with falling voltage, and his conclusion, that under such conditions the machine would eventually lose its voltage when quick-response regulators are not in use, is given at the top of page 327. Fig. 4 shows the proportions of a machine actually used for exciting a 1 500-r.p.m. turbo-alternator, but similar machines with both exciters in the one frame are also in successful operation for large turbo-alternators running at 3 000 r.p.m. I agree that it is unfortunate and perhaps bewildering that the time-constants of both the exciters and the alternators vary with conditions of load. This arises from the fact that in the exciter we have saturation at higher voltages and in the alternator we have different circuits connected as load to the alternator terminals, so that the alternator flux per ampere of rotor excitation, upon which the time-constant depends, is less at high loads than at low loads. These difficulties are dealt with in the paper by defining the time-constant of the exciter and the alternator for the initial straight part of the saturation curves and with no external resistance, and then giving, in the case of the exciter, the response curves at different voltages as in Fig. 7, and, for the alternator, the time-constant at different loads as in Fig. 20. When the time-constant is defined in this way, the statement, that it does not vary for different excitation voltages or when a larger field conductor is used with correspondingly fewer number of turns, will be understood.

ALTERNATING-CURRENT POTENTIOMETERS AND THEIR APPLICATIONS.

By C. V. Drysdale, O.B.E., D.Sc., F.R.S.E., Member.

(*Paper first received* 29*th July, and in final form* 26*th September*, 1929; *read before the* Meter and Instrument Section 6*th December*, 1929.)

Summary.

An historical account of the evolution of the a.c. potentiometer is given, followed by descriptions of the Drysdale-Tinsley, Larsen, Gall, Pedersen, Campbell and other types of the instrument. The theory and accuracy of such instruments are discussed, and examples are given of their application for various tests.

(1) Introduction.

No department of electrical testing involves such difficulties and such costly equipment as that of accurate a.c. measurements. The great majority of alternating-current and p.d. measuring instruments have only a limited range, owing to the square law which underlies their operation, so that to cover the range from, say, a few milliamperes to several thousand amperes, and from a few millivolts to 100 kV, a formidable array of such instruments is required, which is still further increased when polyphase circuits have to be dealt with and wattmeters have to be provided for power and phase measurements. The battery of costly instruments for covering the above requirements within an accuracy of 1/10th of 1 per cent is beyond the resources of all but Government Departments and wealthy concerns: and a single instrument which can deal with the situation, even at the cost of some sacrifice of convenience and accuracy, is certainly the greatest need of the instrument maker and smaller standardizing laboratories.

The most universal of direct-current testing instruments is, of course, the potentiometer, which was first suggested in practical form by Sir Ambrose Fleming in 1885[*] and developed by Col. Crompton. In this form of instrument, which has persisted with only minor modifications to the present day, a number of equal-resistance coils (originally 14) and a slide wire having a resistance a little greater than that of one of the coils are connected in series. If each coil is of exactly 2 ohms resistance, and a current of 0·05 ampere is passed through the whole series, there will be a p.d. of 0·1 volt across each coil, and a total p.d. of a little over 1·5 volt across the coils and slide wire; and any p.d. up to this maximum can be tapped off between two sliding contacts on the studs and slide wire. The correct current is obtained by connecting the potentiometer through coarse and fine rheostats to a steady 2-volt secondary cell and balancing against the known e.m.f. of a standard cell.

The Crompton potentiometer is certainly the most simple and convenient of such instruments, but it suffers from the defect that p.d.'s of less than 0·1 volt can only be measured on the slide wire, which, unless it is extraordinarily uniform, limits the accuracy of measurement to an appreciable fraction of 1 per cent. The measurement of current by the potentiometer is effected by passing the current through a standard resistance or shunt and measuring the p.d. across it, and if the current is, say, 1 000 amperes this involves a power consumption of 100 watts for 0·1 volt, and a proportionately higher consumption for heavier currents. Unless the resistance standards are large and costly and provided with elaborate cooling arrangements, therefore, a drop of 0·1 volt is the maximum which can be allowed for heavy-current measurements, and the whole measurement must therefore be made on the slide wire. It is consequently desirable to relegate the slide wire to the next decimal place so that 9 coils are in series with it when measuring a p.d. of 0·1 volt, and this may be done in any one of three ways. The simplest of these is to employ a "transposition circuit" (Fig. 1) which consists of two coils, one having a resistance of 1/9th of that of the whole potentiometer circuit and the other a resistance 9/10ths of it. By turning a switch the potentiometer is shunted with the former coil, reducing its resistance to 1/10th, while the second coil is connected in series with the combination, restoring the total resistance and current to their former values. The current through the potentiometer, and hence the p.d. corresponding to its readings, are therefore reduced to exactly 1/10th of their normal values. This device has been fitted to the later types of Crompton potentiometer and is quite effective, the only objections to it being that the p.d. of the secondary cell supplying the constant current may be slightly disturbed by the process of switching over, and that for such a low-resistance instrument the shunt must also have a very low value and care must be taken to have a very perfect contact in the switch.

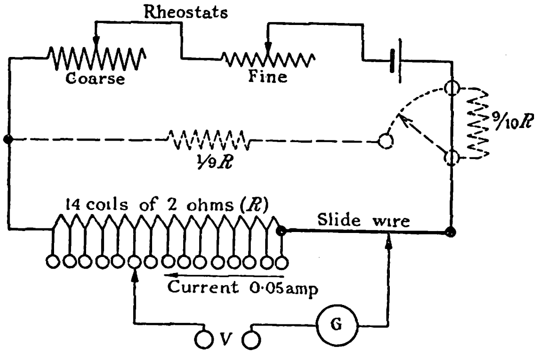

Fig. 1.—Crompton potentiometer—"Transposition circuit" shown dotted.

The remaining two methods consist in employing two resistance dials in series with the slide wire. In one of these (Fig. 2), which may be said to be on the Kelvin and Varley slide principle, the second dial of 10 equal coils has a total resistance equal to that of two coils of the first dial, and is connected across a double-contact switch spanning two studs of that dial so that the parallel resistance of the combination is exactly that of one coil, and the p.d. of 0·1 volt across it is subdivided to 0·01 volt. The slide-wire resistance is then reduced to 1/10th of its former value. Messrs. Tinsley's "universal potentiometer" is of this type. The third device employs the Feussner principle of replacement in which any number of dials can be connected in series, but the resistances are duplicated so that for any increase of resistance between the potential points an equal reduction is made in the resistance of the remainder of the circuit, so that the total resistance, and hence the current, remain constant. In the case of a 2-dial and slide-wire potentiometer only one of the dials need be thus duplicated, as indicated in Fig. 3.

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[*] See Reference (1).

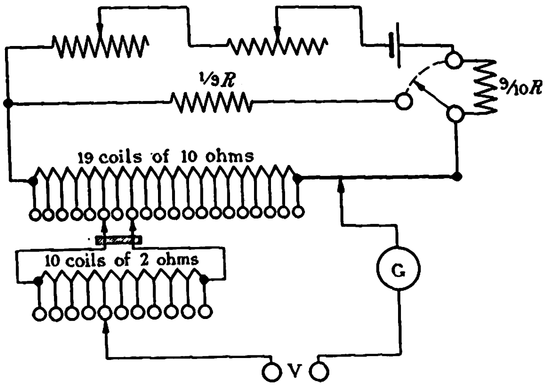

FIG. 2.—Two-dial and slide-wire potentiometer (Kelvin-Varley principle).

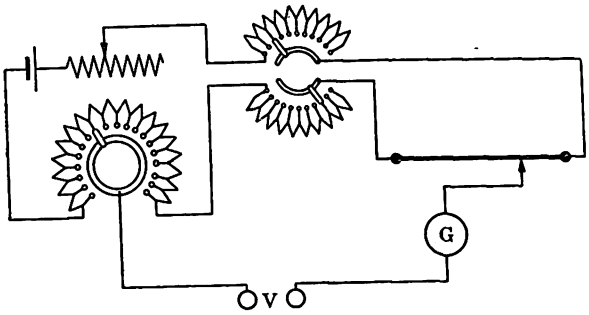

FIG. 3.—Two-dial and slide-wire potentiometer (Feussner).

Both of these double-dial potentiometers have the disadvantage, as compared with the simple Crompton form, of having sliding contacts in the resistance included between the potential leads, but if care is taken over these contacts little error is caused by them. The Kelvin-Varley principle has the advantage over the Feussner form of requiring fewer coils and of having twice the resistance in the second dial, so that contact errors have less effect. On the whole, therefore, it seems preferable; and the author, in his report on the electrical exhibits of the St. Louis exhibition of 1904, suggested this type as the most generally useful and has since adopted it for the a.c. potentiometer to be described in this paper.

Before leaving this section, it may be well to refer to the application of the d.c. potentiometer to p.d., current and resistance measurements, for comparison with a.c. potentiometer measurements later. Fig. 4 shows the standard connections for testing a d.c. load of any kind. The load is simply connected to the appropriate d.c. mains through a standard resistance R_s of suitable current-carrying capacity, and the p.d.'s V_1 and V_2 across the load and resistance are successively measured on the potentiometer, from which the current $I = V_2/R_s$ and the power absorbed by the load and "volt box" combined, $P = V_1 I = V_1 V_2 / R_s$. If V_1 is less than 1·8 volts it can be directly measured, but if it is higher a "volt box" or potential divider is connected across it as shown by the dotted lines, and a known fraction of the p.d. is measured. If the load is a simple resistance, its value is obviously $V_1 I = (V_1/V_2)\ R_s$ if no volt box is used, and a simple correction can be made for the shunting effect of the latter when employed. It will be seen below that a.c. potentiometer testing is conducted in precisely the same manner, and the same standard resistances and volt boxes can be employed for either d.c. or a.c. measurement, provided that they are sufficiently non-inductive.

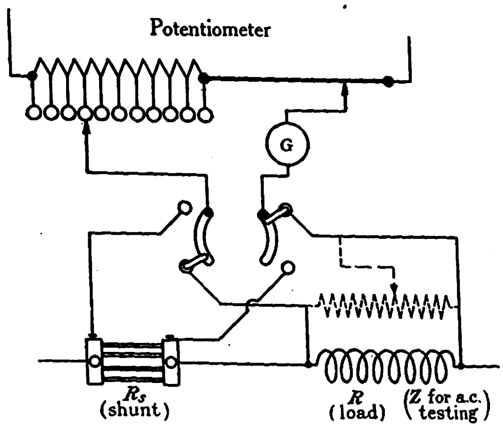

FIG. 4.—Current and p.d. measurement.

(2) EARLY ATTEMPTS AT A.C. POTENTIOMETERS.

The great range and accuracy of the d.c. potentiometer soon led to a desire for a similar instrument for a.c. testing, and various suggestions for what may be termed transference devices, enabling the alternating p.d. to be measured to be balanced against an equal continuous p.d. derived from the potentiometer, were made. One of the first and the most simple in principle was that suggested by Mr. J. Swinburne in 1894 * and consisted of interposing a sensitive quadrant electrometer between the potentiometer and a.c. circuit as in Fig. 5. This manner of connecting the electrometer makes it differential, and balance is obtained when the p.d. V_1 derived from the potentiometer is equal to the R.M.S. value of the alternating p.d. V'; so that all that

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* See Reference (2).

has to be done to measure the latter is to use the electrometer in place of the ordinary galvanometer, and vary V_1 to secure balance. In principle this method is quite correct and it could be used quite well for p.d.'s of about, say, 20 volts and higher, but its application is limited by the extreme insensitiveness of electrometers at the low p.d.'s employed in current measurements; by the difficulty of obtaining exact symmetry in the electrometer; and by the Volta or "contact" e.m.f.'s between the needle and quadrant, which are very difficult to eliminate and which may be a material fraction of the p.d. under measurement. So far as the author is aware, there is no record of this method having been put into practice; and the first transference device to be actually used was probably the heated platinum tube employed by Orlich * at the Technische Hochschule at Charlottenburg for the measurement of large alternating currents. The alternating current to be measured was passed through a platinum tube (Fig. 6) of such section as to heat it to incandescence, and its temperature was then observed by an optical pyrometer of the disappearing-filament type, and reproduced by switching the platinum tube over to direct current, which was measured by the potentiometer. This device, when carefully used, was capable of measuring within an accuracy of a few tenths of 1 per cent, provided that the tubes were sufficiently long to give uniformity of temperature and to eliminate the action of Peltier effects, but the platinum tubes were very costly and took some time to attain a steady temperature, so that measurements were slow and the waste of energy was enormous. The author consequently modified it by using a shunted metal-filament lamp and matching it with a comparison lamp on a Lummer photometer. A further obvious simplification of this method is to connect a thin hot-wire element to the potential terminals of a suitable resistance or shunt and to determine the temperature of the wire by the ordinary cross thermo-junction. If two such elements (Fig. 7) are accurately paired, and their thermo-junctions connected in series and in opposition, they form a differential electrometer, though of course without the advantage of requiring no power for small p.d. measurements. The "thermo-convertors" recently introduced by Dr. Moll of Utrecht * would seem to be ideal for this purpose, as, owing to the large number of thermo-junctions employed, a temperature-rise in the heated wire of only a few degrees is amply sufficient, and they can be very accurately paired.

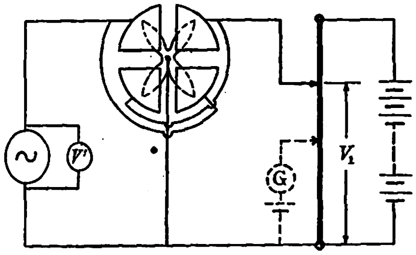

FIG. 5.—Swinburne's electrometer method.

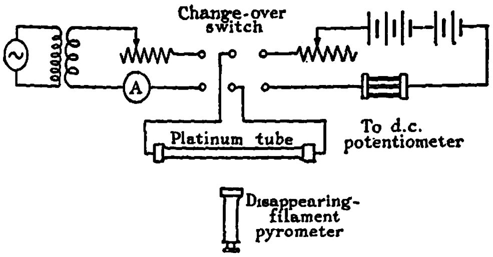

FIG. 6.—Orlich's platinum-tube method.

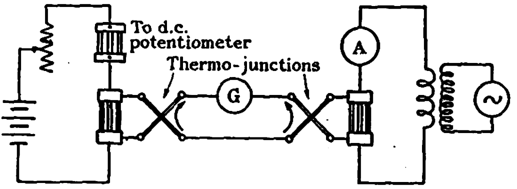

FIG. 7.—Thermo-junction method.

Franke Double Alternator.—As early as 1891 Herr A. Franke,† who had already done some valuable work on d.c. potentiometers, conceived the principle which is now used in all a.c. potentiometers, namely of balancing the alternating p.d. to be measured by a known alternating p.d. which can be varied both in magnitude and phase so as to reproduce the former exactly. His device (Fig. 8) consisted of two small alternators with a common revolving field magnet coupled to a driving motor, the armature G_1 being rotatable round its axis by a worm N_1 so as to alter the phase of its e.m.f. with respect to that of the armature G_2, which could be moved axially by a micrometer screw P_2 which moved it out of the magnetic field and thus enabled the magnitude of its e.m.f. to be continuously varied. The circuit to be tested was connected to the first alternator, and the two points between which the p.d. was to be measured were connected through a detector (usually a telephone receiver) to the second alternator, balance being obtained by rotating the first and sliding the second armature. The device can hardly be described as a potentiometer in the ordinary sense of the word, but it fulfils the same purpose, and it is of interest as being the first device in

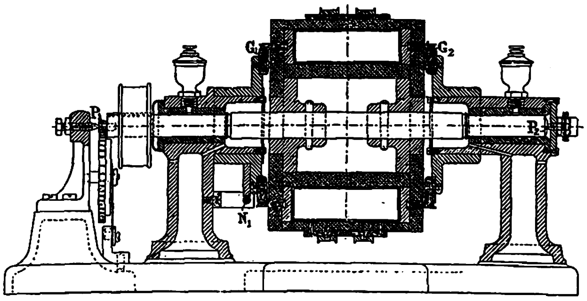

FIG. 8.—Franke double alternator.

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* See Reference (3).

* See Reference (4).

† *Ibid.*, (5)

which the principle of balancing and measuring the phase as well as the magnitude of the p.d. to be measured was employed.

The double-alternator method has much to commend it, as there is no need for phase-splitting devices, and its accuracy of phase displacement is limited only by the accuracy to which the circular scale can be read. It is not, however, convenient for measurements involving large power, as the phase adjustment must be made at the machine itself.

In a later form * the Franke double alternator was enlarged and made with a vertical spindle, and the number of poles was increased to 40, giving frequencies up to 2 000 cycles per sec. with a moderate speed of rotation; but the variation of magnitude by axial displacement of one of the armatures was retained. It seems curious that this should not have been replaced by a potentiometer across the rotatable armature, as a potentiometer device was most probably employed for calibration. The machine was made by Messrs. Siemens and Halske and has proved of great value in telephone and cable investigations.

(3) Modern A.C. Potentiometers.

Drysdale A.C.–D.C. Potentiometer.—Unfortunately the Franke device was little known in this country, and in 1908 the present author, after devising some phase-shifting transformers for facilitating wattmeter and supply-meter testing, independently conceived the principle of considering the alternating p.d. as a vector and balancing it both in magnitude and in phase by a similar p.d. derived from a potentiometer fed with alternating current from such a phase-shifting transformer.† This immediately solved the problem of sensitivity, as it was quite easy to balance within a few microvolts by the aid of a sensitive vibration galvanometer, and it eliminated all transference devices and permitted a.c. measurements to be made with the same " shunts " and volt boxes as those used for d.c. measurements, provided that the former were sufficiently non-inductive. On the other hand, this method was only theoretically accurate for measurements on fairly closely sinusoidal supplies, but a moderate departure from pure sine wave-form involved only a relatively small error, which could be neglected or eliminated in many cases. Modern wave-forms are generally so closely sinusoidal that the errors are inappreciable, except when distortion is introduced by iron-cored inductances.

One advantage of this method, in which both the potentiometer and test circuit are supplied from the same a.c. mains, over the Franke method, is that in the former method the relation between the p.d. in the mains to the potentiometer current is constant, and a single initial reading of this p.d. is sufficient; whereas in the double-alternator method any variation of the load on the supply alternator causes a change of the magnitude and phase of its p.d. and therefore necessitates two readings for each load.

Fig. 9 shows the elementary scheme of such a potentiometer. It consists essentially of an ordinary potentiometer, say of the 2-dial and slide-wire type, with two regulating rheostats. A dynamometer ammeter D, with a fiducial mark corresponding to a current of 50 mA, is connected in series with the coils, and the secondary of a phase-shifting transformer is substituted for the ordinary accumulator. The primary of this transformer has a 2-phase winding, both phases being connected to the supply mains, one directly and the other through a resistance and condenser for splitting the phase and giving the necessary quadrature supply, the correct phase-splitting being obtained by adjusting the capacity and resistance until the dynamometer deflection remains constant when the secondary is rotated. When this condition is secured, turning the secondary through any angle changes the phase of the current in the potentiometer coils, and therefore the p.d. across any section of them, by the same angle.

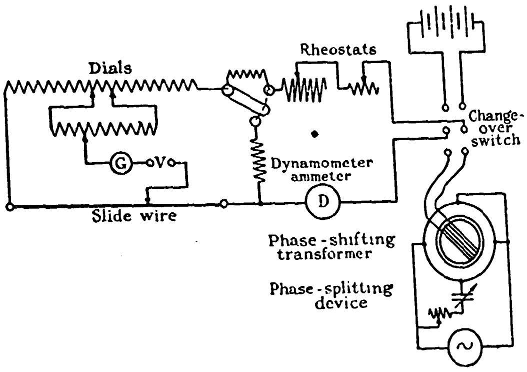

FIG. 9.—Elementary diagram of Drysdale potentiometer.

The two sliding contacts of the potentiometer are connected in the ordinary way to a selector switch through a galvanometer, which in this case is a sensitive vibration galvanometer tuned to the supply frequency.

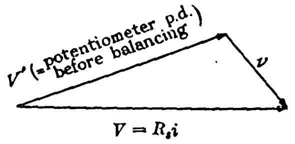

FIG. 10.—Vector diagram of Drysdale potentiometer.

The circuit to be tested, having an effective impedance Z, is connected in series with a known non-inductive resistance R_s to the secondary of a transformer fed from the mains, and R_s and Z are connected to the contacts of the selector switch exactly as for testing d.c. loads (Fig. 4). The current through the combination produces across the shunt (Fig. 10) a p.d. $V = R_s i$ which is in phase with the current, while the p.d. V' between the potentiometer contacts prior to securing balance will generally differ from it both in magnitude and phase, giving a vector difference v which deflects the vibration galvanometer. By successively rotating the phase shifter and adjusting the potentiometer contacts, the galvanometer can be brought to balance, in which case the p.d. between the potentiometer contacts is identical both in magnitude and in phase with the voltage-drop over the resistance, and their values can be read off from the potentiometer and the phase-shifter scales. If the load Z is due to an ammeter it can be calibrated in this way, but if it is an impedance of any kind its value is obtained by turning the selector switch and balancing the p.d. V' across it as before. Then V' is given as a vector the lag or lead of which (ϕ) with respect to $R_s i$ or to i is given by the angle turned through by the phase shifter, from which the impedance $Z = R_s(V'/V)\underline{/\phi}$ and the effective resistance and reactance of the coil are $Z \cos \phi$ and $Z \sin \phi$ respectively. By the aid of a cosine scale on the transformer and two pointers at right angles, $\cos \phi$ and $\sin \phi$ can be directly read off.

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* See Reference (6). † *Ibid.*, (7).

Alternating-current measurements on sinusoidal waveforms may, in fact, be considered as vector surveying or triangulation, and this type of potentiometer is an electrical vector-surveying instrument in which the measuring tape or chain is represented by the dials and slide wire, and the prismatic compass, sextant or theodolite by the phase-shifting transformer.

The detailed description and applications of the instrument will be reserved until later, but one further matter of principle may be referred to here. In standardizing work the d.c. potentiometer is referred to a standard cell, and it is desirable that this feature should be retained in a.c. testing, instead of relying on the dynamometer. This is easily effected in the a.c. potentiometer by providing it with a changeover switch which replaces the secondary of the phase shifter by a 4-cell accumulator (the extra 6 volts being required on account of the resistance of the dynamometer), and the vibration galvanometer by an ordinary moving-coil galvanometer. When this switch is thrown over, the potentiometer becomes an ordinary d.c. instrument, and a standard cell can be balanced in the usual manner. In this case the dynamometer should indicate the standard current of 50 mA in the coils, but if not it can be adjusted to this reading by the ordinary zero adjustment, after which all alternating-current p.d.'s are measured in terms of the standard cell. The instrument is, of course, equally available as an ordinary potentiometer for all d.c. measurements.

Before going into further details of this instrument, reference will now be made to other forms of a.c. potentiometer which have since been devised. It should be pointed out that, as there are two ways of defining a vector, there are two different principles upon which a.c. potentiometers may be based. A vector may be defined either in polar co-ordinates by its magnitude and angle (or $r\underline{/\theta}$), or in rectangular or Cartesian coordinates x and y, the well-known relations between these systems being

$$x = r\cos\theta, \quad \text{and} \quad y = r\sin\theta$$

or

$$r = \sqrt{(x^2+y^2)}, \quad \text{and} \quad \theta = \text{arc tan}\,(y/x)$$

The instrument above described is obviously a polar potentiometer, as it gives the magnitude and phase angle or $r\underline{/\theta}$ directly. For the great majority of purposes this is the most accurate and convenient principle, as if a p.d. or current is to be measured in calibrating an instrument it is much better to read it directly from the potentiometer dials than to measure the two components and calculate their resultant. It was for this reason that the author selected the polar principle in the first instance, and he still considers it to be the best all-round principle, although the rectangular principle has advantages in a limited number of cases.

Kennelly's Demonstration A.C. Potentiometer.—In 1911 Prof. A. E. Kennelly [*] of Harvard devised an instrument consisting of a large square of thin manganin sheet, across which two equal currents in quadrature were passed in rectangular directions (Fig. 11). The sheet was therefore a surface of rotating p.d., and if contact was made on it at any two points the magnitude of the p.d. between them was proportional to their distance apart, and its phase depended on the inclination of the line joining them. By fixing one contact at the centre of the plate, the other contact could be so moved as to balance any required p.d., whereupon the p.d. was immediately exhibited as a vector. Obviously such a device is not adapted for accurate measurements, but it forms a sort of a.c. vector blackboard and is admirably suited for teaching purposes.

Author's Demonstration Potentiometer.—In view of the great value of the a.c. potentiometer for teaching alternating-current theory, a simple form of the author's potentiometer has been made up on a vertical blackboard about 4 ft. square, having a small phase-shifting transformer at its centre. A light arm carrying a slide wire is attached to the phase-shifter spindle, and a sliding block like a slide-rule cursor carries a contact and a point for marking its position on the blackboard, which is marked off both in squares and in circles for reading either in rectangular or polar co-ordinates. A vibration galvanometer can be used for ordinary supply frequencies, but for frequencies of 200 cycles per sec. or higher an amplifier and loud-speaker form a very effective detector.

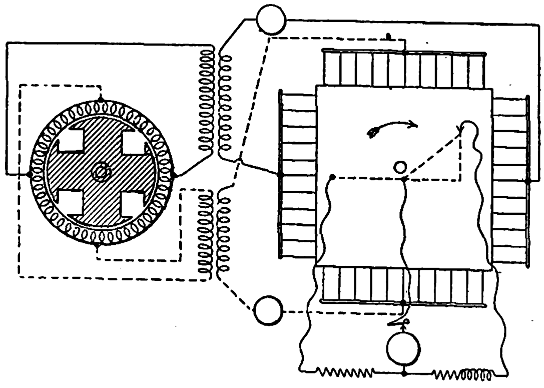

FIG. 11.—Kennelly's demonstration potentiometer.

Sharp and Crawford Potentiometer.—A simple form of polar potentiometer was devised by Messrs. Sharp and Crawford in the United States in 1910.[†] If a resistance with sliding potentiometer contact is connected across two of the terminals of a 3-phase supply, and the potentiometer is connected between this contact and the third terminal of the supply, the phase of the p.d. applied to the potentiometer can be varied over an angle of 60° by sliding the contact from one end to the other, but its magnitude varies from V to $\frac{1}{2}\sqrt{3}V$ between the end and centre positions. By employing two auto-transformers mechanically coupled through linkwork, this variation was eliminated, but the shift of phase could only be increased beyond 60° by changing the connections to the supply.

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[*] See Reference (8).

[†] *Ibid.*, (9).

Larsen Rectangular Potentiometer.—Turning now to the rectangular or Cartesian principle, it is easy to devise on it an accurate potentiometer for a definite known frequency. The most simple method, which was first definitely used for a potentiometer by Prof. A. Larsen of Copenhagen in 1910,* although its fundamental principle had already been conceived and utilized by Mr. A. Campbell in 1908,† is shown in Fig. 12, in which the ordinary resistance coils and slide wire are connected in series with the primary of a variable mutual inductance the secondary of which is joined in series with one of the sliding contacts. If i_1 is the potentiometer current, and R the resistance between the contacts, the p.d. between them will be Ri_1 in phase with the current, while the e.m.f. in the secondary of the mutual inductance M will be $M\omega i_1\underline{/90^\circ}$, where $\omega = 2\pi \times$ frequency. The p.d. v_2 of the combination will therefore be $(R + M\omega\underline{/90^\circ})i_1$ and the dial of the mutual inductance can be graduated directly in volts for a given frequency, so that the potentiometer reads the two components directly when any given p.d. is balanced. It will be seen, however, that, although the total magnitude can be obtained by calculation, the accuracy cannot be high unless the frequency is absolutely at its standard value, whereas in the polar potentiometer, although variations in frequency affect the phase-splitting and consequently the accuracy of the phase measurement, they do not cause any error in the magnitude if care is taken to see that the dynamometer current is correct or to adjust it when the balance is made. Prof. Larsen appears to have made up a complete potentiometer with a circular central-zero slide-wire and a variable mutual-inductance standard of the Campbell type, but with the primary and secondary systems doubled so as to give a central zero and symmetrical scale.

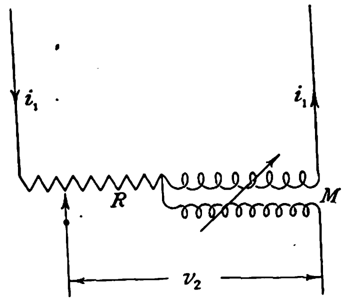

FIG. 12.—Larsen potentiometer—elementary diagram.

Hanson-Kennelly-Velander Potentiometer.—A self-contained potentiometer on the Larsen principle was devised and made at the Massachusetts Institute of Technology in 1919,‡ following a suggestion by Mr. Hanson in an MS. thesis in 1916. The instrument consisted of a 2-dial and slide-wire potentiometer of the Feussner type, and a mutual inductance made up of a number of elements arranged toroidally so as to give as small an external field as possible, the secondary coils being successively thrown into circuit by dial switches. A single small additional secondary coil was arranged to turn in the field of the toroid so as to give continuous variation over a small range, corresponding to the slide wire of the in-phase potentiometer.

Geyger's Potentiometer.—In order to avoid the use of a variable mutual inductance in the Larsen potentiometer, W. Geyger conceived the idea of employing a fixed mutual inductance the secondary of which was connected across a second potentiometer.* This of course involves loading the secondary and destroys the perfect quadrature relation, but Geyger claims that this error can be reduced to from 0·1 to 5 minutes of phase angle, which can be neglected, or allowed for in special cases. His first instrument (1924) was devised for demonstration purposes and had two slide wires along the two adjacent edges of a board, the sliders being provided with long arms the intersection of which showed the p.d. measured as a vector. He has since developed the device into a more accurate measuring instrument, which has been commercially manufactured by Messrs. Hartmann and Braun.

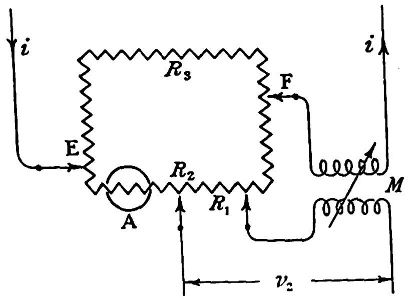

FIG. 13.—Larsen potentiometer—Campbell's loop shunt.

The Larsen principle has also been utilized by C. Déguisne,† who has also developed a method initiated by Schering and Alberti,† of the Reichsanstalt, for measuring the ratio and phase displacement in current transformers; it employs a shunted condenser in series with the potentiometer to shift the phase of its p.d. through small known angles. A special potentiometer method for testing potential transformers has been described by P. G. Agnew and T. T. Fitch,§ of the Bureau of Standards.

Campbell Direct-reading Potentiometer.—The great inconvenience of the Larsen device is the frequency factor in the quadrature component, which prevents the potentiometer from being made direct-reading except for one frequency. Mr. Campbell has, however, recently returned to the subject and has devised a practical form of potentiometer on these lines, in which the troublesome frequency factor in the quadrature component has been eliminated by an elegant application of the well-known Ayrton-Mather shunt.|| In the simple Larsen arrangement in which the same current flows through the resistance and the primary of the mutual inductance, the p.d. across the resistance is Ri_1, and the e.m.f. across the secondary of the mutual inductance is $jM\omega i_1$, so that for a given value of M the e.m.f. is proportional to the frequency. If, however, we arrange that the current through the primary of the mutual inductance is inversely proportional to the frequency, the product ωi_1 is constant and the e.m.f. is proportional to M only. Fig. 13 shows the scheme of the Campbell potentiometer in which the potentiometer resistance R_1 is in series with a non-inductive current indicator A and with a resistance forming a complete loop. The exciting current i is led in at a sliding contact E and divides into two portions flowing through the upper and lower sides of the loop, after which it unites at the sliding contact F and passes through the primary of the mutual inductance M. Then if i_1 is the current through A and R_1, and R_3 and R_2 are the resistances of the upper and lower portions of the loop between the contacts E and F, $(R_2 + R_3)$ is constant for all positions of the sliders and $i = i_1(R_2 + R_3)/R_3$.

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* See Reference (10). † *Ibid.*, (11). ‡ *Ibid.*, (12).

* See Reference (13). † *Ibid.*, (14). ‡ *Ibid.*, (15). § *Ibid.*, (16). || *Ibid.*, (17).

Hence the p.d.

$$v_2 = R_1 i_1 + j\omega M i = \left(R_1 + j\frac{R_2 + R_3}{R_3} M\omega\right) i_1,$$

If we adjust R_3 in proportion to ω so that

$$R_3 = \left\{(R_2 + R_3)/b\right\}\omega, \text{ then } v_2 = (R_1 + jbM)i_1,$$

which is independent of the frequency. For example, if we wish to have a potentiometer in which the current i_1 is 0·01 amp. (100 ohms per volt) and the value of R_3 in ohms is equal to the number representing the frequency, $\left\{(R_2 + R_3)/R_3\right\}M\omega = 2\pi(R_2 + R_3)M = 100$ for $i_1 = 1$ amp.

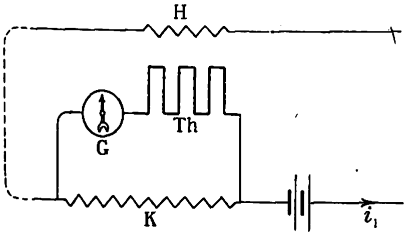

FIG. 14.—Campbell-Larsen potentiometer—thermopile device.

Hence the whole resistance of the loop $(R_2 + R_3) = 100/(2\pi M)$, and if we make $M = 10$ mH $= 0{\cdot}01$ H, $(R_2 + R_3) = 1\,592$ ohms. Then for 25 cycles per sec.

$$R_3 = 25,\ R_2 = 1\,567 \text{ ohms},\ i = 0{\cdot}637 \text{ amp.}$$

and for 1 000 cycles per sec.

$$R_3 = 1\,000,\ R_2 = 592 \text{ ohms},\ i = 0{\cdot}0159 \text{ amp.}$$

If the maximum p.d. across the potentiometer is to be 2 volts, the resistance of the potentiometer coils will be 200 ohms. It is not suggested that these are the actual resistances, etc., in the potentiometer as made, but the calculation illustrates the application of the principle.

An interesting feature of Mr. Campbell's potentiometer is the method he employs for keeping the current i_1 at its correct value. A thermopile Th (Fig. 14) is connected through a galvanometer G to the terminals of a low resistance K through which an auxiliary direct current is passed. A heater H is mounted close to the thermopile, and is at first connected in series with K. On passing the current, the galvanometer circuit has the p.d. across K in series with the e.m.f. of the thermopile, and if these are in opposition there will be some value of the current at which there will be balance, since the p.d. is proportional to the current and the e.m.f. to its square. By varying K this balance can be obtained for the required value i_1 of the current, after which a key is thrown over, disconnecting K from H but putting it in series with an equivalent resistance so that the current remains unchanged. If then an alternating current of strength i is passed through the heater H, balance will be restored. The heater is included in the potentiometer at A and enables the current to be adjusted during use.

The general appearance of the potentiometer is shown in Fig. 27, from which it will be seen that the resistance section and adjusting rheostats and heater are in one case, and the variable inductometer, giving the quadrature component, in a second case on the right. Readings of either component can be taken from about 10 μV up to 1·8 volts in phase or 1 volt in quadrature, and either component can be reversed by a switch so as to obtain readings in any quadrant.

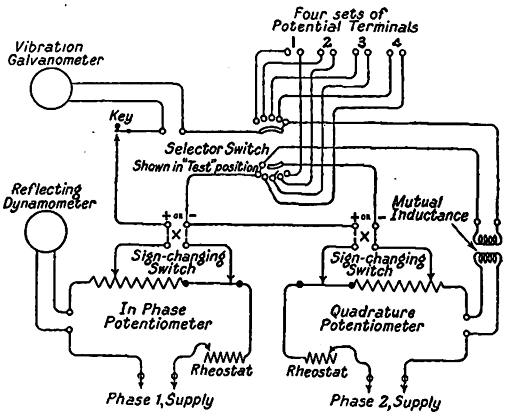

FIG. 15.—Gall co-ordinate potentiometer.

Gall Co-ordinate Potentiometer.—The first commercial potentiometer on the rectangular principle was, however, introduced by Mr. D. C. Gall in 1923 * and was on different lines from the above. Two exactly similar potentiometers (Fig. 15) are fed with equal currents in quadrature, and their sliding contacts are connected in series, so that their combined p.d. $V = V_1 + jV_2$, where V_1 and V_2 are the readings of the two potentiometers. By introducing reversing switches into the two instruments, either V_1 or V_2 can be reversed in sign or phase, allowing p.d.'s in any quadrant to be balanced. The two quadrature currents can, of course, be derived from a 2-phase alternator, but Mr. Gall adopted a phase-splitting device which is similar in effect to the resistance-condenser combination employed in the author's potentiometer, but substitutes a transformer or an ironclad mutual inductance for the condenser. In order to be able to ascertain whether the quadrature relation of the potentiometer currents is exactly correct, one of the circuits has the primary of a mutual inductance in series with it, the value of which is such that the secondary develops 0·5 volt with the normal primary current at 50 cycles, 0·6 volt at 60 cycles, and so on. Since this e.m.f. is in quadrature with the current in the primary, it must be in phase with the p.d. derived from the other potentiometer when the phase relation is correct, so that if the instrument is to be used on a 50-cycle supply all that is necessary is to set the in-phase potentiometer contacts to 0·5 volt and adjust the resistances of the phase-splitting device and those in series with the potentiometer until exact balance is obtained against the secondary of the mutual inductance; the correctness of this adjustment can be easily checked at any time during the tests. This test ensures the equality of the currents and the correct quadrature relation between them, while the correct value of the current is obtained by balancing a standard cell on the first potentiometer in the ordinary way. An external reflecting dynamometer is employed. The connections and vector diagram of the phase-splitting circuits are shown in Figs. 16 and 17, in which the vectors A, B, C and D on the vector diagram represent the p.d.'s across the correspondingly lettered component of the circuits.

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* See Reference (18).

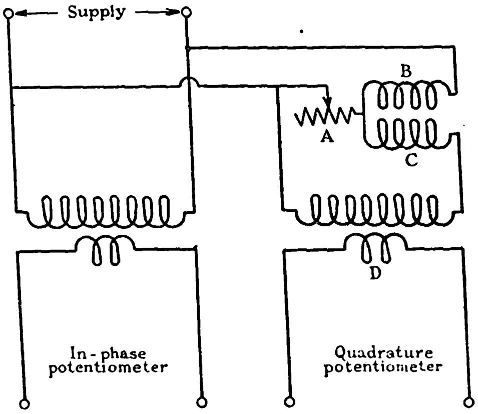

FIG. 16.—Gall potentiometer—phase-splitting device.

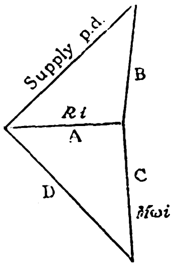

FIG. 17.—Gall potentiometer—vector diagram of phase-splitting device.

Recently Mr. Gall has introduced a simplified or portable self-contained a.c. potentiometer* on the same principle. It was primarily developed for testing the relay circuits in railway signalling work, and contains the vibration galvanometer, lamp and scale, shunts and volt box, so that no accessory apparatus is needed. In this case the quadrature current is obtained by condensers having fixed values for frequencies of 25, 33, 50, 75 and 100 cycles per sec., such condensers being plugged in at the left-hand side of the instrument. The diagram of connections is shown in Fig. 18 and is self-explanatory. The instrument is only intended for approximate commercial tests, and single slide-wire potentiometers only are employed.

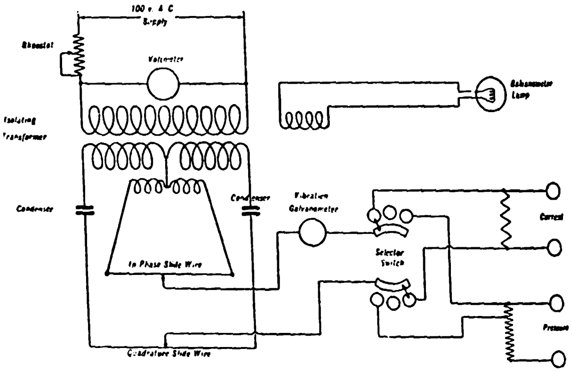

FIG. 18.—Gall portable a.c. potentiometer.

Pedersen Potentiometer.—The latest in principle and one of the most simple of a.c. potentiometers is that devised by Dr. O. Pedersen in 1919.* It is on the rectangular co-ordinate principle, and has the advantage, in common with the Larsen instrument, of maintaining its quadrature relation independently of the frequency, although this advantage is offset by the disadvantage that its p.d. indications in both phases vary with the frequency.

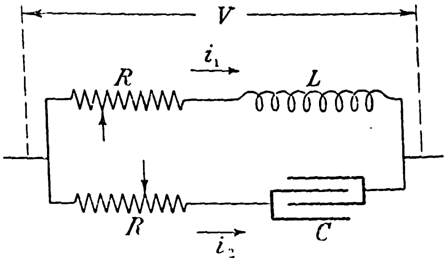

FIG. 19.—Pedersen potentiometer.

In Fig. 19 there are two circuits in parallel, each consisting of a potentiometer in series with an inductance L and capacity C respectively, the total resistance of each circuit being the same and equal to R. Then if V is the p.d. across the combination, the current in the inductive branch

$$i_1 = \left\{V/\sqrt{(R^2 + L^2\omega^2)}\right\}\overline{\backslash\phi_1}$$

while that in the condenser branch

$$i_2 = V/\sqrt{\left[R^2+\left\{1/(C^2\omega^2)\right\}\right]}\,\underline{/\phi_2}$$

where $\tan\phi_1 = L\omega/R$, and $\cot\phi_2 = CR\omega$

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* See Reference (19).

* See Reference (20).

If $\tan \phi_1 = \cot \phi_2$ or $L\omega/R = CR\omega$, i_1 and i_2 will be in quadrature, so that if L is made equal to CR^2 this will be the case for all frequencies. Since the two resistances R have a common point, the p.d. between two potential contacts sliding on them can have components of any magnitude of either component up to the maximum, its value as a vector being represented, in the case where the two currents are equal, by the length and inclination of the line joining the contacts in the figure. As the frequency is increased, however, i_1 decreases and lags more, and i_2 increases and leads less, so that the values of the readings and their phase relation to the supply p.d. vary. The device can, however, be made direct-reading for a standard frequency, and it has recently been put into practical form by Messrs. H. Tinsley and Co.

In practice Dr. Pedersen extends the application of his principle by connecting the two slide-wire potentiometers between two equal inductances and two equal capacities respectively, as in Fig. 20, thus enabling both positive and negative values of the two component p.d.'s to be obtained. This device is used in the commercial form of the potentiometer. The instrument seems to have considerable utility for the measurement of impedances, as the frequency affects the potentiometer and the impedance tested similarly, but it is hardly suited for the direct measurement of p.d.'s unless it is designed for and used with one constant frequency.

A device resembling the Pedersen potentiometer, but using resistances instead of condensers, was described by Mr. A. K. Erlang of the Copenhagen Telephone Co. in 1913.* Two long slide-wires each of about 50 ohms resistance were connected exactly as in the later form of Pedersen potentiometer (Fig. 20), with two equal resistances at the two ends of one slide-wire and two equal inductances at the ends of the other wire. There is therefore a uniform p.d. gradient along each wire, but instead of these gradients being in quadrature they have a phase displacement of some smaller and known value, and the arrangement was found useful for telephonic measurements.

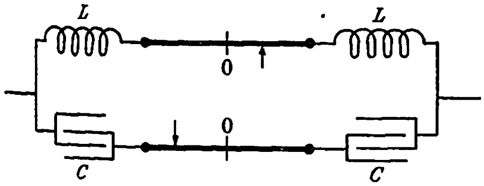

Fig. 20.—Pedersen potentiometer—double form.

B. S. and F. D. Smith's High-frequency Potentiometer.—The a.c. potentiometer principle is also applicable for high-frequency measurements up to radio frequencies, and a valuable start in this direction has been made by Messrs. B. S. and F. D. Smith at the Admiralty Research Laboratory † (see Fig. 21). It is on the polar principle, and follows the lines of the author's instrument in having a phase-shifting transformer which, in this case, consists of two pairs of coils at right angles, each pair being arranged like the coils of a Helmholtz tangent galvanometer in order to produce the most uniform magnetic field possible near their common centre. The high-frequency supply may be obtained from a valve oscillator, and the rotating field is secured by phase-splitting by resistance and capacity, as in the author's instrument.

The secondary coil is mounted on a vertical spindle, and the phase of the e.m.f. induced in it varies with turning in the ordinary manner, but instead of being connected to a potentiometer it is arranged to tilt as well as turn, so that the e.m.f. varies, approximately proportionally to the sine of the angle of the tilt, from zero when the plane of the coil is horizontal to a maximum when it is vertical. Any p.d. up to this maximum derived from the same supply can therefore be balanced by connecting the secondary directly to it through a detector and turning and tilting the coil, when the phase angle can be read off directly from a dial on the vertical spindle, and the magnitude from a scale on the micrometer head which tilts the coil by tension on the leads against an antagonistic spring on its horizontal spindle. The magnitude scale is approximately linear, and the most convenient method of calibrating it is to tilt the coil to approximately its vertical position and to adjust the supply and phase-splitting devices so that it gives about 1·5 volts on a Moullin voltmeter, constant for all orientations of the coil. Detection is most conveniently carried out by telephone and a heterodyne as in ordinary radio measurements.

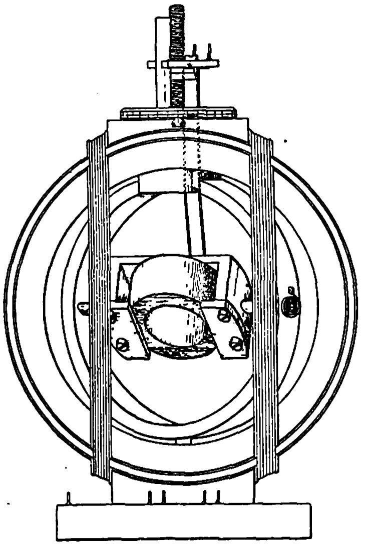

Fig. 21.—B. S. and F. D. Smith's potentiometer.

A device on somewhat similar lines to the above was described by K. Lion of Darmstadt in 1928.* It has two fixed coils at right angles which produce a rotating field by split-phase current, but these coils are of rectangular form, allowing of two secondary coils side by side, each of which can be independently turned round the axis, so that the phase difference between the e.m.f.'s induced in them is equal to the angle between their planes. One of these coils is used to supply current to the circuit under test, while the other is connected to a potentiometer. It is not easy to see what advantage is gained by the use of two secondary coils, and the arrangement seems seriously to limit the power available for the tests. It appears, however, to have proved useful for the testing of valves and amplifiers.

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* See Reference (21).

† *Ibid.*, (22).

* See Reference (23).

Wente Valve Potentiometer.—An ingenious a.c. potentiometer on the polar principle for frequencies up to 10 000 cycles per sec. has been devised by Mr. E. C. Wente of the Research Laboratories of the American Telephone Co. and Western Electric Co.* The diagram is shown in Fig. 22. The exciting supply from an alternator or valve oscillator is brought into the shielded transformer T_1, the secondary of which is connected across a condenser C and resistance R_c in series, thus giving two p.d.'s approximately in quadrature. These p.d.'s are communicated through a common grid-bias battery to the grids of two valves V_1 and V_2 the plates of which are connected through high resistances to the H.T. battery and earth, and also through condensers C_1 and C_2 to two transformers T_2 and T_3, the secondaries of which are connected through reversing switches to two resistances R_1 and R_2 having sliding contacts K_1 and K_2. These resistances are graded between their contact studs according to a sine law, and the p.d.'s across them are adjusted to equality by the help of a differential a.c. galvanometer so that if the contacts are coupled and moved together the p.d. between them is proportional to $v_1 \cos\theta - v_2 \sin\theta$, where $\theta = \frac{1}{2}\pi x/l$, x being the displacement of the sliders and l the length of the resistances. But $v_1 = v \cos \omega t$ and $v_2 = v \sin \omega t$, so that the p.d. between the contacts K_1 and K_2 is $v(\cos \omega t \cos\theta - \sin \omega t \sin\theta) = v \cos(\omega t + \theta)$, the phase of the p.d. thus varying continuously from zero to quadrature as the slider is moved, and by throwing over the reversing switches the whole of the 360 degrees can be covered. The p.d. from the sliders is communicated to the grid of a third valve V_3 which supplies a transformer T_4 connected across the potentiometer R. The whole of the circuit up to the transformer T_4 is therefore equivalent to a phase-shifting transformer supplying the potentiometer R.

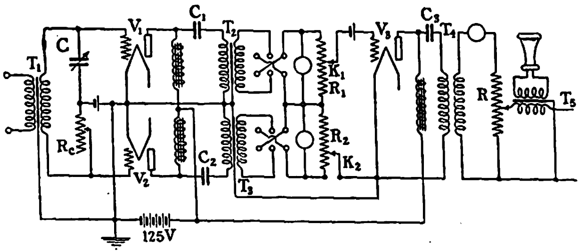
C₁
T₁
C
V₁
T₂
V₃
C₃
T₄
K₁
R₁
R₂
K₂
R
T₅
Rc
V₂
C₂
T₃
125V

FIG. 22.—Wente valve potentiometer.

(4) CONSTRUCTIONAL DETAILS.

In this section the chief constructional features of the three principal types of a.c. potentiometers—the Drysdale-Tinsley, Gall, and Campbell instruments—will be dealt with.

Drysdale-Tinsley Potentiometer.—Fig. 23 shows the arrangement and connections of this instrument as constructed by Messrs. H. Tinsley and Co. The instrument is divided into 6 sections: (*a*) the potentiometer, (*b*) the phase-shifting transformer, (*c*) the dynamometer current indicator, (*d*) the change-over switch for conversion from d.c. to a.c. working, (*e*) the selector switch, and (*f*) the terminal slab.

The potentiometer proper is a standard type of Tinsley universal potentiometer having two dials and a slide wire with transposition circuit, which the author considers to be the best compromise for accurate and rapid working. The first dial has 18 coils of 2 ohms each, which, with the standard working current of 50 mA, gives a p.d. of 0·1 volt per coil. Two brushes move simultaneously over this dial, bridging two coils, and these are connected to the ends of the second dial having 10 coils of 0·4 ohm each, so that the parallel resistance of the combination is 2 ohms, equivalent to that of a single coil of the first dial. The slide wire has a total resistance of about 0·23 ohm and is provided with a scale of 115 divisions, so that each division represents 0·0001 volt (or 100 μV) when the transposition circuit is used, and the total range of the potentiometer is from a few microvolts to 1·8 volts. The coils are of manganin wire double-wound on brass bobbins, and, although they are not perfectly non-inductive, their time-constants are sufficiently nearly equal to avoid readable phase differences. Two keys with locking cams are provided for the standard cell and measuring circuits respectively.

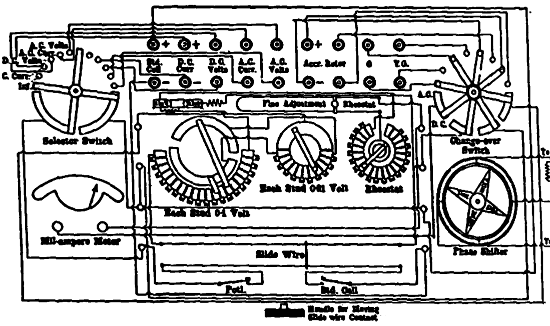
A.C. Volts
A.C. Curr.
D.C. Volts
D.C. Curr.
Inf.
Std. Cell
D.C. Curr
D.C. Volts
A.C. Curr.
A.C. Volts
Accr. Rotor
G
V.G.
Fine Adjustment
Rheostat
A.C.
D.C.
Selector Switch
Change-over Switch
Each Stud 0·01 Volt
Rheostat
Each Stud 0·1 Volt
To A.C. Mains
Phase Splitting Device
Milli-ampere Meter
Slide Wire
Phase Shifter
To A.C. Mains
Potl.
Std. Cell
Handle for Moving Slide wire Contact

FIG. 23.—Drysdale-Tinsley a.c. potentiometer—diagram of connections.

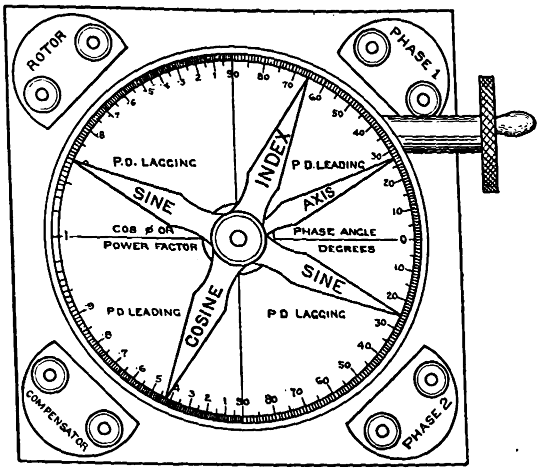
ROTOR
PHASE 1
P.D. LAGGING
INDEX
P D.LEADING
SINE
AXIS
COS φ OR POWER FACTOR
PHASE ANGLE DEGREES
SINE
P D LEADING
COSINE
P D LAGGING
COMPENSATOR
PHASE 2

FIG. 24.—Drysdale-Tinsley phase-shifting transformer.

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* See Reference (24).

The phase-shifting transformer (Fig. 24) is a most important part of the instrument and is fixed at the lower right-hand corner. It consists of a laminated stalloy stator with 48 tunnels, and the windings of the two phases are shown diagrammatically in Fig. 25. The number of coils in each slot is graduated according to a sine law so as to produce a practically uniform magnetic field in the stator tunnel. The rotor has 36 nearly closed slots, and has two windings similarly distributed at right angles. One of these windings is connected through flexible connections to the potentiometer terminals, while the other is permanently connected to a "compensating coil" of resistance and inductance equal to those of the potentiometer circuit including the dynamometer, thus ensuring that the reaction of the rotor is constant for all positions. The rotor is mounted in parallel bearings accurately concentric with the stator, and is provided with a worm wheel and spring worm which can be thrown out of action for quick working, and with a movable stop which permits of a little more than 360° total rotation.

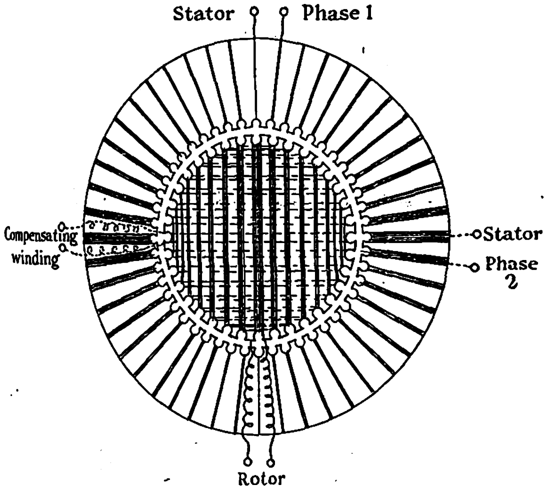

FIG. 25.—Drysdale-Tinsley phase-shifting transformer—winding diagram.

When the phase-splitting has been properly performed, the phase of the rotor p.d. changes by the same angle as that through which the rotor is turned, within an accuracy of about ± 0·1°. The standard primary p.d. is 100 volts and the same transformer will serve with different phase-splitting from 25 to 1 000 cycles per sec., or to 2 000 cycles if the two halves of the primary coils are connected in parallel.

The pointers and dial are of some interest. The dial is divided into two halves, of which the right-hand half is graduated in degrees from zero to 90° lead or lag. The left-hand half is graduated as a cosine scale. A fixed or "axis" pointer is first mounted on the rotor spindle and is in the direction of the magnetic axis of the rotor winding which is connected to the potentiometer. This pointer is of use in phase-splitting. A tightly fitting spring cap carrying four pointers fixed accurately at right angles is then pushed on to the spindle. One of these is marked as the "index" pointer and is used to read off the phase angle directly on the degrees dial. In measuring an impedance, the current is first balanced and the cap is twisted until the "index" pointer is at zero, after which, when the p.d. is balanced this pointer reads the phase angle directly. The opposite pointer is marked "cosine" and directly indicates cos ϕ (the power factor), while the other two pointers at right angles are marked "sine," and read sin ϕ on the cosine scale. The whole arrangement therefore permits of rapid conversion from polar to rectangular co-ordinates without it being necessary to refer to tables, and therefore assists the calculation of the resistance and reactance components, and of the power.

The dynamometer indicator is a standard form of Weston shielded dynamometer having a fiducial mark on its scale corresponding to a current of 50 mA. It is provided with a zero adjustment which enables the pointer to be set exactly to this mark when the dials and slide wire are set to the e.m.f. of a standard cell and the cell is balanced by adjusting the rheostats.

The remaining components need little description. The change-over switch is an 8-pole switch having 4 pairs of contacts connected respectively to a 4-cell accumulator, the secondary of the phase shifter, a moving-coil galvanometer, and a vibration galvanometer respectively. With the switch in one position the accumulator and moving-coil galvanometer are in use, and on turning to the second position the accumulator is replaced by the phase shifter and the moving coil by the vibration galvanometer, so that the instrument is immediately available for either d.c. or a.c. working.

The phase-splitting device consists simply of a sliding-contact dial resistance box having a total resistance of 1 111 ohms and a current-carrying capacity of 0·3 amp., and a plug condenser having a capacity of from 0·001 to 11·11 μF. These are normally connected in series with each other and with one phase of the stator, but for low frequencies the resistance and condenser may be connected in parallel. For the series arrangement the resistance is about 320 ohms and the capacity about 6·9 μF at 50 cycles per sec., the corresponding values at 500 cycles being 740 ohms and 0·03 μF. The theory of phase-splitting is given in the appendices.

Gall Co-ordinate Potentiometer.—In this instrument (Fig. 26) the two potentiometers only are contained in the case, the phase-splitting transformer and dynamometer being external. These potentiometers are of the Crompton or single-dial and slide-wire type with 18 coils each of 2 ohms and a circular slide wire of about 2·4 ohms subdivided to 0·001 volt, with a transposition circuit. These dials and slide wires, as well as the selector switch, are all under a glass cover, the rheostats, plug transposition connections, reversing switches, galvanometer key and terminals being arranged round it. One position of the selector switch marked "test" connects the "in-phase" potentiometer to the secondary of a mutual inductance of 31·82 mH, the primary of which is in series with the circuit of the "quadrature" potentiometer, and which therefore gives balance against 0·5 volt for a frequency of 50 cycles per sec. (or 0·6 volt for 60 cycles, etc.) when the magnitude and phase of the current in the quadrature potentiometer are correct. An additional secondary coil having a mutual inductance of 3·182 mH is employed for frequencies above 180 cycles per sec. The construction of the remainder of the details needs no special description.

Instead of including a pointer dynamometer instrument in the potentiometer, Mr. Gall uses a reflecting dynamometer of somewhat similar construction to the author's torsional wattmeters. The torsion head can be so set that the spot is at some definite point of the scale when the potentiometer is balanced against a standard cell, and the arrangement has the advantage of allowing the observer to see that his potentiometer current is correct at the moment of obtaining balance. On the other hand, the self-contained pointer instrument avoids the risk of errors due to shifting of the scale or instrument, and therefore obviates the need for frequent checking by means of direct current.

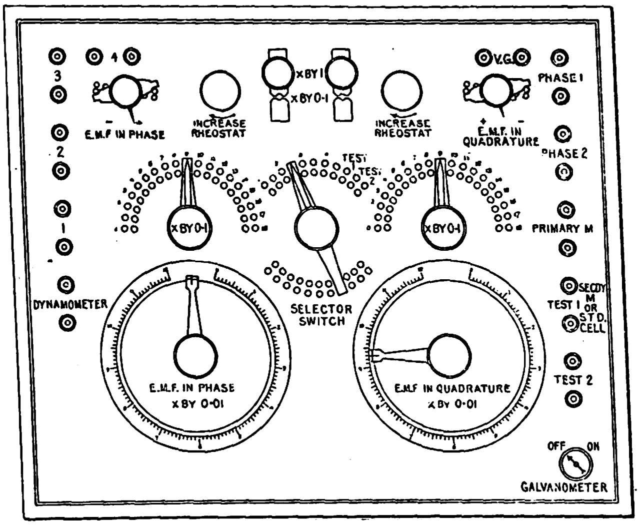
3
4
2
1
V.G.
PHASE 1
PHASE 2
PRIMARY M
DYNAMOMETER
×BY 1
×BY 0·1
E.M.F. IN PHASE
INCREASE RHEOSTAT
INCREASE RHEOSTAT
E.M.F. IN QUADRATURE
TEST
×BY 0·1
×BY 0·1
SELECTOR SWITCH
SECY M OR STD. CELL
TEST 1
TEST 2
E.M.F. IN PHASE ×BY 0·01
E.M.F. IN QUADRATURE ×BY 0·01
OFF
ON
GALVANOMETER

FIG. 26.—Gall co-ordinate a.c. potentiometer.

The original phase-splitting device consists, as mentioned on page 346, of a resistance and transformer connected as in Fig. 16, the secondary being reversed so that its induced e.m.f. is in the opposite direction and produces the required change of phase. This is a very simple and satisfactory device for the small current required for the potentiometer circuit, as it is fairly easily adjusted and is less affected by small changes in frequency than the resistance-condenser combination of the author's potentiometer. The possibility of employing it for the latter instrument has recently been considered, although it is somewhat more difficult to carry out with the heavier currents required to magnetize the phase-shifting transformer with its necessary air-gap between stator and rotor. Mr. Gall has, on the other hand, used the resistance-capacity method of phase-splitting in the primary of a transformer supplying the quadrature potentiometer, and has also used it in connection with valves so as to make his potentiometer available for use with valve oscillator supply. This instrument, like the author's form, is constructed by Messrs. H. Tinsley and Co.

Campbell-Larsen Potentiometer.—This instrument has recently been put into commercial instrument form by the Cambridge Instrument Co. and is shown in Fig. 27. As already mentioned, the potentiometer and variable mutual-inductance standard are in separate cases; this allows of the latter being detached for other uses. The potentiometer consists of two dials and a circular slide-wire carrying 10 mA and reading up to 1·8 volts, at the right-hand side of the case; and immediately behind them are a 5-point selector switch for connection to the five pairs of terminals at the back, and a 4-way reversing switch for measuring in the four quadrants. The four dials running down the centre are the frequency-setting dials, which must be set to the known frequency of the supply before measuring, and have a range from 25 to 1 000 cycles per sec. On the left-hand side are two rheostats for adjusting the alternating current, and two for adjusting the auxiliary direct current through the heater, and also a milliammeter, the thermo-junction and heater, the switches and keys for changing from d.c. to a.c. measurement, and terminals for the connection of the a.c. and d.c. supplies, the standard cell, and d.c. and vibration galvanometers or telephone receiver. Two pairs of terminals are provided on the right-hand side for connection to the primary and secondary circuits of the inductometer, which has a logarithmic or constant-accuracy scale from 1 to 100 μH and additional coils extending the range to 11 mH.

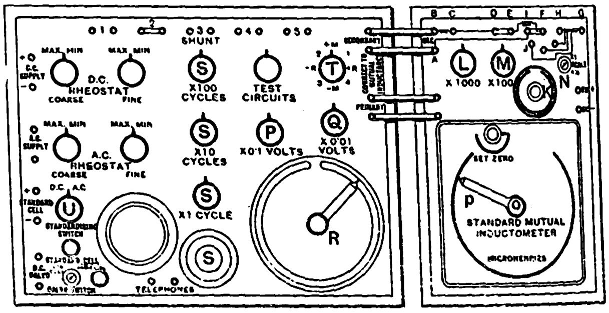
010
2
030
040
050
SHUNT
MAX. MIN
MAX. MIN
D.C. SUPPLY
D.C. RHEOSTAT
COARSE
FINE
S
X100 CYCLES
TEST CIRCUITS
T
SECONDARY
CONNECT TO MUTUAL INDUCTANCE
PRIMARY
A.C. SUPPLY
A.C. RHEOSTAT
S
X10 CYCLES
P
X0·1 VOLTS
Q
X 0·01 VOLTS
D.C. A.C.
STANDARD CELL
U
STANDARDISING SWITCH
S
X1 CYCLE
S
TELEPHONES
R
B C D E I F H G
J
A
L
M
X 1000
X100
K
N
SET ZERO
P
STANDARD MUTUAL INDUCTOMETER
MICROHENRIES

FIG. 27.—Campbell-Larsen a.c. potentiometer.

(5) APPLICATIONS OF THE A.C. POTENTIOMETER.

Of all electrical instruments which have been devised, the a.c. potentiometer is by far the most universal in character, and its applications are so numerous that to describe them all in detail would occupy too much space. In what follows, therefore, a general account of these applications will be given, with detailed instructions and examples of only a few of the most important ones. It must be premised that, in common with other devices of a universal character, there is no pretension that the a.c. potentiometer is superior, or even equally accurate or convenient for any given test, to some of the special instruments, but it does allow of nearly all of these tests being made with ample accuracy for most practical purposes, with very little accessory apparatus. The bulk of the applications will be described with reference to the author's polar potentiometer, as it is the only one with which he has had much experience; but the modifications necessary for the rectangular co-ordinate type of instrument will in most cases be obvious and will sometimes be referred to. The only apparatus required is the potentiometer with its source of supply and regulating arrangements, a d.c.

and vibration galvanometer and standard cell, a main voltmeter and frequency meter, a volt box and set of non-inductive resistances, and a few inductances and condensers. All the ordinary d.c. potentiometer measurements can, of course, be made with the instrument and need no description.

We shall assume in what follows that the potentiometer has been fed from the source of supply, and that the phase-splitting or frequency-setting and the tuning of the vibration galvanometer have been correctly adjusted before measurements are commenced.

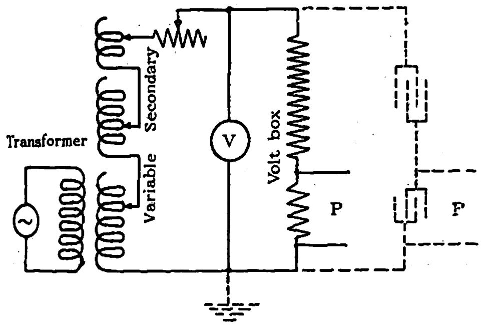

FIG. 28.—Voltmeter calibration.

P.D. Testing and Voltmeter Calibration.—Alternating p.d.'s of any frequency from 25 to 1 000 cycles per sec. (or up to 2 000 cycles with the second phase-shifter) and from 1 mV or less up to 1·8 volts can be measured directly on the potentiometer. For higher voltages any ordinary volt box may be employed, provided that all its coils are either non-inductive or have similar or negligible time-constants (which is always the case for supply frequencies). The connections for voltmeter calibration are shown in Fig. 28, and if the voltmeter under test is not very inductive the phase of the p.d. will change so little as the regulating rheostat is varied for the different readings that little adjustment of the phase shifter is required after the first reading. High accuracy of phase-splitting is not essential in this case, provided that the dynamometer current is adjusted to its standard value when balance is made.

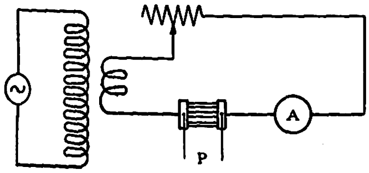

FIG. 29.—Ammeter calibration.

For very high voltages the volt box may be replaced by two condensers in series as shown by the dotted lines, and the circuit should be earthed at the potentiometer side.

Current Testing and Ammeter Calibration.—This can be done in precisely the same manner as for the measurement of direct currents by potentiometer, provided that a set of non-inductive low-resistance standards or "shunts" is available. Fig. 29 shows suitable connections for ammeter calibration in which the current is derived from a transformer fed from the same mains as the potentiometer; if this transformer has good regulation the phase of the current will change very little as its value is altered, so that only a small resetting of the phase shifter is required after the first reading. As in the case of voltmeter calibration, accuracy of the dynamometer current only is essential. In Table 1 are given a set of readings taken on a Kelvin deka-ampere balance, and not only the accuracy of the method but the errors which occur in the balance at high frequencies, due to eddy currents, are shown.

TABLE 1.

Frequency	Kelvin balance reading	P.D. by potentiometer	Current by potentiometer
cycles per sec.	amps.	volt	amps.
0 (d.c.)	20	0·09998	19·996
50	20	0·10002	20·004
600	20	0·1018	20·36
750	20	0·10245	20·49
900	20	0·10275	20·55
1 000	20	0·10315	20·63
1 200	20	0·1043	20·86

If the current wave-form contains large harmonics the readings will not be correct, but the error is inappreciable on fairly sinusoidal supply, as if i_1, i_2, i_3, etc., are the values of the various harmonics, $i = \sqrt{(i_1^2 + i_2^2 + i_3^2 + \text{etc.})}$ and it requires a 14 per cent harmonic to produce 1 per cent error in the value of the current, or a 4·5 per cent harmonic to produce 0·1 per cent error.

Power and Phase Measurement.—Although the a.c. potentiometer cannot compete in convenience and accuracy with a good standard wattmeter, and is only suitable for closely sinusoidal wave-forms, it has the advantage of permitting power measurements to be made over any range with no additional apparatus beyond the shunts and volt boxes required for p.d. and current measurements. Fig. 30 shows the connections for testing the p.d., current and power of any a.c. generator or load, irrespective of its type. The p.d. V is first measured in the ordinary way and the index pointer of the phase shifter is set to zero. On switching over to the "shunt" the magnitude and phase ϕ of the current i can be directly measured and $\cos\phi$ read off from the cosine pointer, from which the power $P = Vi\cos\phi$. When the test is made at various loads on constant-p.d. mains, the phase of the p.d. will remain at zero for all loads, so that it is only necessary to adjust the dials a little at each p.d. reading.

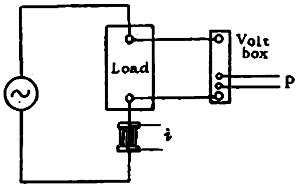

FIG. 30.—Power and phase measurement.

Although the potentiometer can only give correct power measurements on sinusoidal wave-forms, it should be pointed out that there will be no wave-form error if *either* the p.d. *or* the current wave-form singly is sinusoidal. If V_1, V_2, V_3, etc., are the p.d.'s and i_1, i_2, i_3, etc., the currents corresponding to the fundamental and higher harmonics respectively, the power

$$P = V_1 i_1 \cos \phi_1 + V_2 i_2 \cos \phi_2 + V_3 i_3 \cos \phi_3 + \ldots$$

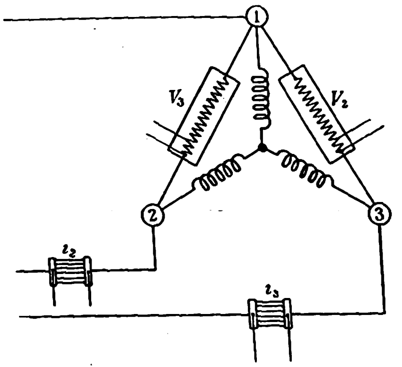

FIG. 31.—Three-phase power measur ment.

If the p.d. is sinusoidal, V_2, V_3, etc., are zero, and if the current is sinusoidal i_2, i_3, etc., are zero; so that in either case $P = V_1 i_1 \cos \phi_1$, which is the power as given by the potentiometer, is correct. There is usually little difficulty in arranging that one or other of these conditions is fulfilled.

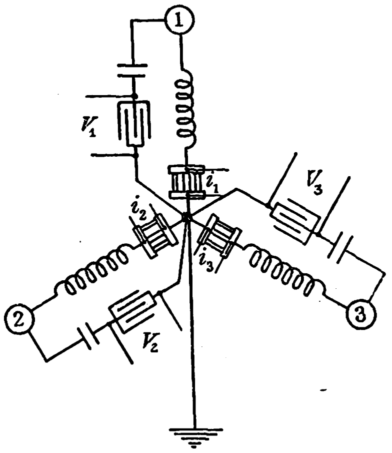

FIG. 32.—Three-phase h.t. generator testing.

Polyphase Power Measurements.—The same method can obviously be applied to polyphase circuits of any type, by measuring the p.d. and current in each phase separately. In the case of a 3-phase circuit, for example, the connections can be made as for the ordinary double-wattmeter method with two equal "shunts" in place of the current coils, and two similar volt boxes, when the power $P = V_3 i_2 \cos \phi + V_2 i_3 \cos \phi'$ (Fig. 31).

The accuracy and convenience of the test in this case are of course inferior to those given by a good polyphase wattmeter, but in the case of large high-voltage and heavy-current generators and motors the a.c. potentiometer may prove to be the only convenient direct method of testing, as wattmeters are difficult to construct and are almost prohibitively costly for the heavy currents now becoming common in large machines. Fig. 32 shows the connections which may be employed in this case. Three equal heavy-current non-inductive resistances are connected at the centre of the star and their common junction is earthed, and three volt boxes or pairs of condensers are connected between this junction and the three terminals of the machine. The whole of the testing circuits are then very nearly at earth potential, and the power is evidently $V_1 i_1 \cos \phi_1 + V_2 i_2 \cos \phi_2 + V_3 i_3 \cos \phi_3$.

Wattmeter and Supply Meter Testing.—Fig. 33 shows the most convenient connections for testing wattmeters and energy meters at any power factor. The supply mains are connected to a step-down transformer for supplying the main coils, and to a phase-shifting transformer, the secondary of which is connected to a variable transformer for the p.d. circuits. The usual shunt and volt box are arranged as shown for connection to the potentiometer, and a small mutual inductance M is included with its primary in the current circuit for accurate checking at zero power factor. The phase-splitting must of course be as accurate as possible for this test. To make a measurement under any desired conditions, the p.d. and current are adjusted to the required values and the rotor of the phase-shifting transformer is turned to an angle corresponding to the desired power factor, after which the potentiometer measurements are made. One of the most important tests is the behaviour of the wattmeter or kWh meter at zero power factor, and this condition can be most accurately secured by turning the phase-shifting transformer until the p.d. across the mutual inductance is in exact phase with that of the supply, after which the p.d. and current measurements are made as before.

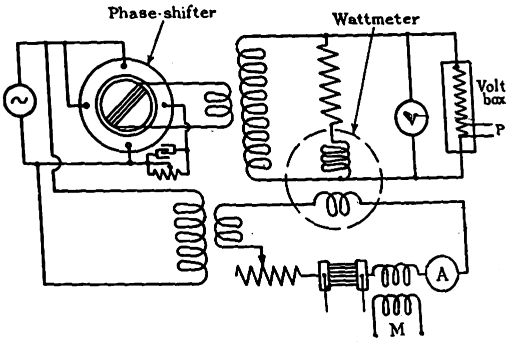

FIG. 33.—Wattmeter and energy meter testing.

Frequency Checking.—The measurement of the frequency employed during the measurements can be fairly accurately effected by the a.c. potentiometer, by measuring the p.d. across the secondary of a mutual inductance in series with its coils. Since this e.m.f. $e_2 = i_1 M\omega = 2\pi i_1 Mf$, we can make up a mutual inductance such that its secondary e.m.f. indicates the frequency directly. For ordinary supply frequencies it is convenient to make 1 volt on the potentiometer correspond to 50 cycles per sec., in which case $M = e_2/(2\pi i_1 f) = 1/(6{\cdot}28 \times 0{\cdot}05 \times 50) = 0{\cdot}0637$ H or 63·7 mH. If the primary of such an inductance is kept permanently connected in series with the a.c. supply from the phase-shifting transformer to the potentiometer, the frequency can be measured at any moment by switching over the selector to the secondary inductance, setting the phase-shifter axis pointer to 90°, and balancing the e.m.f. on the potentiometer. It is evident that accuracy of adjustment of the potentiometer current is not of importance in this test, as variations of it affect the e.m.f. and balancing p.d. equally.

Measurement of Alternating Magnetic Fields.—One of the most useful applications of the potentiometer is to the measurement of alternating magnetic fields, in conditions which would be difficult or impossible with other devices. All that is necessary is to have a suitable search coil and to measure the e.m.f. induced in it by the magnetic field. If A is the mean area of the coil, n the number of turns in it, B the effective or R.M.S. value of the field, and f the frequency, the induced e.m.f

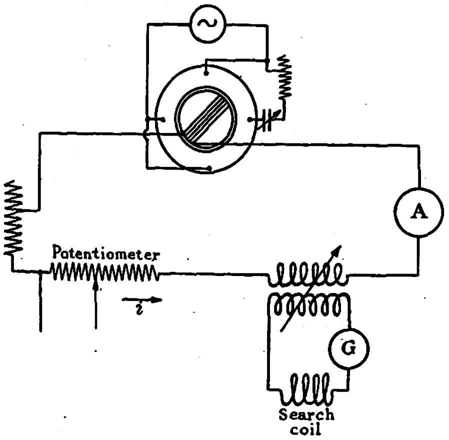

FIG. 34.—Measurement of alternating magnetic fields.

$$e = \frac{2\pi fnAB}{10^8} \text{ volts lagging } 90° \text{ behind the field}$$

or $$B = \frac{10^8 e}{2\pi fnA} \text{ gauss}$$

If we take the ordinary supply frequency of 50 cycles per sec., $2\pi f = 314$, and if $nA = 3\,186$ cm^2 an alternating field of 1 gauss will give 1 volt of e.m.f., which can be measured to about 1 part in 3 000, so that alternating fields of a small fraction of the earth's field can be measured easily and accurately with coils about 10 cm square and having 20 or 30 turns; while fields of the order of 10 000 gauss only require a single loop of wire having an area of a few tenths of 1 cm^2. It is easy, therefore, to measure the induction or flux in a single tooth of an a.c. generator or motor, or the induction in the gap.

The method above described requires a calculation involving the frequency, but by employing a variable mutual inductance standard in series with the potentiometer (Fig. 34), a simple direct-reading method is available. The number of magnetic linkages in the secondary of a mutual inductance is $N = 10^8 Mi$, and since the current in the potentiometer is constant at 0·05 amp., $N = 5 \times 10^6 M$, or 5 maxwells per μH of inductance.

The secondary of the mutual inductance is simply connected to the search coil through a vibration galvanometer or telephone receiver, and balance is secured by turning the phase shifter and varying the mutual inductance, whereupon the number of linkages with the search coil is $5 \times 10^6 M$ and the phase of the magnetic field is the same as that of the potentiometer current. The potentiometer dials are not used in this test, their place being taken by the variable inductance.

A most valuable application of this method is the measurement of stray magnetic fields round the cables and busbars of switchboards, etc., and the author has employed it for investigating the magnetic field around submarine cables fed with alternating current in connection with the "leader gear" method of enabling ships to follow the track of such a cable in a fog. The high conductivity of sea water causes the magnetic field round the cable to be greatly reduced and distorted from the simple circular field produced in a non-conducting medium; and in 1920 the author, with the assistance of Messrs. S. J. Willis and L. Champney, investigated this matter at the Admiralty Research Laboratory, Shandon,* using a barge with a mast at its stern which carried horizontal and vertical search-coils at its upper and lower ends, and also a horizontal boom with electrodes at its lower end for determining the current density in the water. The magnitude and phase of the horizontal and vertical components of the magnetic field above and below water of a cable 3 miles long in the Gareloch, and also of the return current in the water, were determined in relation to the current in the cable by an a.c. potentiometer on the barge, fed by current from the shore through a flexible cable, and it was found, in agreement with theory, that the magnetic field in water progressed in waves having a velocity comparable with that of sound rather than that of light, and that rotating fields were produced in some places above the surface.

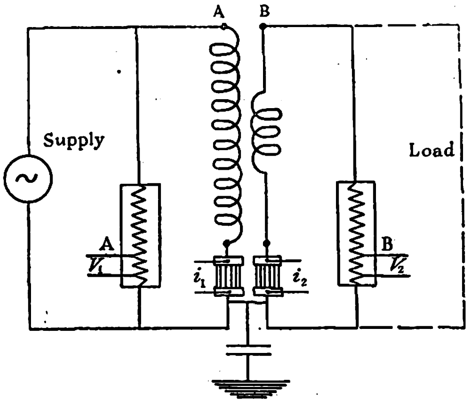

FIG. 35.—Transformer testing.

The propagation of magnetic waves along an iron bar was also investigated by the author in the same manner,† and shown to be of the same character as the propagation of electrical impulses in a submarine cable.

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* See Reference (25).

† *Ibid.*, (26).

Transformer Testing.—The testing of both power and instrument transformers by the potentiometer is a very simple matter. Fig. 35 shows the connections for the test of an ordinary step-down transformer and is self-explanatory. It is desirable to employ shunts and volt boxes which give approximately equal p.d.'s to the potentiometer, and in the case of high-voltage transformers the volt box may be replaced by a combination of two condensers in series as in Fig. 32. The load may be of any desired magnitude and power factor, and the potentiometer readings enable the vector diagram of primary and secondary voltages and currents to be drawn for each load and the complete behaviour of the transformer to be determined.

In the case of instrument transformers in which the phase displacements are made as small as possible and require to be accurately determined, the connections may be the same, but care should be taken to make the p.d.'s across the two volt boxes exactly equal in magnitude by shunting one or other of them when testing potential transformers. The phase displacement can then be accurately determined by measuring the p.d. v between the two terminals A and B, giving the vector difference, from which the phase displacement $a = 57 \cdot 3\ V/V_1$ degrees.

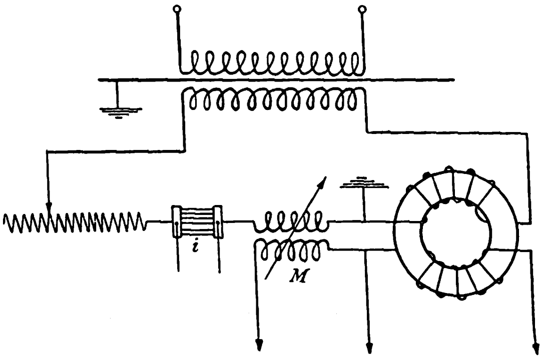

FIG. 36.—Iron testing.

Similarly with current transformers, if care is taken to make the p.d.'s across the two shunts equal in magnitude, which may be effected by shunting one of them, the vector difference giving the phase displacement can be measured on the potentiometer. Two mutual inductances may be substituted for the shunts in this test and the vector difference of their secondary e.m.f.'s measured.

Iron Testing.—The testing of iron stampings in ring form or made up as a magnetic square is effected exactly as in testing an impure mutual inductance, but care must be taken in this case to ensure that *either* the current through the magnetizing coil *or* the p.d. at its terminals is truly sinusoidal, as the non-linear relation of B to H renders it impossible for both to be sinusoidal simultaneously. The most convenient connections generally are as in Fig. 36, which is the same as Fig. 34 except that a moderately large resistance is connected in series with the circuits under test, and the combination is supplied from the secondary of a transformer giving a p.d. of 20 or 30 volts, so that if the p.d. of the supply is closely sinusoidal the resistance swamps the distorting effect of the iron. The current is then measured across the "shunt" in the ordinary manner, from which both H and the number of linkages for a given value of the mutual inductances can be calculated; and the phase-shifter and mutual inductance are then varied until there is balance between the e.m.f.'s of the mutual inductance and the secondary coil on the core, when the number of linkages of the flux with the coil, $N = Mi$ and the phase displacement due to core loss is given directly, from which the core loss can be calculated.

Measurements at Sonic Frequencies.—When a.c. measurements are to be made at frequencies above those of ordinary supply, care must be taken to avoid errors due to inductive and capacitative effects. The circuits to be tested should, as a rule, be a few yards at least away from the potentiometer and vibration galvanometer, and should be connected to the supply and measured through twin flexible or well-twisted leads. This eliminates inductive disturbances, but, unless the circuit under test is very nearly at earth potential, appreciable errors may result from capacity currents from the supply. As the p.d. across the potentiometer is only about 2 volts it can be supplied from a transformer having a low-voltage secondary, and it is desirable to earth the iron of this transformer, or, better still, to have an earthed metallic shield between the windings. In the author's potentiometer the phase-shifting transformer is a fairly effective shield if the rotor iron is earthed, as the windings are embedded in slots and the total p.d. across it is only 12 volts, but it is desirable when making accurate tests on high impedances to supplement this by earthing the potentiometer dial through a condenser. The circuit under test should similarly be supplied from a transformer with earthed shield and giving the minimum secondary p.d. necessary for the test, and the circuit should be connected to earth through a condenser at the most appropriate point. These precautions are especially necessary when telephone receivers are used for detection, as their capacity to the observer's head may cause material error if they are not practically at earth potential. A suitable type of variable shielded "isolating" transformer has been devised by the author.

Inductance Testing.—The measurement of self-inductance is effected in a corresponding manner to that of resistance with the ordinary d.c. potentiometer. The coil to be tested is simply connected in series with a standard non-inductive resistance as in Fig. 30, and supplied with current from a step-down transformer giving about 2 volts on its secondary. The p.d. V_1 is first measured on the potentiometer and the index pointer on the phase shifter is set to zero, after which the p.d. V_2 across the coil is measured and the readings of $\cos\phi$ and $\sin\phi$ are observed on the cross pointers. Then we have $V_1 = Ri$, where R is the non-inductive resistance and i the current, and $V_2 = Zi$, where Z is the impedance of the coil.

Hence $Z = (V_2/V_1)R$, from which the equivalent resistance of the coil $R' = Z\cos\phi$ and reactance $X = Z\sin\phi$, and the inductance $L = Z\sin\phi/(2\pi f)$.

The accuracy of measurement in this case is usually about the accuracy with which $\cos\phi$ and $\sin\phi$ can be read from the dial. It is, of course, desirable to select a standard non-inductive resistance which does not differ very greatly from the impedance of the coil, so that V_2 and V_1 are not very different.

In the case of mutual inductance, the primary is connected in series with the standard resistance, and the second reading is taken on the secondary. Unless the mutual inductance is very impure the second reading will be in exact quadrature with the first, and $M = (V_2/V_1)R/(2\pi f)$. If the mutual inductance is impure the impurity is given by the defect of the phase angle from quadrature, but as the accuracy of the phase indication may not be sufficient for this test, the most satisfactory method is to connect a second variable mutual of perfect purity or known impurity in series with the inductance under test, and to connect the two secondaries in opposition, adjusting the variable inductances until the combined e.m.f. is a minimum. If this e.m.f. is e and that across either of the secondaries singly is E, the phase displacement between the two secondary e.m.f.'s is $57 \cdot 3\ e/E$ degrees.

Capacity Testing.—The simple measurement of capacity is effected in the same manner as that of inductance, the only difference being that the standard non-inductive resistance should generally have a somewhat high value. For the ordinary supply frequency of 50 cycles per sec. the impedance or capacity reactance of a 1-μF condenser is $10^6/314 = 3\,186$ ohms, so that R should be about 1 000 ohms for capacities of a few microfarads, 10 000 ohms for tenths of microfarads, and 1 megohm for capacities of milli-microfarads or under. For sonic frequencies of about 500 cycles the resistance should be about one-tenth of the above values. The condenser is connected in series with the resistance to the secondary of the 2-volt transformer, and the p.d.'s V_1 across the resistance and V_2 across the condenser are measured as before. The index pointer should be set to zero for the first reading, and will be found to be reading nearly 90° lagging for the second balance. Since the capacity reactance or impedance of the condenser $X = 10^6/(C\omega) = (V_2/V_1)R$, $C = 10^6 V_1/(V_2 R\omega)$. The reading on the cosine pointer should give the power factor of the condenser directly, but as it is usually very small, very great care must be taken over the phase-splitting to render the reading of any value, and in any case it can only be regarded as a rough indication.

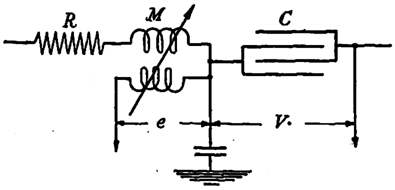

FIG. 37.—Mutual inductance method of testing power factor of condensers.

The power factor can, however, be determined with considerable accuracy by comparison with a variable mutual inductance, provided that it has a high degree of "purity," i.e. absence of internal capacity. For capacities of the order of $0 \cdot 1$ to 100 μF at a frequency of 500 cycles, the condenser may be simply connected in series with the primary of the inductance as in Fig. 37, the secondary being connected so as to give an e.m.f. e in opposition to the p.d. across the condenser. If i is the current across the combination and both the condenser and mutual inductance are perfect, $V = i/(jC\omega)$ and $e = jM\omega i$, so that if M is adjusted until $e = V$, $M = 1/(C\omega^2)$ or $C = 1/(M\omega^2)$, and there will be no p.d. across the condenser and secondary in series. But if the p.d. across the condenser lags less than 90° by a small angle a, $(V - e)$ will not be zero but will be in quadrature with either V or e and can be measured on the potentiometer, and $a = 57 \cdot 3(V - e)/V$ degrees. If $C = 1\ \mu$F (10^{-6} F) and the frequency is 500 cycles per sec., $\omega = 3\,140$ and ω^2 approximately 10^7, so that $M = 10^6/10^7 = 0 \cdot 1$ H (100 mH) for 1 μF, and is inversely proportional to the capacity for a given frequency. Variable mutual-inductance standards are procurable up to 1 H, which enables capacities down to $0 \cdot 1\ \mu$F to be tested at 500 cycles or down to 10 $\mu\mu$F at 1 500 cycles.

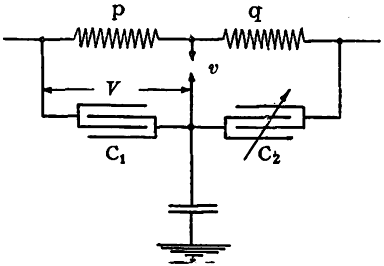

FIG. 38.—Resistance method of testing power factor of condensers.

Very low capacities can, however, best be tested by connecting them in series with an air condenser carefully constructed to avoid absorption across a pair of exactly similar equal-ratio resistances as shown in Fig. 38, where C_1 is the air condenser and C_2 the condenser to be tested, which is supposed to have, or to be adjusted to, the same capacity as C_1. If C_2 were perfect the p.d. v between the junctions of the condensers and of the resistances would be zero, but if not the phase displacement in it would be $2 \times 57 \cdot 3\ v/V$, where V is the p.d. across either of the condensers.

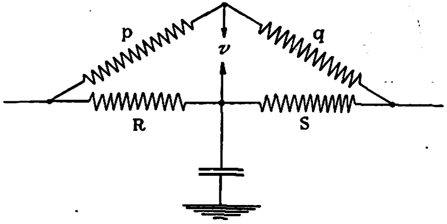

FIG. 39.—Resistance testing.

Phase Displacement in Resistances.—Since resistance standards are the basis of current measurements by the potentiometer, it is of importance to be able to determine whether they are truly non-inductive or, if not, what the phase displacement of their p.d. is, especially in the case of low resistances for heavy-current measurement. Fig. 39 shows the most convenient connections for such tests. The resistance to be tested (R) is connected in series with a resistance S of the same nominal value which is either perfectly non-inductive or has a known phase displacement, and a pair of exactly similar " ratio " resistance coils p and q are connected across the outer terminals in bridge fashion. The p.d. across either R or S is then measured on the potentiometer in the ordinary manner, and also the p.d. between the junctions of p and q and of R and S. The vector diagram of the p.d.'s is then evidently as in Fig. 40, in which the middle vector would obviously be vertical if R and S were exactly equal, and it is therefore evident that the phase displacement ϕ in R is $2 \times 57 \cdot 3\ v/V$ degrees, where v is the perpendicular distance represented by the dotted line and V is the p.d. across either R or S. To ensure accuracy it is advisable to earth the potentiometer and the junction between R and S through condensers, and also to take a second reading of v with p and q interchanged, the mean of the values of v being used if they are different.

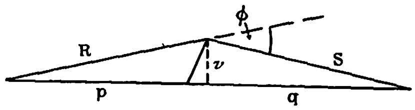

FIG. 40.—Resistance testing—vector diagram.

The only difficulty in such a test is the question of the phase displacement of the standard resistance S, and for this reason methods have sometimes been proposed for comparison with a mutual inductance of assumed perfect purity.

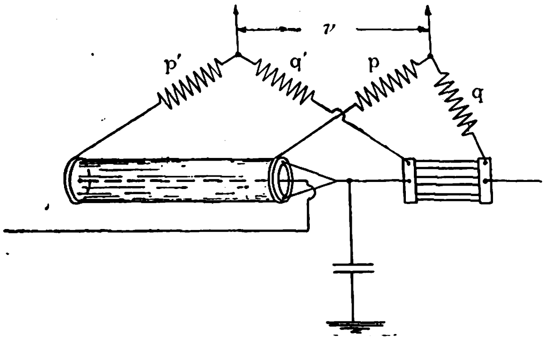

FIG. 41.—Low-resistance testing.

There is no difficulty, however, in making up a perfectly pure resistance for the test on the Moore concentric principle,* and it is far preferable to make measurements of small phase displacements between circuits of similar characteristics, between two resistances, or two inductances. The Moore concentric inductionless resistance is a most valuable device for a.c. testing, but it does not seem to have been sufficiently appreciated. It consists of a tubular resistance in which one current lead is carried through the centre of the tube to the other end, thus confining the magnetic field to the interior so that there is no field outside the tube and therefore no inductive component between any two points on its surface. For low resistances it can, of course, be made of manganin tube, but for tests on coils of tens or hundreds of ohms' resistance the author has employed platinized glass tubes with soldered-on connecting straps. Although these are unsuited for permanent standards they form excellent comparison resistances for phase-displacement tests. Fig. 41 shows the connections for the above test when testing a low resistance against a concentric standard, a second pair of equal ratio coils p' and q' being connected on the Kelvin bridge principle across the inner potential contacts.

Resistance, etc., of Electrolytes.—The testing of electrolytes may be conducted in exactly the same manner as the testing of low resistances (Fig. 41), employing a Moore concentric resistance if it is desired to measure the phase displacement in the liquid. In this connection it is important to note, however, that it is quite useless to attempt to measure such phase displacement between two electrodes in the electrolyte as is usually done, as the polarization effects at the points of entry and exit of the current are quite appreciable. The author has therefore employed a 4-electrode tube as shown in Fig. 42, in which the p.d. is measured across two inner platinum gauze discs having insulating stems passing through the current electrodes. On making a series of careful tests with such electrodes by several methods he was unable to find evidence of any definite phase displacement whatever in sea water, although several observers have given high values for its equivalent dielectric constant.

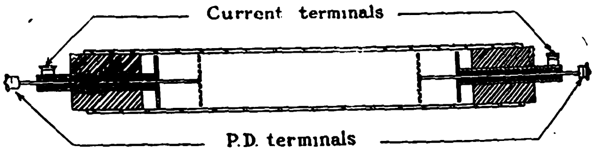

FIG. 42.—Four-electrode tube for measuring resistance of electrolytes.

Cable Testing.—The a.c. potentiometer enables both the characteristics of cables and the distribution of current and p.d. along them to be determined. A cable connected to its receiver has at its sending end a certain impedance Z_1, which can be measured exactly like any other impedance. By the theory of cable transmission we have

$$Z_1 = \frac{(Z_r/Z_0) + \tanh ax}{1 + (Z_r/Z_0) \tanh ax} Z_0$$

where Z_0 is the " characteristic impedance "

$$= \sqrt{[(R + jX)/(G + jB)]}$$

Z_r the impedance of the receiver, a the vector attenuation constant $= \sqrt{[(R + jX)\ (G + jB)]}$ and R, X, G and B the resistance and reactance of the core, and the leakage conductance and susceptance of the sheath respectively. If the receiving end is short-circuited $Z_r = 0$, and $Z_1 = Z_0 \tanh ax = Z_1\underline{/\phi}$, and if it is open-circuited $Z_r = \infty$, and $Z_1' = Z_0/\tanh ax = Z_1'\underline{/\phi'}$, from which

$$Z_0^2 = (R + jX)/(G + jB) = Z_1 Z_1' = Z_1 Z_1' \underline{/\phi + \phi'}$$

and

$$\tanh^2 ax = \tanh^2 x \sqrt{[(R + jX)\ (G + jB)]}$$
$$= Z_1/Z_1' = (Z_1/Z_1') \underline{/\phi - \phi'}$$

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* See Reference (27).

As the potentiometer measures $Z_1\underline{/\phi}$ and $Z_1'\underline{/\phi'}$ directly, this enables R, X, G and B to be readily calculated. In the case of an artificial cable the p.d. and current can be directly measured as vectors at any point along its length. The magnitude and phase of the current at any point of an actual cable can also be measured by a small hinged ring transformer which can be clipped round the cable, and such a transformer was actually used for measuring the current in the Gareloch cable when investigating the magnetic field round it.

Telephonic Measurements.—These measurements have become of increasing importance of recent years, and acoustic measurement in general is destined to become more and more important. Telephone receivers are essentially small synchronous motors and have the same theory and characteristics, including the circle diagram, as such motors. Up to a few years ago many attempts at testing such receivers by oscillographs were made, but such tests were of comparatively little value owing to the relatively large currents required for oscillographs which involved testing under abnormal conditions. By treating the receiver as an impedance and measuring that impedance with different frequencies up to and above its resonance frequency, we obtain its "circle diagram" immediately, as the potentiometer gives the impedances directly as vectors; and the amount of electrical power put into the receiver and the proportion of it converted into mechanical power can be easily determined from this diagram. Repeating this test with the diaphragm prevented from vibrating by the use of wax, we find by difference the mechanical power imparted to the medium as sound. Conversely, the electrical output of a transmitter when excited by sound from a source fed from the a.c. supply can be measured. The whole performance of a receiver or transmitter over the audible range can be determined from the two sets of measurements obtained in this manner.

(6) INSTALLATION.

On account of the universal character of the a.c. potentiometer it is desirable to pay some attention to its first installation, especially as it is not readily portable and lends itself to measurements on distant circuits. If it is once properly set up in a laboratory with the arrangements for various tests permanently connected in different parts of the room, it will be found most useful, but it will be comparatively little used if it has to be specially set up for any particular test.

The potentiometer should be mounted on a sloping desk on a table near to and facing a wall away from the windows (see Fig. 43) and with a translucent scale at eye-level immediately over it. This table should be 5 or 6 ft. wide, giving room for the phase-splitting devices, a voltmeter and frequency meter, and rheostats for adjusting the p.d. and frequency of the a.c. supply on the right-hand side, and for a standard cell, variable mutual-inductance standard and any small testing circuits on the left. On a shelf below the table the accumulator battery for d.c. testing and the isolating transformer may be placed; and on a shelf on the wall immediately in front of the scale a sensitive moving-coil galvanometer and two vibration galvanometers for low- and high-frequency tests should be mounted and illuminated to give good bright spots on the scale. In the case of the Gall potentiometer, the reflecting dynamometer for indicating the correct potentiometer current is also mounted on this shelf.

The alternators for supplying the potentiometer and testing circuit should be in another room and driven from a battery to ensure steady running. The current should be brought in, preferably by well-twinned or concentric leads, and two other pairs of leads should be provided from the exciting and motor-field circuits to the rheostats on the potentiometer table, so that the p.d. and frequency can be accurately adjusted. It is most important that the alternators should give a good sinusoidal p.d., and the author has been inclined to prefer a d.c. motor with slip-rings for the low-frequency machine, as it generally gives a good wave-form. Now that the frequency of outside a.c. supply is so carefully regulated and the wave-form is so good, low-frequency potentiometer measurements can generally be made satisfactorily with it.

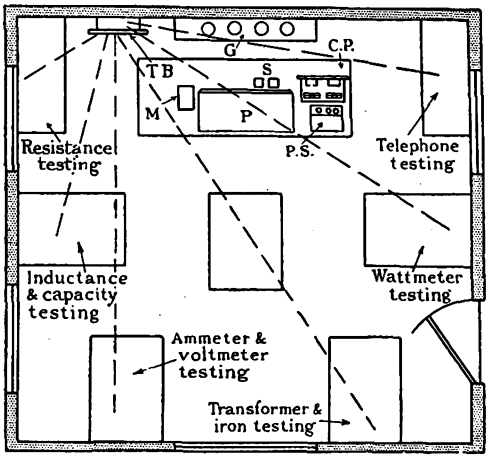
G
C.P.
TB
S
M
P
P.S.
Resistance testing
Telephone testing
Inductance & capacity testing
Wattmeter testing
Ammeter & voltmeter testing
Transformer & iron testing

FIG. 43.—Suggested lay-out for test room.

P = potentiometer; G = galvanometers (a.c. and d.c.) and dynamometer.
M = mutual inductance.
P.S. = phase-splitting arrangements.
C.P. = control panel with voltmeter, frequency meter, rheostats and switches.
S = galvanometer shunts.
T.B. = terminal board for experimental leads.

The apparatus and circuits for the measurements required may then be set up on benches at various parts of the room, and well-twinned supply and potential leads run from each of them to a connection board near the potentiometer, from which board four pairs of leads are taken to the terminals so that they can be rapidly brought into circuit by the selector switch. By this arrangement and by having a regulating rheostat or transformer in the supply leads on the potentiometer table, a complete test can often be carried out without the operator having to move from the potentiometer.

As regards accessory apparatus, any good moving-coil galvanometer may be used for d.c. testing, and any sensitive form of vibration galvanometer, provided that it is not responsive to harmonics. The Duddell double-strip vibration galvanometer, although very sensitive and of long range, is not to be recommended as the overtones of the strips are readily excited. For p.d.

measurements ordinary commercial volt boxes are generally satisfactory, but the low resistances or shunts ordinarily employed for current measurements are not sufficiently non-inductive, and the author therefore designed special low resistances for potentiometer work, the larger sizes being on the concentric principle. These resistances have been made for currents up to 40 000 amperes by Messrs. H. Tinsley and Co.

Variable mutual-inductance standards are very valuable accessories for a.c. potentiometer work, as indicated in the above description of tests, and the Campbell or similar forms of inductometer serve excellently. Care must, of course, be taken to see that they are not near the phase-shifting transformer or other highly inductive or heavy-current circuit.

If a little care is taken in setting up the potentiometer and accessory apparatus in some such way as above indicated, its universal properties will soon be appreciated, and it is remarkable how simple and rapid the various tests become after a little practice, when the operator has learnt to visualize its vector properties, as the connections for almost every kind of test are simple and very similar.

In conclusion the author sincerely hopes that this paper, although admittedly most incomplete, will stimulate interest in a.c. potentiometers and help to give them their rightful place as the most valuable of all testing instruments for both engineering and scientific testing. In view of the great need for such an instrument it is remarkable that a.c. potentiometers have been so little used, but the explanation probably lies in the fact that so little has been written in regard to their general application, and it is hoped that the above description of the various tests may do something to remedy this defect.

As to the various types of potentiometers, only three appear to be suited for general testing—the author's, the Campbell-Larsen and the Gall forms. As mentioned at the outset, the author feels bound to maintain the advantage of the polar principle for general purposes, but excellent work can be done by the Campbell and Gall instruments and they have some advantages for measurements on circuits having either very low or very high power factors.

The phase-shifting transformer of the author's potentiometer takes about 0·4 amp. at 100 volts, 50 cycles, and 0·09 amp. at 160 volts, 500 cycles, which precludes its use with small valve oscillators. The Larsen instrument, of course, takes very little power in itself but it is advisable to supply it or the circuit under test from a screened transformer. This involves the use of a certain amount of power, and the measurements are greatly facilitated in many cases by supplying the circuit under test by a phase-shifting transformer, so that it is advantageous as a rule to have a fair amount of power available. Valve oscillators are also liable to give non-sinusoidal wave-forms unless special circuits are employed, which usually reduce their output, and the p.d. from them is generally considerably affected by variations in the testing circuit. It is therefore usually desirable to employ alternators with a good margin of power, in which case the current required for the phase-shifting transformer is not of importance.

If we review the various tests above described and consider the apparatus which would be required to cover them by the ordinary methods, the saving of cost and time in equipping and testing is too overwhelming to need any stress being laid upon it here. The mere fact of being able to measure p.d.'s from a few microvolts to thousands of volts, and currents from fractions of a microampere to 40 000 amperes, either for direct current or for alternating current from 25 to 2 000 cycles, to an accuracy of about 0·1 per cent, with the potentiometer and a set of volt boxes and shunts, is in itself sufficient, without reckoning its application for phase measurements, inductance and capacity testing, etc. Of course, for every special test there is some instrument which for accuracy and convenience is superior to the potentiometer, but the measurements obtained with it are sufficiently accurate for the bulk of practical purposes, and if it is kept set up as indicated its immediate applicability for any test outweighs the superior convenience of a special instrument unless it is already set up for constant use. These features have caused the a.c. potentiometer to be specially appreciated in new countries where the facilities for obtaining special instruments are limited, but they apply with considerable force even to well-equipped test rooms.

APPENDIX I.

THEORY OF THE PHASE-SHIFTING TRANSFORMER.

The function of the phase-shifting transformer is to provide in all positions of the rotor an e.m.f. of constant magnitude but changing in phase by exactly the same angle as that through which the rotor is turned. For this purpose all that is necessary is for the stator to produce a perfect rotating field, but as the 2-phase supply is obtained by splitting the single-phase supply from the mains it is necessary to have some simple means of testing when the current in the split phase is equal in magnitude and in exact quadrature with that in the main phase, and to know what error will be caused by any departure from equality of magnitude or defection from quadrature. Let the current in the main phase $I_1 = I \sin \omega t$, producing an e.m.f. $e_1 = e \sin \omega t$ in the rotor coil when it is parallel to the stator coil carrying the current I_1. Then let the current in the split phase $I_2 = I(1 + \delta) \cos (\omega t - \alpha)$, producing an e.m.f. $e_2 = e(1 + \delta) \cos (\omega t - \alpha)$ in the rotor coil when it is turned into parallelism with the stator coil carrying I_2, or perpendicular to its former position. Here δ is the fractional excess of e_2 over e_1, and α is the angle by which the current I_2 lags behind 90° lead from I_1. Both δ and α are supposed to be so small that their squares may be neglected. Then $e_1 = e \sin \omega t$, and $e_2 = e(1 + \delta) \cos (\omega t - \alpha) = e(1 + \delta) (\cos \omega t + \alpha \sin \omega t)$. When the rotor coil makes a leading angle θ with the direction of I_1 the e.m.f. in it will be

$$\begin{aligned} & e_1 \cos \theta + e_2 \sin \theta \\ & \quad = e\left\{\cos \theta \sin \omega t + (1 + \delta) \sin \theta (\cos \omega t + \alpha \sin \omega t)\right\} \\ & \quad\quad = e\left\{(\cos \theta + \alpha \sin \theta) \sin \omega t + (1 + \delta) \sin \theta \cos \omega t)\right\} \end{aligned}$$

The magnitude of this is

$$e\sqrt{[(\cos\theta + a\sin\theta)^2 + (1+\delta)^2\sin^2\theta]} \\ = e(1 + \tfrac{1}{2}a\sin 2\theta + \delta\sin^2\theta)$$

while the angle of phase lead ϕ is given by

$$\tan\phi = \{(1+\delta)\sin\theta\}/(\cos\theta + a\sin\theta)$$

If δ and a are both zero e is constant, and $\tan\phi = \tan\theta$ or $\phi = \theta$ as is required.

If a only is zero, or the two stator currents are in exact quadrature but differ in magnitude, the e.m.f. increases from e when $\theta = 0$ to $e(1+\delta)$ in the perpendicular direction, as is obvious; and $\tan\phi = (1+\delta)\tan\theta$, from which $\phi - \theta = \Delta\phi = \frac{1}{2}\delta\sin 2\theta$. This means that there is no error in the phase angle when θ is near zero or 90°, and that a maximum error of $\frac{1}{2}\delta$ occurs at 45° and of $-\frac{1}{2}\delta$ at 135°. If δ is $0\cdot01$ or the current in the split phase and the corresponding rotor e.m.f. are 1 per cent higher than in the direct phase, ϕ will be greater than θ by $\frac{1}{2} \times 0\cdot01 \times 57\cdot3 = 0\cdot29°$ at 45°, and less by the same amount at 135°.

If δ only is zero or the stator currents are equal but with a defection a from true quadrature, the e.m.f. $= e(1 + \frac{1}{2}a\sin 2\theta)$ and $\tan\phi = \sin\theta/(\cos\theta + a\sin\theta)$, from which $\Delta\phi = -a\sin^2\theta$. The e.m.f. therefore has a maximum value of $e(1+\frac{1}{2}a)$ at 45° and a minimum of $e(1-\frac{1}{2}a)$ at 135°, and the phase error increases from zero to $-a$ at 90°. Consequently if the two e.m.f.'s at 45° and 135° differ by 1 per cent the maximum error $\Delta\phi = a = 0\cdot01$ radian or $0\cdot57°$ at 90°.

In the general case the e.m.f. $= e(1+\frac{1}{2}a\sin 2\theta + \delta\sin^2\theta)$, which is a maximum or minimum when $\tan 2\theta = a/\delta$, from which the maximum and minimum values of the e.m.f. are

$$e\left\{1 \pm \tfrac{1}{2}a^2/\sqrt{(\delta^2 + a^2)} + \tfrac{1}{2}\delta(1 \pm \delta/\sqrt{(\delta^2+a^2)}\right\}$$

In this case $\Delta\phi = \frac{1}{2}\delta\sin 2\theta - a\sin^2\theta$.

The general conclusion from this investigation is that any departure from equality of magnitude or from quadrature of the two currents produces an elliptical instead of a circular field, and that if the ratio of the maximum to the minimum e.m.f. in the rotor is $(1+a)$, where a is small compared with unity, the maximum deviation in the phase angle from the angle of rotation is a radians or $57\cdot3a°$ or plus or minus half this angle if the scale is set so as to be correct at the best point. A 1 per cent difference between the major and minor axes will therefore produce a maximum phase error of $\pm\ 0\cdot29°$, and if the variation in the rotor e.m.f. is less than $0\cdot3$ per cent the phase angle will be correct within $0\cdot1°$.

An important result of the investigation is the most simple method of adjusting the phase-splitting. As already mentioned, the rotor of the phase-shifter is provided with a fixed pointer (the "axis pointer"), which when at zero indicates that the rotor winding is co-axial with the direct phase of the stator. The dynamometer in series with the potentiometer circuit acts as a voltmeter indicating the rotor e.m.f. If the dynamometer readings are the same when the axis pointer is at zero or 90° this shows that the split-phase current is equal to the main-phase current, and the phase-splitting device can be adjusted until this is the case. On then setting the axis pointer to 45° and 135° successively the two dynamometer readings should also be equal, but if the former is higher the split phase leads by less than 90°, while if it is lower the lead is greater than 90°. A few successive adjustments of the phase-splitting device until the dynamometer readings at 0, 45°, 90° and 135° are all equal ensures that the field is a truly rotating one, and if the maximum difference between these readings is less than $1/2\cdot9$ or $0\cdot32$ per cent the greatest error in the phase angle will be $0\cdot1°$. There is no great difficulty in securing this result if the frequency is kept constant to about $0\cdot1$ per cent.

APPENDIX II.

THEORY OF THE RESISTANCE-CONDENSER PHASE-SPLITTING DEVICE.

The phase-splitting device employed with the a.c. potentiometer is usually a simple combination of a resistance and condenser in series with one of the windings. Since the currents in the two phases are to be equal in magnitude, the impedances of the two circuits must be equal, and since the currents are to be in quadrature the total resistance of the split phase must be equal to the reactance of the direct phase, and the total reactance of the split phase must be equal to the resistance of the direct phase. Hence if R_D and X_D are the resistance and reactance respectively of the direct phase, and R_S and X_S those of the split phase, $R_S = X_D$, and $X_S = -R_D$. If L is the inductance of the stator, C the added capacity and $\omega = 2\pi \times$ frequency, $R_S = L\omega$, or the added resistance must be $L\omega - R_D$. Also $1/(C\omega) - L\omega = R_D$, and the added capacity must be $C = 1/\{(L\omega + R_D)\omega\}$. If R_D is very small compared with the reactance, $L\omega$, the added resistance is $L\omega$ and $C = 1/(L\omega^2)$, so that the resistance is proportional to the frequency and the capacity is inversely proportional to the square of the frequency. Further, if R_D is small compared with $L\omega$, the current in the direct phase is nearly in quadrature with the p.d., so that the split-phase current is nearly in phase with it, and the magnitude of the latter is varied almost entirely by the added resistance, and its phase by the condenser. Fig. 44 gives the actual variation of the phase-splitting resistance and capacity with frequency for one of these instruments. It should be observed that the effective resistance of the phase-shifter coils rises with the frequency, owing to eddy currents in the core, so that the added resistance actually has to be negative when the frequency is above 400 cycles per sec. For such high frequencies the resistance may therefore have to be transferred to the direct phase, and the supply p.d. increased.

In combination with the previous theory of the rotating field, this gives rise to a simple procedure for obtaining correct phase-splitting with the aid of the dynamometer included in the potentiometer. The direct phase is connected to the main supply, which is maintained carefully at its correct p.d. and frequency; the axis pointer is set to zero, which means that the rotor derives its e.m.f. from that phase; and the potentiometer rheostats are adjusted until the dynamometer indicates the standard current of 50 mA. The axis pointer is then set to 90° and the phase-splitting resistance adjusted until the current is the same, which indicates that the magnitudes of the currents in the two phases are equal. Next, the axis pointer is set to 45° and if the dynamometer reading is higher this means that the current in the split phase leads by less than 90° and the phase-splitting capacity must be reduced. By a few successive adjustments of the resistance at 90° and of the capacity at 45° a condition is reached in which the dynamometer reading is the same at 0, 45°, 90°, 135° and 180° within 0·1 per cent, when the potentiometer will be in adjustment and its phase indications will be correct to within ± 0·1°.

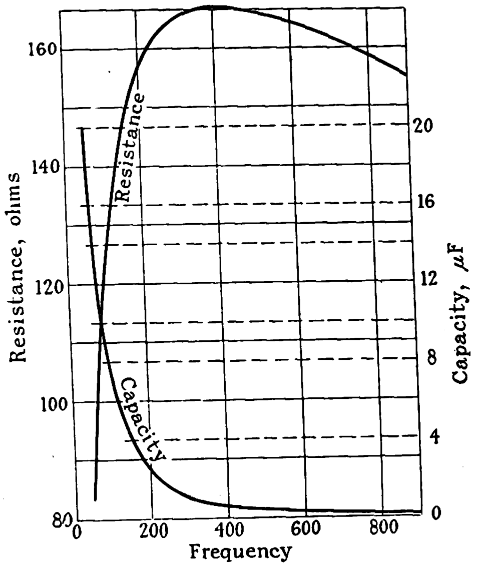

FIG. 44.—Curves of phase-splitting values.

ADDENDUM.

(*Received* 23*rd November*, 1929.)

A successful application has just been made of the principle of the Gall phase-splitting transformer to the author's potentiometer, which will probably result in simplification of the procedure and in reduced influence of small frequency variations.

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Discussion before the Meter and Instrument Section, 6th December, 1929.

Prof. W. C. Clinton: The question of alternating-current measurement by potentiometer methods is again engaging considerable attention, and the author is the pioneer inventor of apparatus for this purpose, at any rate as far as this country is concerned. Although harmonics are not likely nowadays to give much trouble, there are special cases in which they become of importance. Would it be possible to measure these harmonics separately, preferably, perhaps, on a co-ordinate arrangement, without too much alteration and adjustment of the circuits and apparatus? With reference to screening, if the methods specified are to be used with confidence at frequencies of, say, over 5 000 cycles per sec., will it not be necessary to consider the arrangement and connection of screens, with the same care as is now employed in the design of high-frequency bridges?

Prof. J. T. MacGregor-Morris: Referring to Dr. Kennelly's demonstration potentiometer, such an instrument was constructed at East London College some 15 years ago; and in order to minimize stray magnetic fields due to the return leads of the two phases, I added two return-current sheets: one in phase A, folded back underneath but insulated from the main sheet, and the other in phase B, folded back at right angles and again insulated from the other sheets. This arrangement largely reduced the stray fields of the two circuits A and B. In this arrangement, therefore, the four sets of manganin leading-in wires appear only on two sides of the square. Unfortunately, we did not devote sufficient time to obtaining the necessary technique, and the apparatus has not been employed for many years. I think that some trouble was experienced in holding the leads in the correct positions. In view, however, of the demonstration potentiometer shown by the author, the use of a light arm, centred at the centre of the square and carrying a slide, but with no slide-wire or phase-shifter, would very materially assist in its use, and I propose to attempt its further development in the near future. Having used a Drysdale form of potentiometer in a fair number of measurements, I feel that one is limited very definitely by the accuracy of the dynamometer, which should indicate 50 milliamperes flowing through the slide-wire. The percentage accuracy of the measurements would appear to me to depend entirely upon the accuracy of the dynamometer when reading 50 milliamperes. A 1 per cent change in the current only gives 1½ mm alteration of the position of the pointer, and hence a precision of one part in 400 is all that is possible; and there is also the question as to the constancy of the dynamometer with temperature-changes and other variations. I am aware that it can be calibrated with direct current, but this has to be done with the current flowing first in one direction and then in the other, and the mean value taken. Referring to the vibration galvanometer and the constancy of the frequency of the a.c. supply, I find difficulty, when trying to obtain the most perfect balance, in deciding whether the deflection of the vibration galvanometer has been reduced practically to zero owing to the actual potential difference having been reduced to zero, or owing to a frequency-change of the supply affecting the sensitivity of the response of the vibration galvanometer. Since a vibration galvanometer does not indicate whether the measured a.c. potential difference is higher or lower than the corresponding quantity for the slide-wire, is it not possible to use a stroboscopic disc driven by a synchronous motor (say of the Everett-Edgcumbe Warren type) for examining the phase of the deflection?

Mr. R. S. J. Spilsbury: The author states that his a.c. potentiometer can be referred to a standard cell in the same way as the d.c. instrument. This does not seem to be quite correct, for the assumption is implicitly made that the reading of the dynamometer is the same for both alternating and direct currents of the same value. This condition can quite easily be obtained by paying attention to magnetic shielding and eliminating solid metal near the coils, but it is a much less simple thing to check than the correctness of the resistance ratios of the d.c. potentiometer. With regard to the accuracy with which phase angles can be determined, the author's reference to 0·1 degree is, I think, a little optimistic. It must be remembered that the error includes any error in the phase-splitting, in the reading of the pointer, and in the drawing of the scale. I believe I am right in saying that the phase-shifter scales of commercial instruments are drawn by trial, and are not scales of geometrical degrees: certainly some which I have seen have not been regular. It has to be borne in mind that the phase-splitting is very critical with frequency, as shown by Fig. 44; and unless the power is taken from a good battery-driven alternator, the instrument can be a most difficult one to operate, as the phase-split continually varies. I would suggest, therefore, that in practice the error will be nearer to 0·5 degree than to 0·1 degree. The a.c. potentiometer, while invaluable for research, is not well suited for test work or instrument calibration, except in cases where only a single instrument can be afforded. For instance, the test of a high-power alternator which the author illustrates would involve three measurements of current and three of voltage, each consisting of two settings, in order to obtain a single value of the output in kilowatts; on the commercial load on which large turbo-alternators must be tested, conditions would be varying during the readings, while the amount of calculation necessary to reduce the results would be considerable. The type of work for which the instrument seems to be admirably suited is the investigation of fields round cables, as mentioned in the paper: such work could hardly be done with any other instrument, and many problems of this type are met with in research.

Mr. F. D. Smith: It is evident from the author's description of the a.c. potentiometer in its various forms that the instrument has reached an advanced stage of development and that there is not much more to be gained in accuracy and convenience. There is, however, an urgent need for an extension of its range to radio frequencies. The measurement of phase at radio frequencies is becoming more and more important and, apart from the cathode-ray oscillograph and experimental apparatus of the kind shown in Figs. 21 and 22, there is little available for the purpose. The fundamental principles which must determine the design of an a.c. potentiometer for radio frequencies are now well understood. The possible sources of error are those common to all radio-frequency measurements, and the remedies and precautions to be taken are similar. In a compact assembly of apparatus, there exist capacities between the component parts which present alternative paths for the flow of alternating current. Consider a potentiometer whose upper limit of frequency is 1 000 cycles per sec. and assume that the impedance of some part of it is 1 000 ohms. A capacity of 100 $\mu\mu$F in parallel with this impedance has a reactance of 1 600 000 ohms at 1 000 cycles per sec., and does not introduce any appreciable error. If such a potentiometer is used at 1 000 000 cycles per sec., the reactance of the condenser falls to 1 600 ohms and it becomes comparable with the impedances of the components of the potentiometer. The obvious remedy is to design these components to have impedances of 10 ohms or less, whereupon the shunting effect of the stray capacities is no longer serious. The high-frequency potentiometer shown in Fig. 21 was designed with this general principle in mind. The two pairs of Helmholtz coils which produce the rotating field have only 6 turns of wire each, and the components of the phase-splitting circuit are of similar impedance. Up to 50 000 cycles per sec. the potentiometer can be used without screens; and very simple screens suffice for a considerable range above this frequency. It is, of course, essential to use screens if the greatest possible accuracy is to be obtained. The use of low-impedance components necessarily involves the use of heavy currents in order to gain the necessary sensitiveness. There is no objection to this, because the power consumption in the potentiometer need not be greater than that in a high-impedance potentiometer supplied with a small alternating current. I have found that alternating currents of 10 amperes may be maintained in the 6-turn coils (Fig. 21) with a very moderate expenditure of power. I hope that the author will follow up his pioneer work on the a.c. potentiometer by extending its range to radio frequencies.

Dr. A. H. Davis: I am chiefly interested in audio-frequency measurements for acoustical purposes, the range required being up to, say, 5 000 cycles, or, preferably, to 20 000 cycles per sec. The ear, however, is not very sensitive to changes of intensity, and great precision of the measurement is not often necessary. The author states that most of the instruments described in the paper have an upper limit of 2 000 cycles per sec. Presumably this is due to practical considerations, as the principles appear to be general. In any case, however, it is a low limit for acoustical work. I should like to know whether any of the instruments with which the author deals would, in fact, give substantially accurate results for acoustical measurements well above the 2 000-cycle limit. For instance, the Larsen type involves a resistance and a mutual inductance which can each be made reasonably accurate at much higher frequencies. It is true that the Campbell frequency-setting device which the author has shown us does not go higher, but it is not essential to the Larsen potentiometer if there is any difficulty in extending its application. The apparatus of Messrs. B. S. and F. D. Smith deals, of course, with high frequencies, but its scale appears to be a short linear one, insufficient to deal with the very wide ranges in amplitude which are usual in acoustical work.

Mr. R. M. Longman: I have recently had to consider the purchase of equipment of the type dealt with in the paper, and, so far as I can gather, my decision as to type has been to a great extent confirmed by the author. I have been responsible for the purchasing of two a.c. potentiometer equipments, the first, immediately prior to the outbreak of the War, being of the Tinsley-Drysdale pattern as described by the author. Unfortunately, owing to the War, I was unable to complete the necessary a.c. equipment, and it was later transferred to a more fully equipped laboratory, where I understand it has given excellent results and is in regular use. When considering the question recently, I decided upon the Gall co-ordinate potentiometer. This instrument, although delivered, is not yet in full use. With a little practice, it is extraordinary how quickly and accurately results can be obtained with either of these instruments, although they appear to have a number of rather complicated parts. I am proposing to operate thise quipment through suitable transformers direct from the supply mains, and the question arises as to the steadiness of the supply system. It is most important that such equipments should be suitable for satisfactory operation under these conditions.

Mr. W. H. Grinsted: It may be of interest to mention the device used by Mr. Wigan in connection with the indicating telephone in audio-frequency potentiometer measurements, referred to by him as the "listening point." * This "listening point" consists of an ordinary telephone receiver associated with a microphone, the observer's telephone being actually in the secondary circuit so formed, instead of directly in the indicating circuit of the potentiometer. This simple device is very effective: it provides a fair degree of amplification and it removes the difficulties due to the earth capacities of the telephone leads. I should like also to draw attention to another method of obtaining two currents, e.m.f.'s or other vector quantities in quadrature. If we have two vector quantities of equal magnitude but with any suitable phase difference, and if we can by some means form a quantity corresponding with their sum and another quantity corresponding with their difference, then these two latter quantities are in quadrature. This is a scheme which I have found useful in an alternating-current measuring device other than a potentiometer, and it would be interesting if the author could say whether it has ever found application in potentiometers.

Mr. F. L. Best: The author has, on previous occasions regretted the fact that the a.c. potentiometer, in any form, has not proved a popular instrument, and I think the probable reason for this is that its capabilities and limitations have not been understood—far less appreciated—by those who could gain by its use. The ideal form of a.c. potentiometer is one in which the polar ordinate and the phase angle are measured. The author's potentiometer is an instrument of this type. So far, potentiometers designed to enable the measurement of a single vector and its phase angle have not permitted the phase angle to be measured with any great degree of precision. The co-ordinate potentiometer undoubtedly does enable the phase angle—and, what is often more important, differences in phase angle—to be measured with a fairly high degree of accuracy. In the co-ordinate potentiometer of the Campbell-Larsen type, for instance, the top dial reads in steps of 0·1 volt, whilst the slide-wire reads down to graduated divisions each having a value of 100 μV. This applies to both the in-phase and quadrature components. Since even small departures or differences in phase angle are bound to alter either the in-phase or the quadrature components by relatively large amounts, the improved measurement of phase angle is clear. With regard to the standardization of the reference current, the author has almost said that this is effected by reference to the d.c. standard cell. Undoubtedly he is fully aware of the fact that this reference is via the dynamometer in the case of his own potentiometer, but I think that there is still a good deal of justification for the assertion. In the case of the Campbell-Larsen instrument, the reference current is also standardized by reference to the standard cell, but via the thermal convertor. In the absence of any piece of apparatus which can take the place in the a.c. circuit corresponding to that occupied by the standard cell in the d.c. circuit, dynamometers or thermal convertors must inevitably be used. Generally speaking, it is possible to know the performance of such apparatus at the essential frequencies, and the errors resulting need not be large. In the practical realization of the theories, the Campbell-Larsen potentiometer appears in the form of two distinct and separable instruments: the resistance unit, which can be used as a d.c. potentiometer, and the Campbell standard mutual inductometer (with long logarithmic scale). The latter, when separated from the combination which it forms with the resistance unit to constitute the a.c. potentiometer, is available for all the various well-known high-frequency bridges due to Campbell, Wein, Carey Foster and others. Considering a.c. potentiometers as a whole, there is no general opinion prevailing as regards the accuracy obtainable. Faced with carrying out a piece of work where the potentiometer might conceivably be employed, few electrical engineers would be able to say whether the desired accuracy was obtainable. References to makers, obviously, should put one in possession of this information, but the instrument finds no place in any of the specifications for standards, although it falls in a class which should enable it to qualify as the subject for a British Standard Specification. The accuracy of the Campbell-Larsen instrument is, for the resistance unit, 0·1 per cent for all dials; the slide-wire is accurate at all marked points to 10 μV. The standardization of the mutual inductance is accurate to 0·1 per cent for the dials, the scale being accurate to 0·1 μH at each marked point. Each division of the scale corresponds to 1 μH and 100 μV when associated with the a.c. potentiometer. The scale is accurate to 10 μV at all points. These figures apply from zero frequency to 2 000 cycles per sec.

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* See *Electrician*, 1929, vol. 103, p. 561.

Mr. E. W. Hill: With regard to fundamentals, I admit having had a feeling of distrust when I first considered the principle of the a.c. potentiometer. This was due to the fact that, while measurements on a d.c. potentiometer are referred directly to a primary standard of e.m.f., there is an impassable barrier in the way of this direct reference in the a.c. potentiometer. This barrier has to be bridged by some artifice which always involves an assumption. In the a.c. potentiometer the reference back to the primary d.c. standard has always to proceed via some such link as the dynamometer ammeter, which we have to assume behaves precisely the same on alternating as it does on direct current. This is a point which has been emphasized by several speakers, but, on the other hand, we should reflect that it is a difficulty which is not peculiar to the a.c. potentiometer, but is common to practically all a.c. measuring instruments in respect of the original source of their standardization. With reference to the section dealing with polyphase power measurements, I do not think the author's implication regarding the apparent difficulty of using wattmeters is justified; on the contrary, the indicating wattmeter method is perfectly practicable for any magnitude of current, and for most voltages, by making use of carefully calibrated current and potential transformers. In the section dealing with potential transformer testing, the expression "shunting one or other of them" does not seem to be quite clear, and I shall be obliged if the author will give some further explanation. With regard to the phase-shifting transformer, according to my experience there seems to be difficulty in obtaining from it a really constant e.m.f. for all positions of the rotor. Using the phase-splitting method described on a single-phase supply, it is essential, according to the author, to maintain the frequency within 0·1 per cent of constancy. In practice, this is certainly not always easy. On the other hand, this frequency difficulty can be obviated by employing a polyphase supply on a suitably constructed phase-shifter, but I have never found it possible, even then, to get reasonably constant e.m.f. from the stator. These objections may not be very serious, because it is always within one's power to make, from time to time, the adjustment necessary to keep the reading of the dynamometer ammeter steady. The a.c. potentiometer as described seems unsurpassed as a general-purpose apparatus; but for routine testing work of a specialized nature, such as is required in a factory or a supply undertaking's test room, it must give way, from considerations of convenience, to indicating wattmeters used in conjunction with other special-purpose apparatus, such as rotating standards, etc. It would, however, be most useful both as a standard of reference for such routine apparatus and as an instrument of research.

Mr. D. C. Gall (*communicated*): After several years of experience with the a.c. potentiometer, I have found it an ideal instrument for investigational work involving the measurement of current, voltage, power, flux and torque in all the various manifestations. It is, however, inferior to a bridge arrangement for the measurement of circuit constants, e.g. inductance, capacity and effective resistance, unless these are variable with current, etc. As regards the limitations of the instrument, the chief defect of the author's instrument is the phase-shifter.

This depends upon a phase-splitting appliance which is essentially a frequency device, and the phase-splitting and, consequently, the angles indicated vary with frequency fluctuations. Further, the least count of the phase-shifter is 1°, which may be subdivided by the worm to, say, 0·1°. This corresponds to a vector magnitude of approximately 1 in 600. Thus the accuracy with which the phase-shifter can be set limits the accuracy with which a voltage can be balanced. I am aware that a finer setting than this can be obtained, but it is tedious, and in use a certain jumpiness, when approaching balance, is found to arise from this cause. A second, and finer, phase-shifting dial is really required, which would subdivide to, say, 0·01°. There would seem to be no great difficulty in obtaining this by the obvious means of two superimposed fields with a small time or space displacement. A further difficulty is the stray field from the phase-shifter. This can be very perplexing in its effects, since part of it rotates with the rotor and part is stationary. For this reason I consider that the strongly magnetized parts should be remote from the instrument. The phase-splitting defects are most noticeable at large phase displacements. Thus low power factors are least accurately measured and, where circuits are isolated, triangular measurements cannot be made to check small angles. For this reason I think the co-ordinate type of potentiometer a considerable advantage, particularly for the measurement of power at low power factors, since the power is given by the sum of two products without involving any angle, whereas with the Drysdale type of potentiometer the angle, which is not very accurately known, is involved. The ideal form is a combination of the author's potentiometer and the co-ordinate type, i.e. a co-ordinate potentiometer provided with a suitable phase-shifter. The whole potentiometer can then be rotated to any phase position, where power and wattless components can be measured separately on the two potentiometers with the greatest accuracy and without the complication of an inclined system of co-ordinates. The power taken by the author's phase-shifter makes the use of the potentiometer upon valve circuits rather difficult. With the co-ordinate type of potentiometer, the phase-splitting can be done on the input side of the supply valves, and great economy in phase-splitting results. Further, the phase-splitting can be made independent of frequency. Phase-shifting arrangements can be also inserted there to bring about the conditions, mentioned above, of a combined Drysdale and co-ordinate potentiometer.

Mr. A. Campbell (*communicated*): In 1900 I constructed a phase turner for measuring the magnitudes and phases of unknown alternating voltages with the help of an electrostatic voltmeter.* This instrument embodied an essential part of some modern a.c. potentiometers, namely, a phase-splitter. This was of the simplest type, but could be easily set correctly for any unknown frequency. The simple Larsen type of instrument requires very little power to work it, as no external phase-splitter is necessary, the instrument being in itself the simplest form of phase-splitter. Even with the elaboration of a loop shunt which I have added, it only takes a fraction of a watt, and is thus quite suitable for use with an ordinary valve oscillator as source of power. The methods of measurement described in the latter part of the paper are very interesting, and the straightforward simplicity of the potentiometer tests is much in their favour. In some cases, however, bridge null methods would prove easier. The results obtained on the resistance of electrolytes should be of interest to physical chemists.

Dr. C. V. Drysdale (*in reply*): I should like to express my appreciation of the interest which has been manifested in the subject. The points raised in the discussion are all of interest and show that the speakers are fully alive to the importance and limitations of a.c. potentiometer measurements.

Prof. Clinton raised the important question of harmonics, and asked whether they can be separately measured. Unfortunately this does not appear to be generally possible, for the fundamental reason that every form of a.c. potentiometer involves a phase-changing device, and there is at present no method known or conceivable for altering the phase of a non-sinusoidal potential difference, without changing its form or the ratio of the harmonics to the fundamental. If the supply to the potentiometer is sinusoidal and the p.d. to be measured is distorted by the nature of the load, then when balance is secured with a vibration galvanometer tuned to the fundamental, the harmonics in the p.d. will be unbalanced. They may be detected by a telephone receiver and separately measured by a second vibration galvanometer tuned to any given harmonic. If, however, the wave-form of the supply p.d. has no harmonics exceeding 2 or 3 per cent of the fundamental, they may be neglected in all ordinary measurements. The importance of screening and earthing in high-frequency testing is referred to in Section (5) of the paper.

Prof. MacGregor-Morris's method of constructing the Kennelly demonstration potentiometer is ingenious and appears to be quite sound in principle. I am surprised that he should have experienced difficulties with it. Apart from contact troubles, which surely are not insurmountable, the only source of error would probably be non-uniform current distribution in the sheet. It should be possible easily to determine the inaccuracy by connecting one phase at a time and plotting the equipotential lines with two contacts and a telephone. If these lines are found to be straight and perpendicular there would seem to be no cause for serious error; if not, adjustment of the leading-in wires should rectify them. Using the dynamometer, I have never had any difficulty in adjusting the current to within ± 0·1 per cent, and Prof. MacGregor-Morris's remarks concerning the change of sensitiveness of the vibration galvanometer lead me to think that all his troubles are due to insufficient constancy of the supply frequency; variations are extremely likely to occur in an educational laboratory. In the paper, emphasis has been laid on the necessity for constancy of frequency to within ± ¼ per cent, and it may be pointed out that this constancy is needed not only for the potentiometer but also for the circuits under test, since the impedance of the latter varies with the frequency. I therefore think it better to concentrate attention on securing a constant frequency, rather than on the development of stroboscopic or other devices for observing the galvanometer; especially in view of the fact that the phase of the galvanometer oscillation changes extremely rapidly from lead to lag as the frequency passes the resonance point.

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* See *Electrician*, 1901, vol. 46, p. 399.

Mr. Spilsbury is quite correct in stating that the comparison with the standard cell is vitiated by any errors in the dynamometer, but as the current is only 0·05 ampere there is no difficulty in avoiding eddy-current errors by reasonably careful construction. The dynamometer actually used is a Weston standard shielded instrument. As to the accuracy of phase measurement, the dial can of course be engine-divided, but on account of the non-uniformity of the cosine scale it is reproduced from a standard dial, and in all the instruments which have passed through my hands it has been accurate to 0·1°. Reference should be made to my paper, "The Alternate-Current Potentiometer as a Standard Instrument,"* in which Certificates of Test by the national Physical Laboratory of one of the author's potentiometers at 1 000 cycles per sec. are reproduced. Out of six measurements of phase angle, four showed no error, one an error of 0·1° and one of 0·2°. Mr. Spilsbury, having the resources of the National Physical Laboratory at his command, naturally prefers to calibrate instruments by comparison with its excellent standards; but if he were working in an ordinary test-room he would probably be thankful to be able to make use of the potentiometer. I quite agree that direct measurement of 3-phase currents by a double wattmeter is distinctly preferable, but until the last year or two the ratio and especially the phase errors of current transformers were too large for accurate measurements, and heavy-current wattmeters were costly and liable to eddy-current errors. Now that we have mumetal current transformers of high accuracy, the situation is changed, but the potentiometer may still be of great service when the resources of the test-room are inadequate, and it must be remembered that it enables a large number of other measurements (e.g. of gap or leakage flux) to be made simultaneously with measurement of output. From the designer's point of view, the ability to measure almost every detail of the performance of the machine is a great asset.

Mr. F. D. Smith's emphasis on the value of a suitable a.c. potentiometer for high-frequency measurements is justified, and the simple device due to Mr. B. S. Smith and himself is the best so far produced. Several years ago I planned a high-frequency potentiometer on similar lines to my ordinary potentiometer, but employing the Moore concentric non-inductive principle for the coils and slide-wire. Unfortunately, there has been no opportunity for constructing this instrument, but there should be no great difficulty in making an accurate a.c. potentiometer for radio-frequencies, although considerable precautions would naturally have to be taken in its use.

Dr. Davis mentions his need of an instrument for frequencies up to 5 000 or even 20 000 cycles per sec., and there is no reason why any of the potentiometers described in the paper should not be modified to work with such frequencies. During the past few years the constancy of frequency of a.c. supplies has become remarkably high, so that they can be satisfactorily employed with the potentiometer. They are, however, liable to sudden small fluctuations of p.d. when heavy loads are switched on or off.

Mr. Grinsted's method of obtaining the quadrature relation is quite correct in principle. I do not think that it has actually been applied to a.c. potentiometers, though this should not be difficult. On the whole, however, I am inclined to think that Mr. Gall's transformer device supplies the best method of phase-splitting. It is the simplest and the least affected by frequency variations; I have recently applied it in place of the resistance-condenser combination for feeding the phase-shifting transformer.

Mr. Best's information concerning the Campbell-Larsen potentiometer is of interest, and I am in general agreement with him. The great simplicity of this instrument, which is ready for use immediately the dials are set for the known frequency, is a most attractive feature. Mr. Campbell's ingenious thermo-current indicator has great advantages in its low power consumption and suitability for high-frequency working, where the inductance of the dynamometer would be objectionable. On the other hand, I must adhere to my objection to the rectangular co-ordinate principle for general measurements, and I am quite sure that the average user would rarely employ such a potentiometer if he had both types available, unless it were supplemented by a phase-shifting transformer to bring any desired p.d. into phase. Such a combination is equivalent to a polar potentiometer with a rectangular co-ordinate addition, which is undoubtedly of value for measurements of small phase displacements. There is no doubt that a combination of the polar and rectangular principles gives rise to the most perfect universal potentiometer. I have used a variable mutual-inductance standard in combination with the polar potentiometer for several tests, especially those relating to magnetic fields. This combination is, in my opinion, the best and most convenient for all-round practical testing, but this may be a bias due to greater familiarity with it.

For power measurements Mr. Hill prefers a wattmeter with current transformers to the potentiometer, and I am in agreement with him provided that suitable instruments are available. As emphasized in the paper, I do not pretend that the potentiometer or any other universal instrument can be as good for any particular test, as an instrument specially devised for that test. In my opinion, however, a device which enables a measurement to be made in the test-room when the special instrument is not available is of very great value. As Mr. Hill has found, the phase-shifting transformer should not be excited from a polyphase supply, for the latter may not be perfectly balanced. The use of Mr. Gall's phase-splitting transformer will probably remove the objection to single-phase working.

My reference on page 354 to "shunting" one or other of the volt boxes when testing p.d. transformers was rather cursory, and seems to have been misunderstood. The shunt should be connected across the "output" terminals of one or other volt box, so as to lower the resistance of, and consequently the p.d. across, the section connected to the potentiometer.

I am in general agreement also with Mr. Gall's remarks, to which many of the above comments apply. In common with others, including myself, who have had experience with a.c. potentiometers, he has come to the conclusion that the triple combination of phase-shifter, potentiometer, and variable inductometer is the most perfect; the only question is as to whether the bulk of the measurements are to be taken on the polar or the rectangular combination. I prefer the former alternative, but such a combination would allow each user to suit himself. Mr. Gall refers to the influence on the circuits of the stray field of the phase-shifting transformer. This has not proved serious, even with the open form of transformer hitherto used. I have, however, recently produced a considerably improved transformer which is totally enclosed in iron, has a smaller stray field, and absorbs far less power. The question of power, raised both by Mr. Gall and Mr. Campbell, is of great importance when valve oscillators are used, as is almost imperative for high frequencies. From this point of view, the Campbell-Larsen instrument is at first sight the more attractive, but I am quite sure that some form of phase-shifting transformer is essential for convenient working, and the improvements referred to above should bring it within the compass of valve oscillators of moderate output.

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* *Electrician*, 1915, vol. 75, p. 157.

In conclusion, I should like again to express my appreciation of the skill and ingenuity with which Mr. Campbell, Mr. Gall and others have attacked this important problem, and my hope that this paper and discussion will give an impetus to the more general use of a.c. potentiometers. I should like also to express my thanks to Messrs. H. Tinsley and Co. and the Cambridge Instrument Co. for the loan of the potentiometers exhibited at the meeting, and to Mr. S. J. Willis for arranging the experiments with the demonstration polar potentiometer, which I think should prove of great value for teaching purposes.

THE IMPEDANCE AND POWER LOSSES OF THREE-PHASE OVERHEAD LINES.[*]

By P. D. MORGAN, M.Sc., and S. WHITEHEAD, M.A., Associate Members.

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SUMMARY.

This report deals with two problems of primary importance in connection with the transmission of three-phase power by high voltage lines, viz.:—

(a) The effects of transposing the line conductors on the operation characteristics and power losses.[†]
(b) The impedance of a line conductor and earth return when one phase is accidentally earthed.

Item (a) affects the design and construction of the line and its normal operation, while item (b) is the principal factor in determining the magnitude of the "failure" current returning through the earth (under fault conditions) upon which the amount of interference with communication circuits is dependent.

Transposition makes the power lines electrically balanced, equalizes the phase impedances and reduces the induction from normal operating currents and voltages. On single circuit lines transposition entails practically no additional cost and ought to be adopted as standard in all cases. On double circuit lines, however, special "transposition towers" (costing in the case of the "grid" lines several hundred pounds extra per tower) have to be employed at each transposition point (to prevent the conductors touching in the span), and this factor renders it desirable to avoid transposition whenever practicable. On long lines (fed entirely from one end) transposition appears essential both on account of inductive interference and to avoid large differences between the phase impedances.

On short lines (say up to 50 miles long, which covers most practical cases in this country), the latter effect is negligible compared with the transformer impedances, and transposition is unnecessary when, *in addition, interference with communication circuits arising from normal operating currents and voltages is unimportant.* Thus on short double circuit lines no general recommendation regarding transposition can be made and each case must be judged on its merits.

On all double circuit lines, *whether transposed or not*, the time-phase sequence of the conductor currents in the two circuits must be co-ordinated to obtain the best results from the standpoint of operation of the system.

For transposed lines the maximum reduction in phase impedance occurs when the top conductor of each circuit conveys a current of the same time phase as the bottom conductor of the other, the two circuits being transposed at the same frequency and in the same direction of spiral. This gives a small reduction in phase impedance (3 per cent for the "grid" lines) compared with that of a single circuit at similar spacings, but allows a small interchange of power (by transformer action) between the circuits which, however, is negligible in most practical cases (0·28 kW per mile at 220 amperes on the "grid" system).[*]

For non-transposed lines there are two practicable current sequences. In the first method, which gives minimum phase impedance, the current sequence is the same as that given above for transposed circuits. In the second method, conductors in the same horizontal plane convey currents of the same time phase and have equal impedances, thus giving equality of loading of the two circuits when operated in parallel. The ultimate choice depends on the magnitudes of the power transference between the circuits, the phase impedances and the differences between them. These in turn depend upon the particular conductor spacings, etc., employed, but a few simple calculations by the formulæ herein soon indicate which is the better method in a given case. For the "grid" lines the same phase sequence already given for transposed circuits is recommended.

As regards *power losses*, the effects of transposition are negligible except on "long" lines fed entirely from one end, a condition which will seldom, if ever, arise in this country.

If one phase is accidentally short circuited to earth the interference caused to communication circuits is proportional to the magnitude of the current returning through the earth. The percentage of the total short-circuit current returning in this way may be reduced by the employment of an earth conductor bonded to the towers, which provides an alternative path for part of the failure current. The principal *design* factors affecting the reduction obtained are:—

(a) Impedance of the earth conductor.
(b) Method of "earthing" the earth conductor. ("Multiple" earths.)

The earth current is reduced in magnitude by increasing the cross-sectional area of the earth conductor, but not in proportion, because the impedance of the latter depends on the mutual inductance from the earth and short-circuited phase. For this reason after a certain point it is impracticable for economic reasons further to increase the cross-sectional area as the additional reduction obtained thereby is negligibly small, and a second earth wire in parallel with the first should be employed. For example, making the "earth" conductor on the "grid" lines of the same section as the line conductors, which corresponds to increasing the cross-sectional area of aluminium from 0·114 to 0·285 square inch (i.e. by 115 per cent) only decreases the percentage of failure current carried by the earth from about 66 per cent to 58 per cent (for an earth resistivity of 20 000 ohms per centimetre cube, see Table 6 and Fig. 8), whereas a second wire equal in cross-section to the first and suitably positioned below the phase conductors would give a much greater reduction.

On existing systems the use of an all-steel earth conductor is common practice, primarily for mechanical reasons, but because of the high self-impedance of such conductors the above considerations lead to the condemnation of this method

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[*] The Papers Committee invite written communications, with a view to publication, on papers printed in the *Journal* without being read at a meeting. Communications (excepting those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] "*Power*" *losses* mean herein the heat losses in the conductors due to the line currents. Losses due to corona and leakage conductance are excluded.

[*] These conclusions in no way modify the well-known advantages of co-ordinating the points of transposition of the power and communication circuits.

in favour of a steel-cored aluminium cable, which combines the advantages of great mechanical strength and high electrical conductivity and protection of the steel from corrosion.

With "multiple" earthing (i.e. earthing the earth conductor at every tower) the percentage of failure current returning via the earth is still further reduced, but the extra reduction is only a few per cent except in the immediate vicinity of the ends of the short-circuited section (see Fig. 9). For most practical purposes (i.e. except when the short-circuited section is very short in length, perhaps one or two kilometres) the effect of "multiple" earths may therefore be ignored. The general adoption of multiple earthing is, however, advocated to ensure the earth conductor being "earthed" close up to a "fault" wherever it occurs on the system; thereby preventing the *whole* short-circuit current passing through the earth for any appreciable distance.

These conclusions are based largely on theoretical and experimental work by the authors.

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I. INTRODUCTION.

(A) OBJECT OF REPORT.

The determination of the impedance and power losses of a transmission line is a matter of considerable importance. Under normal operating conditions these factors materially affect the efficiency, operation and loading of the system, while if one phase is accidentally earthed the impedance of a line conductor and earth return wholly or partly determines the amount of interference caused to neighbouring communication circuits.

Under both conditions the losses and impedance are dependent upon a number of dimensional and electrical factors, some of which in turn depend upon the material and construction of the line and earth conductors and the manner in which they are laid.

By a suitable control of the different variables, the regulation of the line may be improved and the interference caused to other interests reduced, and the object of this report is to show how this may be done.

(B) SCOPE OF REPORT.

A large amount of information has been published on the impedance of, and losses in, overhead line conductors under normal working conditions, and the general theory underlying the pre-determination in a given case is well understood and supported by experimental evidence. There are, however, certain aspects of the problem which appear to have been inadequately dealt with [*] and at least one aspect upon which current opinion is in error.[†] For this reason a general theory is given in Appendix II which covers all cases likely to arise in practice.

The problem of the impedance of a line conductor and earth return (which arises under short-circuit conditions) has not in the past been completely investigated. Two cases have to be considered, namely, with earth return alone and with an earth conductor bonded to the towers in parallel with the earth path. The case when no earth conductor is employed has been investigated theoretically by Breisig, Mayr, Rüdenberg, Carson [‡] and Pollaczek, but no experimental evidence appears to have been published.

The present authors have recently carried out tests[§] on the 33-kV Runcorn–Ellesmere Port Line of the Mersey Power Company, and the results obtained are

[*] For example, published data on the effects of mutual inductance between the six conductors of a double circuit line only deal with particular time sequences of conductor currents, and no general treatment has previously been given.

[†] See, losses in long line at unity power factor, Section III.

[‡] From private sources of information the authors understand that tests carried out in America substantially confirm Carson's theory.

[§] These tests were made for the Central Electricity Board and carried out in co-operation with the Post Office.

in good agreement with Rüdenberg's method and also on the Bedford–Little Barford "grid" lines. The case when an earth wire is employed has not previously been dealt with, but the authors have extended the theory based on Rüdenberg's assumptions to include this case and have confirmed their results experimentally. The theory for both the above cases is given in Appendix III, together with a comparison of the theoretical and experimental results obtained.

(C) WORKING FORMULÆ.

Working formulæ are given in Appendix IV. Numerical examples are worked out for some typical cases employing the dimensions of the conductors and towers of the 132-kV "grid" system.

II. IMPEDANCE OF A LINE CONDUCTOR WITHOUT EARTH RETURN.

(A) INTRODUCTION.

On a three-phase system[*] the line currents set up a magnetic field around the axis of the conductors. This magnetic field gives rise to a reactance voltage along the lines, and in this way the phase impedance becomes dependent on the line currents and the configuration and spacing of the conductors.

The factors on which the impedance depends are as follows:—

(i) Configuration of the conductor.
(ii) Axial separation of conductors.
(iii) Time-phase sequence of conductor currents.
(iv) Transposition.
(v) Mutual inductance from near-by circuits.

The impedance also depends on the material, stranding and dimensions of the conductors, but this aspect will be considered separately later in the report.

In discussing the impedance voltage-drop along a line it is necessary to take account of the length of line concerned.

The impedance voltage-drop may be defined as the vector difference between the sending and receiving end voltages. It is well known that this is not the same numerically as the product of the receiving-end current and the line impedance because, owing to the effects of capacity and leakage conductance, the magnitude of the current and the impedance voltage-drop per unit length vary all along the line. For a well-maintained line worked well below the corona limit, the effects of leakage conductance may be neglected, and in such cases the error introduced in the estimation of the impedance voltage-drop by ignoring the line capacitance is usually negligible on lines up to about 50 miles long, under practical load conditions. This is shown for the "grid" system by the figures in Table 1. It will be seen that at full load current[*] (220 amperes per phase R.M.S.) the errors introduced by this assumption at 80 per cent power-factor lagging at the receiving end are 2·7 per cent and 6·0 per cent for lines 50 and 100 miles long respectively, while at unity power factor the corresponding figures are 0·23 per cent and 1·8 per cent. At half full load the error on a 50-mile length is about 5 per cent at 80 per cent power-factor lagging.

TABLE 1.

Comparison of Exact and Approximate Values of Impedance Voltage-Drops and Power Losses on the Single-Circuit "Grid" Lines at Full-Load Current (220 Amperes per Phase R.M.S.).

Length of line, miles	Power factor at receiving end	Impedance-drop in line, volts		$\frac{\text{Col. 3}-\text{Col. 4}}{\text{Col. 3}}\times 100$	Power losses, watts		$\frac{\text{Col. 5}-\text{Col. 6}}{\text{Col. 5}}\times 100$
		Exact value	Value neglecting capacitance of line		Exact value	Value neglecting capacitance of line	
50	80 per cent lagging	7 590	7 800	− 2·7	$0\cdot572 \times 10^6$	$0\cdot607 \times 10^6$	− 6·3
100		14 710	15 600	− 6·0	1·11	1·21	− 9·8
200		28 070	31 190	− 11·1	1·99	2·43	− 22·4
500		57 420	77 980	− 35·9	3·82	6·07	− 58·9
50	100 per cent	7 780	7 800	− 0·23	0·607	0·607	0
100		15 530	15 600	− 0·42	1·21	1·21	0
200		30 970	31 190	− 0·72	2·43	2·43	0
500		75 010	77 980	− 4·0	5·99	6·07	− 1·4
50	80 per cent leading	7 980	7 800	2·3	0·643	0·607	5·5
100		16 250	15 600	4·0	1·32	1·21	8·2
200		33 600	31 190	7·2	2·84	2·43	14·5
500		88 920	77 980	12·2	8·16	6·07	34·4

This degree of accuracy is probably greater than that to which the fundamental constants of resistance and inductance of the conductors, upon which the impedance voltage depends, are known. It is doubtful if lines longer than about 50 miles fed entirely from one end will occur in this country, and for this reason attention is mainly directed in this report to the characteristics of such "short" lines in which the effects of capacitance have been neglected.

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[*] A balanced three-phase system is assumed unless otherwise stated, i.e. one in which the vector sum of the three currents is zero and their time phases are spaced 120° apart.

[*] By "full load current" is meant "full load current at *unity power factor at the receiving end of the line*" unless otherwise stated.

(B) SINGLE CIRCUIT TOWERS.

(i) *Without transposition.*

(*a*) *Short and long lines.*—With asymmetrical spacing of conductors, a three-phase transmission line is not electrically balanced without transposition, and the impedance and admittance per unit length vary at different places. For long lines, in which the effects of capacitance cannot be disregarded, the estimation of the impedance voltage-drop therefore presents some difficulty. No solutions of the problem have been published, although a theoretical solution is obtainable if required. In practice, regular transposition is adopted on all long lines primarily from the standpoint of inductive interference, so that a solution for the untransposed case has no practical utility and has not, therefore, been attempted. The following discussion of untransposed lines has consequently been restricted to short lines, which cover practical requirements in this country.

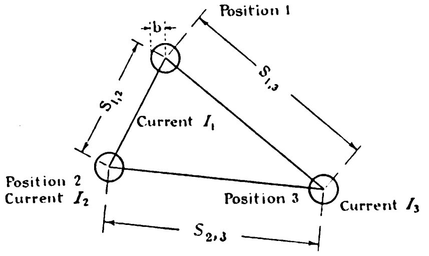

FIG. 1.—Asymmetrical arrangement of conductors on single circuit tower.

(*b*) *Configuration and axial separation* (*short lines*).—When the three conductors are spaced asymmetrically (see Fig. 1) and are not transposed, the impedances are different in all three phases. At practical spacings of conductors the reactance of any phase is approximately proportional to the logarithm of the product of the axial distances from that phase to each of the other two. Thus the amounts by which the reactances of the three phases differ is dependent on the degree of asymmetry of the conductors, but in practical cases the inequality in the reactances is not very great. On the single circuit towers* of the "grid" system, the three reactance values (see Table 2) are 0·654, 0·660 and 0·686 ohm/mile to neutral,† giving a total variation of only 5 per cent, although the distances between the axes of the three conductors are 377, 636 and 724 cm, i.e. have a maximum variation of over 90 per cent.

The effect of asymmetrical spacing in the phase resistance is much greater. This factor causes an interchange of power between the phases through the magnetic field, which makes the apparent resistance‡ of a conductor different from its a.c. resistance.* A measure of the power transferred to or from any phase is the product of the absolute value of the current and the difference between a.c. and apparent resistances. If this product is negative then the phase considered is transferring power to the other phases and *vice versa*.

On the single circuit towers of the "grid" lines (see Table 2), the power transferred is + 2·23 kW, − 2·76 kW and + 0·53 kW per mile for the three phases for the conditions shown in Fig. 1, at an assumed current of 220 amperes per phase. Obviously these three quantities sum up to zero.

The apparent resistance thus only affects the impedance voltage-drops and not the power loss which is the same in all phases and is equal to the square of the absolute (or measured) value of the current multiplied by the a.c. resistance. In practical cases the differences thus caused in the apparent resistances may be considerable. On the "grid" system the a.c. resistance of the conductors is 0·251 ohm/mile at 60° F., but two of the phases have apparent resistances about 20 per cent above and below this value (see Table 2).

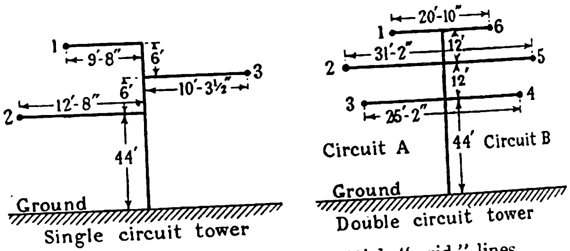

FIG. 2.—Dimensions of Scottish "grid" lines.

$S_{1,2} = 12\cdot37' = 377$ cm
$S_{1,3} = 20\cdot84' = 636$ cm
$S_{2,3} = 23\cdot73' = 724$ cm

$S_{1,2} = 13\cdot06' = 398$ cm
$S_{1,3} = 24\cdot09' = 735$ cm
$S_{1,4} = 33\cdot24' = 1\,013$ cm
$S_{1,5} = 28\cdot64' = 875$ cm

$S_{1,6} = 20\cdot83' = 636$ cm
$S_{2,3} = 12\cdot37' = 377$ cm
$S_{2,4} = 30\cdot62' = 935$ cm
$S_{2,5} = 31\cdot17' = 951$ cm
$S_{3,4} = 25\cdot17' = 774$ cm

Note.—Maximum sag of line conductor at centre of span is 21′ 6″.

Line conductor; constants and dimensions.
Stranding = 30/0·110″ diameter. Aluminium on 7/0·110″ diameter steel.
A.C. resistance = 0·251 ohm/mile at 60° F. External diameter = 0·77″ (1·955 cm).

Earth conductor; constants and dimensions.
Stranding = 12/0·110″ diameter. Aluminium on steel core, 7/0·110″ diameter.
External diameter = 0·55″ (1·397 cm).
Assume a.c. resistance of isolated earth conductor at 50 ~ = 0·629 ohm/mile at 60° F.

(*c*) *Time-phase sequence of conductor currents.*—The time-phase sequence of the conductor currents for a given spatial configuration, does not affect the phase reactance, but the effect on the apparent resistance and the impedance is important. For a single three-phase circuit there are only two possible ways of permuting the phase sequence of currents, namely, the sequences 1, 2, 3, and 1, 3, 2, and investigation shows that the direction of the power transference is opposite in the two cases (see Table 2). If for the former sequence the apparent resistance of any phase exceeds the a.c. resistance by a given amount, then for the latter sequence the apparent resistance will be less than the a.c. resistance by the same amount. For a given phase sequence the inequality of the apparent resistances makes the impedances unequal, but usually to a less degree in practical cases. For the "grid" lines the total variation in apparent impedance is only about 6–7 per cent, though the apparent resistances differ by nearly 50 per cent.

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* See Fig. 2 for dimensions of towers, etc.

† All reactances quoted are at 50 cycles unless otherwise stated.

‡ The numerical values of the apparent resistance and reactance of a conductor are the values obtained by dividing the voltage drops along the conductor which are respectively in phase with and in quadrature with the line current, by the R.M.S. value of the current.

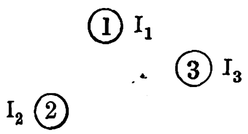
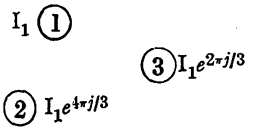
* The a.c. resistance of a conductor means herein the a.c. resistance of an *isolated* conductor under the conditions assumed. For non-magnetic conductors this is, for practical purposes, equal to the d.c. resistance, but for steel or steel-cored conductors a material difference may exist depending on the stranding, chemical composition and current density.

(ii) *With transposition* (*short and long lines*).

Regular transposition causes the interchange of power between the conductors to balance out in any phase over an integral multiple of three transpositions and makes the line electrically balanced.

TABLE 2.

Single Circuit Tower Line Constants of "Grid" System.

Configuration	Phase sequence of currents	Regular trans-position	Apparent resistance (ohm/mile)		Apparent reactance to neutral at 50~ (ohm/mile)		Apparent impedance to neutral at 50~ (ohm/mile)		Power trans-ferred to or from the phase per mile*
			Phase		Phase		Phase		kW
Asymmetrical triangular (grid system)	 $I_2 = I_1 e^{2\pi j/3}$ $I_3 = I_1 e^{4\pi j/3}$	Not†	1 2 3	0·205 0·308 0·240	1 2 3	0·654 0·660 0·686	1 2 3	0·685 0·728 0·727	+ 2·23 − 2·76 + 0·53
Asymmetrical triangular (grid system)		Not†	1 2 3	0·297 0·194 0·263	1 2 3	0·654 0·660 0·686	1 2 3	0·718 0·688 0·735	− 2·23 + 2·76 − 0·53
Asymmetrical triangular (grid system)	Any	Yes	0·251		0·667		0·711		Zero

Under such conditions the impedances of all phases are equal,‡ the apparent resistance being the same as the a.c. resistance of an isolated cable and the reactance the average of the values for the three conductor positions.

(C) DOUBLE CIRCUIT TOWERS.

(i) *Introduction.*

When two three-phase circuits are carried on the same transmission tower, the phase impedance depends on the same dimensional and electrical factors as a single circuit and, in addition, on the mutual inductance between the two circuits. In the following discussion it will be assumed (unless otherwise stated) that the two circuits are symmetrically spaced about the vertical centre line of the tower, are separately balanced and carry equal loads, which is the usual practical case.

(ii) *Phase impedance without transposition* (*short lines*).

The mutual inductance between the two circuits depends upon the time phase sequence of the conductor currents, and when neither circuit is transposed the effects are rather complicated. For any given spatial configuration and axial separation of the conductors, if the time sequence in one circuit is kept fixed, there are 6 possible ways of permuting the currents in the other circuit (see Figs. 3 (*a*), (*b*), (*c*), (*d*), (*e*), (*f*)). There are, however, only 12 possible ways of permuting the currents in *both* circuits (see Figs. 3 (*a*) to 3 (*l*)), since if the time phase of *all* the currents is advanced by any given amount (say, $2\pi/3$ or $4\pi/3$) the impedances are unaltered.

Investigation shows that these 12 arrangements only lead to 36 different impedance equations (i.e. half as many as there are conductor positions) for the following reasons:—

Ten of the arrangements (all except Figs. 3 (*d*) and 3 (*g*)) may be divided into two sets of five in which the $5 \times 6 = 30$ impedance equations are the same for each, the only difference being that in any two corresponding figures (one from each set of 5) the phase impedances of the two circuits are interchanged. Corresponding arrangements are Figs. 3 (*a*) and 3 (*j*), 3 (*b*) and 3 (*k*), 3 (*c*) and 3 (*l*), 3 (*e*) and 3(*f*), 3 (*h*) and 3 (*i*).

For the other two arrangements (viz. 3 (*d*) and 3 (*g*)) the 3 impedances of the two circuits in each figure are equal, thus giving a total of $30 + 6 = 36$ possible impedance equations.

---

* A + sign indicates a power transference to the phase considered from the other phases and *vice versa*. Current assumed is 220 amps. per phase corresponding to 50 000 kVA transmitted three-phase at unity power factor at receiving end of line.

† These values apply to short lines only.

‡ Equality in phase impedance also occurs when the 3 conductors are arranged at the corners of an equilateral triangle, but this construction is not often employed in practice.

In the general case where the conductors of each circuit are asymmetrically spaced, the numerical value of the impedances may be greater or less than that of a single circuit at similar spacings according to the phase sequence selected. At practical conductor spacings the apparent reactance in any arrangement * is approximately proportional to the logarithm of the product of the axial distances from the conductor considered to the other four carrying current of different time phase, minus twice the logarithm of the product of the radius of the conductor and the axial distance between it and the conductor carrying current of the same time phase. Since there are only *three* possible values for the latter dimension for any given conductor (conductors having currents of the same time phase being in different circuits), there are only three possible reactance values for any given conductor position (in all 12 current permutations) and only *nine* different reactances for *all* the 36 impedance equations.

The apparent resistance is equal to the a.c. resistance of an isolated conductor plus a term (due to power transference between the conductors and which may be positive or negative in sign) proportional to the logarithm of the product of the axial distances from the conductor considered to the two carrying currents $2\pi/3$ later in

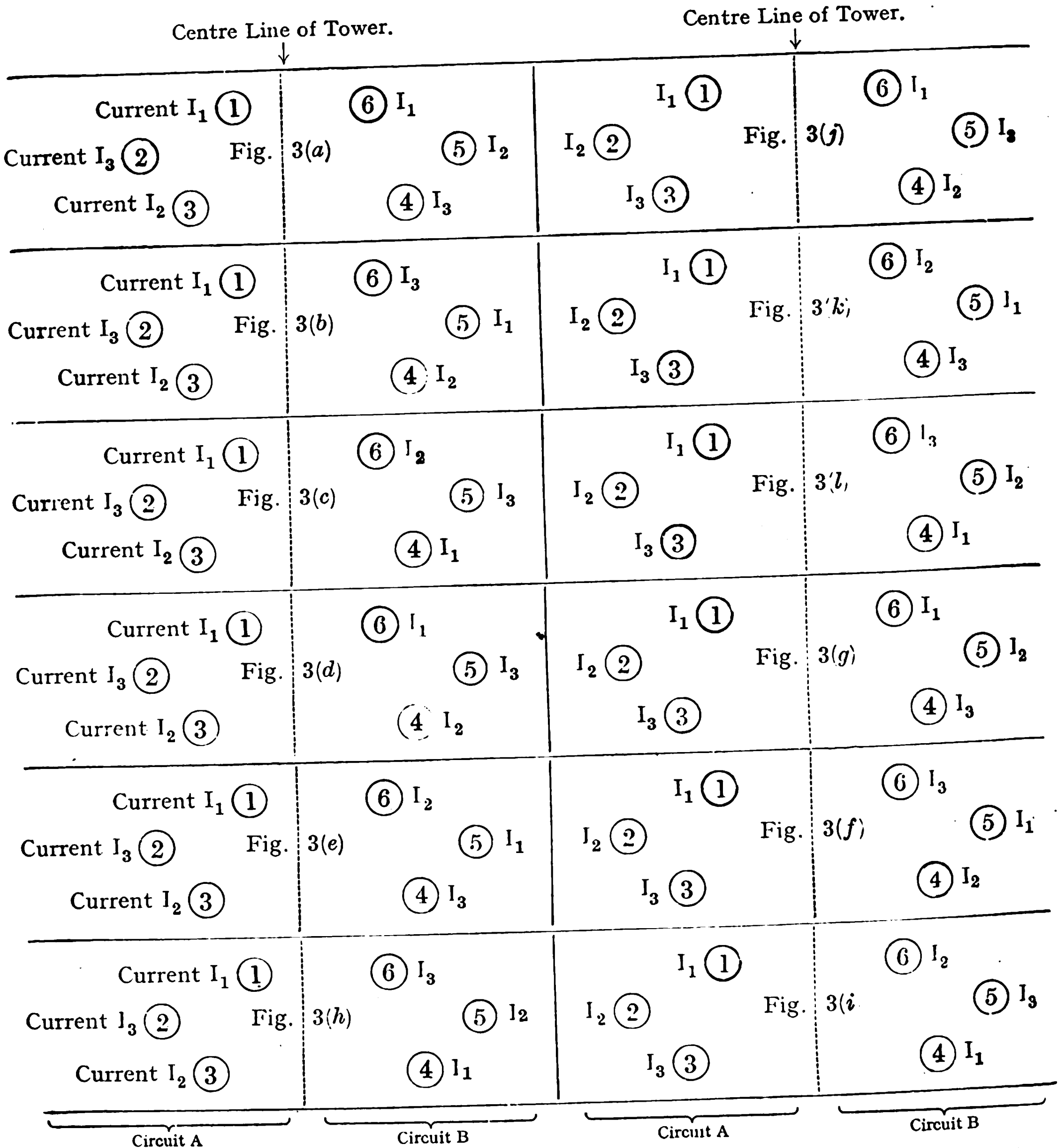

Centre Line of Tower.
Centre Line of Tower.
Current I_1 ①
Current I_3 ②
Current I_2 ③
Fig. 3(a)
⑥ I_1
⑤ I_2
④ I_3
I_1 ①
I_2 ②
I_3 ③
Fig. 3(j)
⑥ I_1
⑤ I_3
④ I_2
Current I_1 ①
Current I_3 ②
Current I_2 ③
Fig. 3(b)
⑥ I_3
⑤ I_1
④ I_2
I_1 ①
I_2 ②
I_3 ③
Fig. 3(k)
⑥ I_2
⑤ I_1
④ I_3
Current I_1 ①
Current I_3 ②
Current I_2 ③
Fig. 3(c)
⑥ I_2
⑤ I_3
④ I_1
I_1 ①
I_2 ②
I_3 ③
Fig. 3(l)
⑥ I_3
⑤ I_2
④ I_1
Current I_1 ①
Current I_3 ②
Current I_2 ③
Fig. 3(d)
⑥ I_1
⑤ I_3
④ I_2
I_1 ①
I_2 ②
I_3 ③
Fig. 3(g)
⑥ I_1
⑤ I_2
④ I_3
Current I_1 ①
Current I_3 ②
Current I_2 ③
Fig. 3(e)
⑥ I_2
⑤ I_1
④ I_3
I_1 ①
I_2 ②
I_3 ③
Fig. 3(f)
⑥ I_3
⑤ I_1
④ I_2
Current I_1 ①
Current I_3 ②
Current I_2 ③
Fig. 3(h)
⑥ I_3
⑤ I_2
④ I_1
I_1 ①
I_2 ②
I_3 ③
Fig. 3(i)
⑥ I_2
⑤ I_3
④ I_1
Circuit A
Circuit B
Circuit A
Circuit B

FIG. 3.—Diagrams showing the twelve possible permutations of the time phases of the currents in the conductors of a double circuit tower.

The conductors of each circuit are asymmetrically spaced, but the two circuits are symmetrical about the vertical centre line of the tower.

The left- and right-hand circuits on double circuit lines are termed circuits "A" and "B" respectively in Appendices II and IV.

---

* See Appendix II for mathematical expression.

time phase, minus the logarithm of the product of the axial distances from the conductor to the two carrying current $4\pi/3$ later in phase.

The power transference above mentioned takes place not only between the conductors of each circuit, but between the two circuits. The latter is usually of negligible amount in practical cases and for the "grid" system varies between zero and 2·5 kW per mile at a line current of 220 amperes R.M.S. Each phase receives power from or transmits power to each of the four conductors carrying current having a different time phase from its own. There is, however, no interchange of true power between conductors in which the currents have the same time phase, as the term in the apparent resistance due to power transference does not involve the axial dimension between them, which dimension would be involved if transformer action were occurring. It may be noted that since this dimension does enter into the apparent reactances, there is an interchange of "wattless" power between conductors carrying currents of the same time phase. The heating of the conductors is unaffected by the power transference and is equal in all phases. On single circuit lines the cost of transposition is small and involves no practical difficulties, but on double circuit lines special "transposition" towers have to be employed (at which the lines are cut and the transposition effected by means of "jumpers") in order to avoid difficulties due to the conductors touching in the span. This involves considerable expense (about £250 to £300 extra for each transposition tower on the "grid" lines) and objections have also been raised to these towers on account of unsightliness.

Transposition is customary on long lines to reduce inductive interference and to avoid large differences in the impedance voltage-drops along the different phases, but on short lines the latter effect may be negligible when taken in conjunction with the greater impedance of the transformers, and where a wide separation exists between power and communication circuits the elimination of transpositions may be practicable. For this reason it is important to know which of the twelve possible current permutations is most desirable from the standpoint of operation of the system. The three factors of primary importance are parallel operation of the two circuits, reduction of power transference between the circuits and reduction of phase impedance. For parallel operation the three impedances of the first circuit must be the same as those of the second, otherwise the load will not divide equally between them. This condition is fulfilled only by the arrangements of Figs. 3 (*d*) and 3 (*g*) in which the impedances of phases in the same horizontal plane are equal. An additional advantage is that there is no interchange of power between the circuits under these conditions.

From the standpoint of reduction of impedance the arrangements of Figs. 3 (*c*) and 3 (*l*) are the best and give, in the case of the "grid" lines, values between about 1 per cent and 3 per cent (for the different phases) lower than those of a single circuit. The total variation of impedance between the various phases is about 6 per cent [compared with about 15 per cent for Figs. 3 (*d*) or 3 (*g*)], while the maximum variation in the apparent resistances is plus or minus 17 per cent of the a.c. resistance (see Table 3). Figs. 3 (*c*) and 3 (*l*) are also favourable from the aspect of power transference between the two circuits, the amount for the "grid" system being only 0·28 kW per mile at a line current of 220 amperes, which is less than for any other arrangement except Figs. 3 (*d*) and 3 (*g*).

(iii) *Effects of transposition* (*short and long lines*).

(*a*) *Foreword.*—From a practical standpoint, transposition is of great importance and in dealing with its effects two cases have to be considered, namely, with the frequencies of transposition in the two circuits equal and unequal.

(*b*) *Circuits transposed at same frequency.*—Regular transposition makes the impedance the same in all three phases of each circuit over an integral multiple of three transpositions, *provided the two circuits are transposed in such directions as to maintain the same relative positions of conductors carrying currents of the same time phase.*

The impedance in a given case is the average of the three values applying to the separate phases of the circuit when not transposed. Since for any given spatial configuration and axial separation there are 36 different impedance equations for the 12 permutations of conductor currents *without* transposition, it follows that there cannot be more than $36/3 = 12$ different equations *with* transposition. Actually there are only eleven (see equations 15 (*a*)–(*g*), Appendix II) because in Figs. 3 (*d*) and 3 (*g*) owing to the disappearance of the power transference between the circuits, the impedances of all four circuits are the same. For the remaining 10 arrangements (i.e. all except Figs. 3 (*d*) and 3 (*g*)), the 10 impedances of one half (viz. 5 arrangements) equal those of the other half, corresponding arrangements in the two halves having their impedance equations interchanged. The impedance equations for the 12 possible current permutations (involving six different reactances and nine resistances) fall naturally into three groups as under:—

Group 1: Figs. 3 (*a*), 3 (*b*), 3 (*c*), 3 (*j*), 3 (*k*), 3 (*l*).
Group 2: Figs. 3 (*d*) and 3 (*g*).
Group 3: Figs. 3 (*e*), 3 (*h*), 3 (*f*), 3 (*i*)

In the *first group* the apparent reactances of the two circuits in any arrangement are equal, while the terms in their apparent resistances due to power transference are numerically equal and of opposite sign. There is also an interchange of power between the two circuits in each arrangement.

In the two arrangements forming the *second group*, the resistances, reactances and impedances of all four circuits are equal. There is no power transference between the circuits in either arrangement.

In the *third group* the apparent reactances of the two circuits in any arrangement are unequal. The terms in the apparent resistances due to power transference are numerically equal and of opposite sign, and there is a power interchange between the two circuits.

The chief practical aspects of transposed circuits are the same as for the non-transposed case, namely, reduction of impedance, elimination of power transference and parallel operation of the circuits. Since the arrange-

Table 3.

Double Circuit Towers. Line Constants in Different Arrangements.

Configuration	Phase sequence of currents		Transposition circuit		Frequency of transposition	Apparent resistance (ohm/mile)		Apparent reactance to neutral at 50~ (ohm/mile)		Apparent impedance to neutral at 50~ (ohm/mile)		Power transferred to or from the phase per mile*	
	Circuit A	Circuit B	A	B									
Asymmetrical triangular (grid system), see Fig. 3 (*l*)	I_1 ① Circuit A I_2 ② I_3 ③	⑥ I_3 Circuit B ⑤ I_2 ④ I_1	No†	No†	—	Phase		Phase		Phase		Phase	kW
						1	0·225	1	0·635	1	0·674	1	+ 1·25
						2	0·240	2	0·624	2	0·669	2	+ 0·52
						3	0·293	3	0·644	3	0·707	3	− 2·04
						4	0·209	4	0·644	4	0·677	4	+ 2·04
						5	0·262	5	0·624	5	0·676	5	− 0·52
						6	0·277	6	0·635	6	0·692	6	− 1·25
Asymmetrical triangular (grid system), see Fig. 3 (*d*)	I_1 ① I_3 ② I_2 ③	⑥ I_1 ⑤ I_3 ④ I_2	No†	No†	—	Phase		Phase		Phase		Zero	
						1	0·317	1	0·701	1	0·769		
						2	0·249	2	0·621	2	0·669		
						3	0·185	3	0·682	3	0·707		
						4	0·185	4	0·682	4	0·707		
						5	0·249	5	0·621	5	0·669		
						6	0·317	6	0·701	6	0·769		
Asymmetrical triangular (grid system), see Figs. 3 (*l*)	I_2 ① I_1 ② I_3 ③	⑥ I_3 ⑤ I_2 ④ I_1	Yes	Yes	Same in A and B	Circuit		Circuit		Circuit		Circuit	
						A	0·253	A	0·637	A	0·683	A	− 0·28
						B	0·249	B	0·637	B	0·681	B	+ 0·28
and 3 (*c*)	I_1 ① I_3 ② I_2 ③	⑥ I_2 ⑤ I_3 ④ I_1	Yes	Yes	Same in A and B	Circuit		Circuit		Circuit		Circuit	
						A	0·249	A	0·637	A	0·681	A	+ 0·28
						B	0·253	B	0·637	B	0·683	B	− 0·28
Asymmetrical triangular (grid system), see Figs. 3 (*g*)	I_1 ① I_2 ② I_3 ③	⑥ I_1 ⑤ I_2 ④ I_3	Yes	Yes	Same in A and B	0·251		0·671		0·716		Zero	
and 3 (*d*)	I_1 ① I_3 ② I_2 ③	⑥ I_1 ⑤ I_3 ④ I_2	Yes	Yes	Same in A and B	0·251		0·671		0·716		Zero	
Asymmetrical triangular (grid system)	See Fig. 3 (*l*) above		Yes	Yes	$B = \frac{1}{3}A$	0·251		0·654		0·700		Zero	

For dimensions of towers and line conductors, see Fig. 2.

* A + sign indicates a power transference to the phase considered from the other phases and *vice versa*. Current assumed is 220 amps. per phase corresponding to 50 000 kVA transmitted three-phase at unity power factor at receiving end of line.

† These values apply to short lines only.

ments of Figs. 3 (*d*) and 3 (*g*) are the only ones in which the two circuits have equal impedances when transposed at the same frequency,[*] strictly speaking these are the only cases in which the load will divide equally with parallel operation, but at practical conductor spacings the inequalities arising from this cause in *any* of the arrangements are usually negligible. On the "grid" lines the impedance in the above two cases is about 2 per cent greater than for a single circuit at similar spacings (see Table 3). Respecting reduction of impedance, clearly this reduction will be greatest for the same arrangements as when the conductors are not transposed, viz. Figs. 3 (*c*) and 3 (*l*). For these arrangements the impedance for the "grid" system is about 3 per cent less than that of a single circuit at similar spacings, while the power transference between the circuits is only 0·28 kW per mile and, therefore, of no importance.

(*c*) *Circuits transposed at different frequencies.*—There is only one important case, namely, when the frequencies of transposition in the two circuits are in the ratio 3 : 1. Under such conditions the effects of mutual inductance between the circuits balance out over an integral multiple of three transpositions of the circuit having the lower frequency of transposition. The line constants are then the same in all six phases and equal to that of a single transposed circuit at similar spacings, irrespective of the phase sequence of conductor currents. For practical cases this method of transposition has no advantages over those of Figs. 3 (*d*) and 3 (*g*) and is inferior to those of Figs. 3 (*c*) and 3 (*l*), when the frequency of transposition in the two circuits is the same.

(D) CONSTRUCTION OF CONDUCTOR.

The construction of a conductor affects both its resistance and reactance. In non-magnetic conductors the only important effect is that due to stranding which increases the resistance by one or two per cent and decreases the reactance by a like amount at close conductor spacings, i.e. a few feet. At the wide spacings commonly used on high-voltage lines (such as the "grid" system) the effect of stranding on the reactance is only a fraction of one per cent, and for practical purposes may be ignored. In aluminium conductors with steel cores the spiralling of the strands produces an axial field which tends to increase the self-inductance, but the higher resistivity of the steel reduces the current density in the core and thus the linkages and the two effects partly or wholly neutralize. With only one layer of aluminium over the steel the solenoid effect is the greater, and a net increase of inductance results which may reach 17 per cent, depending on the current density. With two or more layers spiralled in opposite directions the reverse is the case, and a net decrease of about 5 per cent at three-feet spacing occurs compared with the inductance of a non-magnetic conductor of similar stranding and overall diameter. The extra cross-section afforded by the steel tends to reduce the resistance by 1 per cent or 2 per cent, but the hysteresis and eddy-current loss set up in the steel by the axial field above mentioned may increase the loss by many times this amount, depending on the frequency and current density. With a single layer of aluminium, the a.c. resistance at high-current densities may be 25 per cent greater than at low values, while for three-layer conductors the increase may be 20 per cent. For double-layer conductors, the increase is negligible and the a.c. resistance may be taken as equal to the d.c. resistance (at commercial frequencies and current densities).[*]

III. POWER LOSSES (SHORT AND LONG LINES).

On a short line the sending and receiving end currents are substantially equal in magnitude. The power loss is then equal to the product of the square of the (R.M.S.) line current and the a.c. resistance (of an isolated conductor), and is thus directly proportional to the length of line and independent of transposition, line voltage, power factor, etc.[†] On long lines regularly transposed (which is the only practical case) the losses are no longer directly proportional to the length of the line, but depend in a complicated way on the resistance, impedance and admittance per unit length, the load current and the receiving-end power factor and voltage. It is usual in such instances to determine the power losses as the difference between the power at the sending and receiving ends,[‡] but this is an indirect and not very accurate method and the authors have, therefore, developed a single expression from which the losses may be determined directly[§] from the receiving-end conditions and length of line, etc.

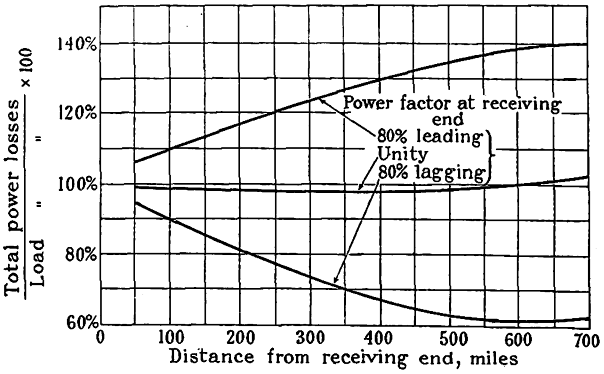


FIG. 4.—Curves showing the relation between the ratio (Power losses)/(Load power losses) and distance from receiving end of line at full load current 220 amps. for "grid" lines.

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[*] It may be noted that for the sequence of Figs. 3 (*d*) and 3 (*g*) the two circuits in either arrangement are transposed in opposite directions of spiral, while for Figs. 3 (*c*) and 3 (*l*) the directions are the same.

[*] In some agricultural districts galvanized steel conductors have been used for the transmission of small amounts of power. For such conductors, hysteresis and eddy-current losses greatly increase the ratio of

$$\frac{\text{a.c. resistance}}{\text{d.c. resistance}}$$

while the non-uniform current distribution over the cross-section makes the internal reactance (which is usually negligible in non-magnetic conductors) greater than the external reactance, at practical spacings. These constants moreover vary widely according to the chemical composition and must be determined experimentally. See WALTON, Bib. Ref. No. 34, for typical figures.

[†] The error in estimating the losses at full load on the "grid" system for a line 50 miles long due to neglecting capacitance is substantially zero at unity power factor and about 6 per cent for 0·8 leading or lagging. For a line 100 miles long the errors are zero and about 9·5 per cent respectively. See Table 1 and Fig. 4. At one-half full load the percentage error on a 50-mile line is about 12 per cent at 0·8 power factor lagging.

[‡] Assuming the leakage conductance to be zero.

[§] See Appendix II, equation (21).

The capacity current may increase or decrease the "load" losses (i.e. the losses due to the load current alone) depending on the power factor at the receiving end and length of line.

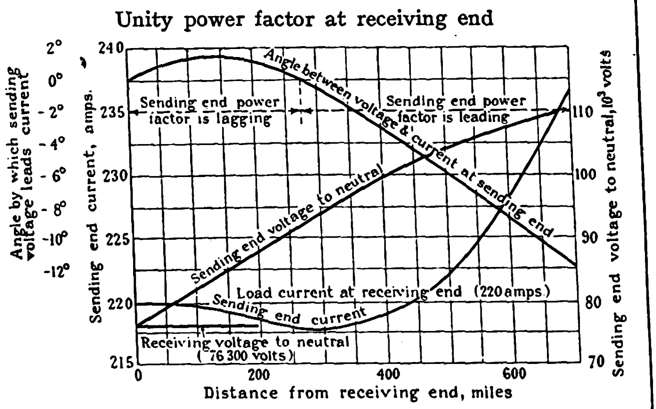

FIG. 5.—Curves showing the variation in magnitude of the sending-end current and voltage, and in the angle between the latter quantities, with distance from the receiving end for the "grid" system at full-load current 220 amperes at receiving end. (Receiving voltage to neutral maintained constant at 76 300 volts.)

If the power factor is lagging the charging current neutralizes part of the lagging component and thus decreases the absolute value of the current at a given point, upon which the losses depend. As the length of line increases, the percentage reduction increases up to a certain length, after which there is a rise again.* By similar reasoning the losses for a leading power factor at the receiving end are always greater than the load losses alone.

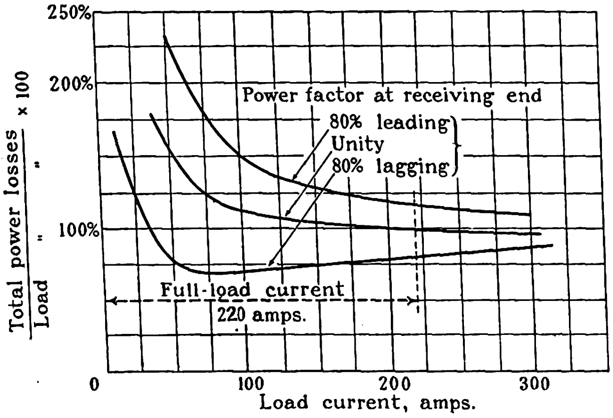

FIG. 6.—Curves connecting $\frac{\text{Power losses}}{\text{Load power losses}}$ with load current for "grid" lines on a length of 200 miles.

At unity power factor it is usually stated † that the losses are necessarily increased, but this is incorrect. Investigation shows that on the "grid" lines the absolute value of the sending-end current decreases slightly (at full load) as the distance from the receiving end increases from 0 to 300 miles, where the current has a minimum value. The current then rises again until the sending- and receiving-end currents are equal at a line length of 440 miles, after which the sending-end current rises rapidly with increasing length of line (see Fig. 5).

For this reason the full load losses at unity power factor are *less* than the losses due to the load current alone for any length of line up to about 620 miles (see Fig. 4).

The line losses are increased by raising the line voltage, but not in proportion. In the above example on a 500-mile line raising the line voltage from 132 kV to 220 kV increases the full load losses by 11 per cent, 32 per cent and 40 per cent for receiving-end power factors of 0·8 lagging, unity and 0·8 leading respectively.

In most cases arising in this country the error introduced in the losses by neglecting the line capacitance, will be less (except at very light loads, see Fig. 6) than that with which the fundamental constants of line resistance and reactance are known.

IV. IMPEDANCE OF A LINE CONDUCTOR AND EARTH RETURN.

(A) INTRODUCTION.

On a three-phase transmission line the magnitude of the short-circuit current flowing when one phase is accidentally earthed, depends wholly or in part on the impedance of the earthed phase and earth return.

Two practical cases arise in which the effects are materially different, namely, with and without an earth conductor bonded to the towers. The principal functions of the earth conductor are as follows:—

(*a*) A protection against lightning discharges.
(*b*) A protection against the results of mechanical failure of the live conductors.
(*c*) A means of reducing inductive interference in communication circuits.

For the requirements of electrical protection a conductor of relatively small cross-sectional area would suffice, but should a mechanical failure of a line conductor occur the mechanical stresses would have to be transmitted to adjacent towers, and this factor determines the mechanical strength required.

The reduction obtained in inductive interference depends upon the percentage of the short-circuit current in the earthed phase which can be shunted through the earth conductor back to the supply. This is to some extent a matter of the relative impedances of the earth and earth conductor, so that it is advantageous for the latter to have a low impedance.

In the past only the first two of the three above-mentioned uses of an earth conductor appear to have been fully recognized, and the dimensions of the conductor have been based on considerations of mechanical strength alone. This has resulted in the frequent use of steel earth conductors, a construction which, as we shall show, is disadvantageous from the standpoint of interference.

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* At 0·8 power factor lagging the ratio of the $\frac{\text{Total losses}}{\text{Load losses}}$ is a minimum on the grid lines at a line length of 650 miles (see Fig. 4).

† E.g. NESBIT: Bib. Ref. No. 1.

(B) IMPEDANCE WITHOUT EARTH CONDUCTOR.

When no earth conductor is employed the impedance of the line and earth depends upon the following factors:

(*a*) Conductivity and dimensions of the line conductor.
(*b*) Supply frequency.
(*c*) Electrical resistivity of the earth.
(*d*) Impedance of earth plates and fault connection.

(*a*) and (*b*) are determined by considerations outside the present scope and are thus, in this instance, not controllable factors. It may be noted, however, that the impedance is reduced by decreasing the resistance of the line conductor and/or increasing its overall diameter. Increase of frequency increases both resistance and reactance and on the grid system the impedance is roughly proportional to frequency. For example (assuming an earth resistivity of 20 000 ohms/centimetre cube) the impedance values are 1·25 ohms/mile and 0·69 ohm/mile at 50 cycles and 25 cycles respectively (see Table 4). The effect of increasing the earth resistivity is to increase the reactance and thus the impedance, but the effects are small in practice. In the case last quoted a variation in resistivity from 500 ohms/centimetre cube to 20 000 ohms/centimetre cube, which covers most practical cases, only causes a variation in impedance from 1·07 to 1·25 ohms/mile at 50 cycles (see Table 4). The impedance will also obviously increase with increase in resistance of the earth plates and fault connections. In practice this factor may be neglected as this leads to an over-estimate of the fault current and its inductive effects, which is an error on the safe side. It may, however, readily be taken into account, if desired, in instances where the values are known.

TABLE 4.

Effect of Resistivity of Earth and Supply Frequency on Impedance of Line Conductor and Earth Return.

Single Circuit Towers "Grid" System.

Earth resistivity, ohms per cm cube	Impedance in ohms per mile of line conductor and earth					
	Without earth wire in parallel with earth			With earth wire in parallel with earth		
	50 ~	40 ~	25 ~	50 ~	40 ~	25 ~
20 000	1·25	1·02	0·688	1·06	0·894	0·638
10 000	1·22	0·995	0·672	1·05	0·880	0·628
5 000	1·18	0·969	0·654	1·03	0·865	0·614
1 000	1·10	0·908	0·620	0·993	0·832	0·590
500	1·07	0·883	0·602	0·975	0·820	0·573

The above figures refer to a short-circuit to earth on the middle phase of a single circuit tower on the Scottish grid lines. See Fig. 2 for dimensions of towers and line and earth conductors.

It is interesting to note that the impedance is, for all practical purposes, independent of the height above earth of the earthed phase.

(C) IMPEDANCE WITH EARTH CONDUCTOR.

(i) *Introduction.*

When an earth conductor is employed, the impedance of the line conductor and return path (through the earth and earth wire in parallel) depends on the same factors as in the previous case, the effects being in general similar and of the same order of magnitude (see Table 4). In addition, the impedance depends upon the location of the earth conductor and fault phase with respect to each other and the earth, on the impedance of the earth conductor, and on the magnitude of the resistance between the earth wire and earth at each tower. We shall first deal with the case where the earth wire is insulated from earth except at the fault and the generator end of the line (see Fig. 7).

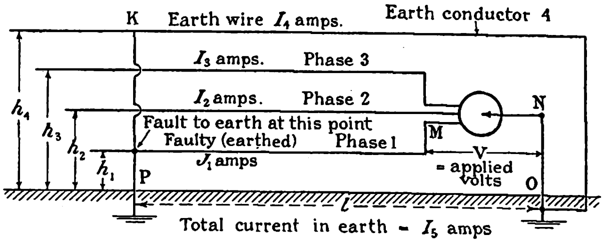

FIG. 7.—Explanatory diagram in connection with the calculation of the impedance of an overhead line with earth return. (See Appendices III and IV (2).)

Total current in earth = I_5 amperes.
Short-circuit current J_1 = earth current + earth wire current = $I_5 + I_4$.

(ii) *Impedance without "multiple" earthing.*

It is usual for the earth conductor to be situated at the top of the tower, and its position and those of the phase conductors are decided upon for mechanical and other reasons outside the present scope. The influence of the location of the earth and line conductors reduces, therefore, in a practical case to a variation of impedance according to which phase is earthed. For a given position of the earth conductor the impedance decreases as the height above earth of the earthed phase increases, but the effect is small and only amounts to 3 per cent for the "grid" lines (see Table 5).* This factor also causes a small variation in the percentage of the short-circuit current which returns via the earth. For the example already quoted this percentage varies 5 per cent between the top and bottom phases (see Table 5).

The impedance of the earth conductor is a factor of much greater importance. The magnitude of the effect depends upon the value of the impedance of the line and earth return compared with that of the rest of the circuit in which the fault occurs. This in turn partly depends on the location along the line at which the phase is earthed.

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* In the practical example shown in Table 5, the horizontal distances of the three line conductors from the vertical centre line of the pole vary slightly so that there are two variables, but the effects are similar in a theoretical case in which the above-mentioned horizontal distances are equal.

Two extreme cases will be considered as follows:—

(*a*) When the impedance of the line and earth is negligible compared with that of the transformers, etc.

(*b*) When the impedance of the line and earth is the principal impedance.

All other cases lie between these two extremes. Under condition (*a*) above, the magnitude of the short-circuit current in the earthed phase is independent of the impedance of the line and earth and may, therefore, be assumed constant. The percentage of this current returning via the earth which determines the amount of interference, depends on the relative magnitudes of the impedance of the earth conductor and the earth. Interference will obviously be a maximum when the earth conductor has infinite impedance (i.e. is absent), while if the impedance of the earth conductor could be made zero there would be no appreciable interference. These effects are illustrated in the case of the "grid" lines by curve A (Fig. 8) and Table 6. Ordinates to this curve are proportional to the percentage of the total short-circuit current (in the earthed phase) which returns via the earth, and it will be seen that the impedance of the earth conductor exerts a material effect. Point "x" corresponds to the particular size of steel-cored aluminium earth conductor to be employed in this country, and it will be seen that this reduces the interference by about 34 per cent. If the cross-section is increased about 2·5 times (which corresponds to making the earth conductor the same size as the phase conductors) a further reduction of 8 per cent is obtained (point "y"), but further increasing the conductivity of the earth conductor 4·3 times only reduces the interference by another 4 per cent (point "z"). The reason why a given increase in conductivity of the earth wire does not give a proportionate reduction in interference is that the impedance of the latter depends not only on its resistance and self-inductance, but also on the amount of mutual inductance from the earthed phase, and under practical conditions the latter is the controlling factor. Under the other extreme condition, namely (*b*) above, the impedance of line and earth determines the magnitude of the short-circuit current. In this case the percentage of this current shunted via the earth conductor is the same as before (other things being equal), but the net reduction in interference is less because an increase in conductivity of the earth conductor also increases the short-circuit current in the earthed phase. To obtain a measure of the interference it is necessary, therefore, to multiply the percentage of the total short-circuit current which passes through the earth by the ratio of the impedance of the line conductor and earth alone to that of the line conductor, earth and the particular earth wire employed. For the "grid" lines, the result is given by point x', Curve B (Fig. 8) and Table 6, which shows that about 78 per cent of the total current now returns through the earth compared with 66 per cent before.

TABLE 5.

Effect of Height of Conductor on Impedance of Line Conductor and Earth Return (assuming Resistivity of Earth as 10 000 *ohm/cm cube).*

Single Circuit Towers "Grid" Lines.

Approximate mean height of line conductor above earth cm	Impedance at 50 ~ in ohms/mile of line conductor and earth return (earth wire in parallel with earth)	$\frac{\text{Current in earth wire} \times 100}{\text{Total short-circuit current}}$
		Per cent
Top phase, 1 370	1·03	38·8
Middle phase, 1 190	1·05	35·6
Bottom phase, 1 005	1·06	33·2

It is evident that although increasing the conductivity of the earth wire always decreases the amount of interference, yet a limit in dimensions is soon set by economic considerations.

For these reasons, to obtain further reduction in interference on the "grid" lines it would be more economical to employ 2 earth conductors in parallel one above and the other below the phase conductors, the second being, say, of the same cross-section as the present earth wire, as this would reduce the interference by perhaps 55 per cent compared with a total reduction of about 46 per cent if the cross-section of aluminium of the present single earth conductor wire were increased even *10·5 times*.

For any given set of conditions (i.e. line voltage, spacing and height of conductors, etc.) there would be an optimum position for the second earth wire to give maximum reduction in interference, which position could readily be calculated by the present methods. The ultimate choice of position would, however, also have to take into consideration other variables such as cost, possible dangers from flash-overs due to swaying of wires, ground clearance, etc. Up to the present, no instances of this kind have arisen in this country.

The figures given above are based on an assumed earth resistivity of 20 000 ohms/centimetre cube, and to cover the range of 20 000–500 ohms which includes most practical cases, curves C and D have been drawn in a similar way to A and B respectively, but for 500 ohms/centimetre cube, which increases the percentage current returning through the earth in a given case. It may be said that the percentage of short-circuit current carried by the "earth" conductor on the "grid" system may vary in practice between about 18 per cent and 34 per cent, depending on the earth resistivity and the impedance of the transformers, etc., connected to the line.

(iii) *Effect of "multiple" earths.*

The fact that the earth conductor is connected to earth at each tower introduces some additional features.

The authors' tests on the Bedford–Little Barford section (9 miles long) of the "grid" lines show that under usual conditions the effect of these intermediate earths is to cause a large current to flow in the earth conductor (as much as 70–90 per cent of the total short-circuit current) at the ends of the section of the line under short-circuit. As the centre of the section is approached this current decreases rapidly to the value which would be obtained were the intermediate earths absent (see Fig. 9). Under usual conditions this effect does not reduce the interference compared with the case previously considered by more than a few per cent and may from a practical standpoint be ignored.

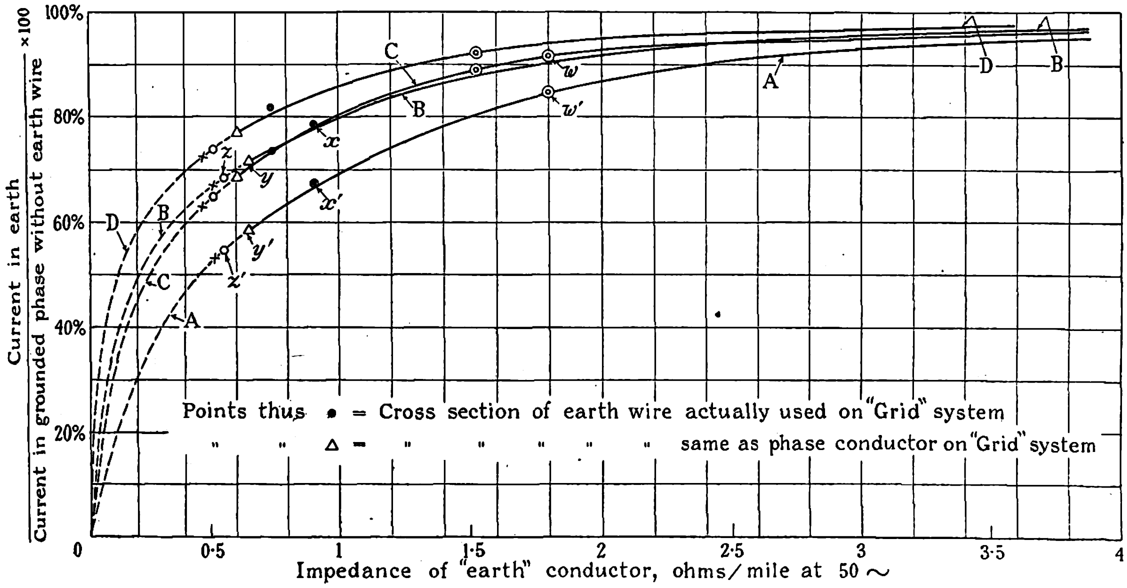

FIG. 8.—Curves showing how the percentage of total short-circuit current passing through the earth under fault conditions varies with the impedance of the earth conductor employed. (For explanation of points, see Table 6.)

For curves A and C.—It is assumed that the impedance of the line conductor and return path via the earth and earth wire in parallel is negligible compared with the impedance of the transformers, etc.

For curves B and D.—It is assumed that the impedance of the line conductor and return path via the earth and earth wire in parallel is the principal circuit impedance.

TABLE 6.

Explanatory Table for Fig. 8.

Dimensions of earth wire			Curves A and B Earth resistivity=20 000 ohms per cm cube			Curves C and D Earth resistivity=500 ohms per cm cube			Notation of point
Stranding		Aluminium section, sq. in.	Impedance in ohms/mile at 50 ∼	Earth current / Total current per cent		Impedance in ohms/mile at 50 ∼	Earth current / Total current per cent		
Aluminium	Steel			A	B		C	D	
120/·170	7/·170	2·66	0·514	52·4	66·9	0·475	62·5	72·4	×
54/·170	7/·170	1·20	0·557	54·4	68·9	0·522	64·3	74·0	o
30/·110	7/·110	0·279	0·644	58	71·2	0·610	67·6	76·6	Δ
12/·110	7/·110	0·114	0·906	66·5	78·4	0·762	74·4	81·7	·
6/·0935	1/·0935	0·0404	1·8	84·6	90·5	1·53	88·6	92·2	⊙
6/·059	1/·059	0·0164	3·84	95·7	97	3·54	96·5	97·5	(See footnote *)

Points thus · = cross-section of earth wire actually used on "grid" system.
Points thus Δ = cross-section of earth wire same as phase conductor in "grid" system.

[*] To avoid confusion the notation points have been omitted from the curves.

The magnitude of the effect depends chiefly upon the effective "earth plate" resistance at the fault and end of the line, and the manner in which the earth conductor is in electrical connection with the return path of the current. In Appendix III some formulæ † are given for the case where the fault occurs at a tower, that is the earth conductor is directly connected to the return path of the current, while the earth current proper must flow through the earth plate resistance at the fault tower.

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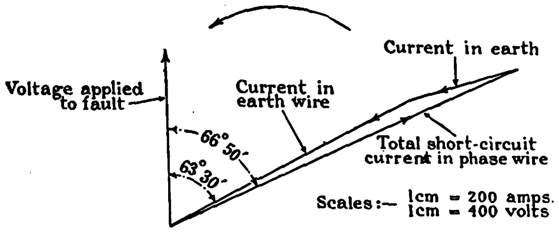
† These formulæ are in close agreement with the authors' tests above mentioned.

It is clear, however, that a general treatment is difficult owing to the number of ways in which a fault may occur. Fortunately, however, as already mentioned, the effect is not usually of great importance even in the case treated herein mathematically, which should give a large effect. With very short lines of a few kilometres or in the case of a fault close to a generating station the effect may indeed be large. Accordingly, it is desirable that the earth conductor should be capable of carrying the majority of the short-circuit current in order to avoid failure should such conditions arise.


Voltage applied to fault
Current in earth wire
Current in earth
66°50'
63°30'
Total short-circuit current in phase wire
Scales:— 1cm = 200 amps. 1cm = 400 volts

Vector diagram of observed currents and voltages at point X on curve below

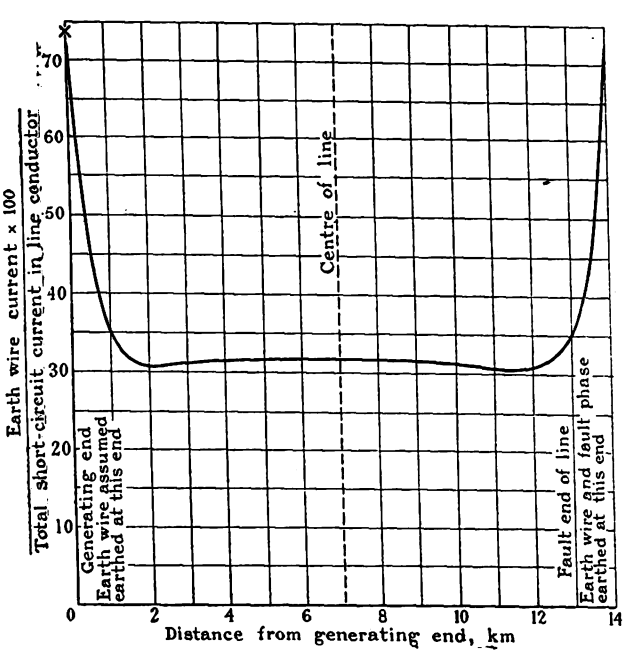


FIG. 9.—Calculated curve showing how the percentage of short-circuit current (in line conductor earthed at 14 km from generating end) flowing in the "earth" wire varies with the distance from generator end on the Bedford–Little Barford "grid" lines. Earth wire earthed at all intermediate towers, which were spaced 900 feet apart. Check point on curve where power measurements were made marked thus ×. For tower dimensions, see Fig. 2.

The most important feature of the "multiple" earthed earth wire from an impedance and interference point of view is that it ensures that there shall be an earth on the earth conductor near the fault wherever the latter may occur on the system.

V. CONCLUSIONS.

(A) POWER LOSSES.

Owing to the well-known fact that the magnitude of the current in a transmission line varies from point to point, the power losses are different from the losses due to the load current alone. The influence of the charging current on the losses is most pronounced when the load current is small or the line very long, but no serious error is involved in neglecting its effects on the "grid" system for lines up to about 50 miles in length and carrying currents above about half full load. Lines of greater length than this which are fed entirely from one end will seldom arise in this country. For such short lines, although the percentage errors in the losses at smaller currents than the above (due to neglecting the line capacitance) become relatively large, yet the losses, being proportional to the square of the R.M.S. currents, are themselves small, so that this is not important.

For practical purposes in this country, the losses (except at very small loads) may therefore be taken as independent of transposition, etc., and dependent only on the R.M.S. value of the load current and the a.c. resistance of the line conductor.

For long lines (regularly transposed) the authors' formula (equation 21) gives the losses directly when the line constants and receiving-end conditions are known.

(B) IMPEDANCE AND INTERFERENCE UNDER NORMAL WORKING CONDITIONS.

Regular transposition of conductors * makes the lines electrically balanced, equalizes the phase impedances and reduces the amount of interference under normal working conditions. It is well known that to obtain the maximum reduction in interference, the points of transposition of the power and communication circuits must be co-ordinated. On single circuit lines transposition involves little, if any, practical difficulty or extra cost and there is *every reason for its general adoption.*

On double circuit lines, transposition involves the use of special "transposition" towers and additional expense and ought, therefore, to be avoided whenever possible. On "long" lines (fed entirely from one end) transposition appears essential, both on account of inductive interference and to avoid large inequalities in the impedance voltage-drop of the conductors. On "short" lines the latter effect may often be negligible compared with the impedance of the transformers and when, in addition, *the interference with communication circuits due to normal* † *operating currents and voltages is also negligible,* transposition is unnecessary.

As already mentioned, lines exceeding about 50 miles in length fed from one end alone, will seldom occur in this country, and for such double circuit lines no definite rules can be laid down regarding transposition. Each case must be judged on its merits with the power and communication authorities in co-operation, the deciding factor being the importance or otherwise of induction from normal operating currents and voltages of the power circuit. Whether transposition is adopted or not, the best results are obtained from the standpoint of operation when the time-phase sequence of currents in the two circuits are co-ordinated. For transposed lines the circuits should be transposed at the same frequency and, to derive the maximum reduction in phase impedance due to mutual inductance between the two power circuits, the time-phase sequence of currents should be such that the top conductor of each circuit carries a current of the same time phase as the bottom conductor of the other circuit (see Figs. 3 (*c*) and 3 (*l*). Under these conditions the two circuits must be transposed in the same direction of spiral.

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* For double circuit lines, the directions of transposition of the two circuits must be such as to maintain the same relative positions of conductors carrying currents of the same time phase.

† In practice, the effect of transposition on the interference arising under short-circuit conditions is unimportant.

The impedances of the two circuits are then slightly different (unless the outer conductors of each circuit are symmetrical about their middle phase) but in practice the amount of difference is usually so small that a negligible difference in loading occurs with parallel operation. For both circuits the impedances are less than for a single circuit at similar spacings. If the circuits are not transposed the choice of phase sequence lies between that given above which gives minimum impedance, and that in Figs. 3 (*d*) or 3 (*g*), for which conductors in the same horizontal plane have equal impedances, and therefore equal loading of the two circuits takes place with parallel operation. The final choice between the two depends to some extent on the particular spacing, etc., employed. For the "grid" lines the arrangements of Figs. 3 (*c*) and 3 (*l*) are superior to Figs. 3 (*d*) and 3 (*g*), the difference of loading in the former case being unimportant, and the phase impedances, and the differences between them, smaller.

(C) IMPEDANCE AND INTERFERENCE UNDER FAULT CONDITIONS.

Accurate methods are now available for the determination of the short-circuit currents in the line and in the earth under fault conditions both with and without "multiple" earthing of the earth conductor.

When no earth wire is employed, the impedance of the line conductor and earth return is substantially constant all along the line and independent of which phase is earthed or the height of the conductors above earth. This arrangement is disadvantageous from the standpoint of interference, as all the short-circuit current returns via the earth and the voltages induced in earthed conductors of communication circuits are proportional to this current.*

When an earth conductor is employed,† part of the short-circuit current is shunted and the earth current reduced. With the usual construction in which the earth wire is at the top of the towers, the impedance of line and earth (without "multiple" earthing of the earth wire) is still substantially constant all along the line, but now decreases slightly with increasing height of the earthed phase above earth (3 per cent at 50 cycles on the "grid" lines between top and bottom phases). This results in the earth current being slightly less for an earth on the top phase than at the middle or bottom. (For the "grid" lines the maximum difference is 5 per cent at 50 cycles).‡

The percentage of short-circuit current returning through the earth decreases with decrease in impedance of the earth wire, but not in proportion, the reduction obtained falling off rapidly after a certain size of conductor is reached. The reduction obtained also depends upon the relative magnitudes of the impedances of the line and earth and that of the transformers, etc., in circuit with the faulty phase. On the "grid" lines (with the particular steel-cored aluminium conductor to be employed in practice) the earth wire reduces the earth current by between about 18 per cent and 34 per cent, depending on the earth resistivity and the impedance of other apparatus connected to the line. If the cross-section of the wire is increased about 10·5 times, the reduction is only increased about 12 per cent, so that after a certain point the extra reduction in earth current obtained is out of all proportion to the increased cost of the earth conductor.

If a still greater reduction in interference is desired, then it is more economical to employ a second earth wire (suitably positioned below the phase conductors for the "grid" system) than further to increase the cross-section of the first.

On existing American systems the earth wire has in the past usually been made of steel, but this is not the best construction on account of the high a.c. resistance and internal self-inductance of wires of this material.

The best practice is undoubtedly the use of a steel-cored aluminium earth wire, as this meets the requirements of high mechanical strength, high electrical conductivity, and protection from corrosion.

The above conclusions remain, on the whole, unmodified even when the effects of "multiple" earthing of the intermediate towers (between the fault and supply ends of the line) are taken into account, as the percentage of total short-circuit current returning through the earth wire is not materially affected except near the ends of the section under short-circuit. At these points the earth wire current may be a large percentage of the total (viz. 70 per cent in the example in Fig. 9), but it rapidly decreases, as the centre of the section is approached, to the value which would be obtained were the "intermediate" earths absent. Unless the short-circuited section is very short (of the order of 1 or 2 kilometres on the "grid" lines) the reduction in earth current is, on the average, only a few per cent and for practical purposes may be neglected, as this leads to a slight over-estimate of the inductive effects.

From the standpoint of interference the main benefit to be derived from "multiple" earthing is that it ensures the "earth" wire being "earthed" in the immediate vicinity of a fault (to earth) *wherever it occurs on the system*. The whole short-circuit current can then never pass *entirely* through the earth for a distance greater than that from the "fault" to the nearest tower on the return route, and for this reason "multiple" earthing is advocated.

The authors desire to acknowledge indebtedness to Mr. E. B. Wedmore, and to Dr. E. H. Rayner, Dr. A. H. M. Arnold, and Mr. R. O. Kapp for valuable criticism and suggestions received during the preparation of the Report.

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* Interference due to this cause is obviously unaffected by transposition of the line conductors.

† Assumed earthed at each tower.

‡ Transposition reduces the possibility of any such difference.

INTRODUCTION TO APPENDICES.

The following Appendices give the mathematical theory and methods of calculation of the quantities discussed in the preceding pages. Some experimental data from the authors' tests on the impedance of a line conductor and earth return are also included. Numerical examples for the 132-kV "grid" towers are worked out in detail.

Symbols (Appendix I). Appendix I gives a list of the principal symbols used.

Impedance and Copper Losses (Appendix II). In Appendix II formulæ are derived for the impedance and power loss of a line conductor without earth return, i.e. under normal working conditions.

Impedance with Earth Return (Appendix III). In Appendix III formulæ are deduced for the impedance of a line conductor with a return circuit via the earth alone or via an earth conductor and the earth in parallel. These conditions apply when one phase is accidentally earthed.

Working Formulæ (Appendix IV). Appendix IV gives working formulæ for the impedance of a conductor with or without earth return. The formulæ are applied, in illustration, to the 132-kV "grid" system.

Bibliography (Appendix V).

APPENDIX I.—SYMBOLS.

The following is a list of the principal symbols used:—

A_1 and A_4 are constants defined in Appendix III.

b = outside radius in cm of stranded conductor.

B = induction density in absolute units.

E = electric force in absolute units.

$\Delta E_1, \Delta E_2, \Delta E_3$ = impedance voltage-drops per cm along Phases 1, 2 and 3 when carrying currents I_1, I_2, I_3 respectively.

E_s = sending-end voltage to neutral.

E_r = receiving-end voltage to neutral.

Δe_1 = potential-drop per cm along Phase 1 when carrying a short-circuit current J_1.

Δe = potential-drop in earth when carrying current I_5.

f = frequency in periods per second.

G = leakage conductance per unit length of a short-circuited section of the line, equivalent to the effect of intermediate (or "multiple") earthed towers.

$= R'_i l_0$.

h = height in cm of conductor above earth.

h_1, h_2, h_3, h_4 = heights in cm of phase conductors 1, 2, 3 and earth wire respectively above earth.

H_0 and H_1 = Bessel functions defined in Appendix III.

i = current density in the earth in absolute units.

$I_r = \mathfrak{J}_1 \pm j\mathfrak{J}_2$ = receiving-end current.

I_l = current at distance "l" from receiving end.

I_1, I_2, I_3 = currents in conductors 1, 2 and 3 respectively.

I_4, I_5 = currents in earth wire and earth respectively.

J_1 = short-circuit current in Phase 1.

$K = 2\pi\sqrt{(f/u)}$.

$K_1 = K\sqrt{2}$.

l = length in cm between neutral of generator and point where Phase 1 is earthed.

l_0 = length in cm between consecutive towers.

l_1 = length of line between receiving end and point considered.

L = self-inductance of earth per unit length in absolute units.

L' = inductance of earth plate and fault connection in absolute units.

L_1, L_2, L_3 = self-inductance in henrys per cm to neutral of Phases 1, 2 and 3 respectively.

M = coefficient of mutual inductance between conductors ($M_{1,4}$ indicates the mutual inductance coefficient between the conductors in Positions 1 and 4) in henrys per cm.

R = resistance of earth per unit length in absolute units.

R_K = a.c. resistance in ohm/cm of phase conductors when isolated.[*]

R_{KM} = a.c. resistance in ohm/mile of phase conductors when isolated.

R_{Ka} = a.c. resistance per cm in absolute units of phase conductors when isolated.

R' = a.c. resistance in abohms of earth plate and fault connections at fault towers (or towers).

R'_i = a.c. resistance in abohms of earth plates at intermediate towers (i.e. towers other than those at each end of the short-circuited section).

R_4 = a.c. resistance of earth wire per cm length in abohms when isolated.

R'_4 = a.c. contact resistance of earth wire connections, in abohms.

r_4 = outside radius of earth conductor, cm.

ρ = distance of a point from axis of line conductor, cm.

u = specific resistance of earth in absolute units.

$S_{,1,4}$ etc. = distances in cm between conductors 1 and 4, etc.

t = time co-ordinate.

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[*] For a non-magnetic conductor the a.c. and d.c. resistance for practical sizes and frequencies, etc., are sensibly equal. This also applies to steel-cored conductors having two oppositely spiralled layers of wires over the cores. For steel conductors or steel-cored conductors with one or three layers over the core, the a.c. resistance may be 25 per cent greater than the d.c. value. See Section III (*c*).

$\omega = 2\pi f$.

γ = Bessel's constant 1·7811. . . .

Y = vector admittance per unit length of line.

$= (g + jc)$, where g = leakage conductance per unit length, and c = capacity susceptance per unit length.

Z = vector impedance per unit length of line.

$= (R_{KM} + jx)$, where R_{KM} = a.c. resistance of isolated conductor per unit length; x = reactance per unit length.

Some additional symbols are defined in appropriate places.

APPENDIX II.—THE RESISTANCE, REACTANCE AND POWER LOSSES ON THREE-PHASE OVERHEAD LINES.

(A) INTRODUCTION.

In this Appendix methods and formulæ are given for evaluating the resistance, reactance and power losses on a three-phase system of overhead lines in any practical configuration of line conductors. Worked numerical examples illustrating the use of the formulæ are given in Appendix V.

(B) ASSUMPTIONS.

Unless otherwise stated, the line conductors are assumed to be solid homogeneous cylinders having unit permeability. The modifications due to stranding iron-cored conductors, etc.,* are pointed out in appropriate places. The conductor currents are assumed to form a "balanced" three-phase system as follows:—

$$\begin{aligned} &\text{Current in conductor 1} = I_1 \\ &\text{Current in conductor 2} = I_2 = I_1 e^{2\pi j/3} = I_1(-0\cdot5 + 0\cdot866j) \\ &\text{Current in conductor 3} = I_3 = I_1 e^{4\pi j/3} = I_1(-0\cdot5 - 0\cdot866j) \end{aligned}$$

A unit length of line is considered in the theory (which in the case of transposed lines contains three transpositions), over which the line current is assumed constant in magnitude. In certain instances on long lines this assumption is not permissible, and these cases are dealt with at the end of the Appendix.

The current in each conductor is taken as returning through an imaginary "neutral" wire parallel to the phase conductors, but situated at a very large distance "l" away. When the currents are balanced, the magnetic effect of this conductor is zero and, as will be seen later, the terms in the formulæ involving "l" cancel out.

(C) SINGLE CIRCUIT TOWERS.

(i) *General theory.*

We shall first consider the case of a tower carrying only one three-phase circuit and in which the conductors are spaced in any irregular configuration (as shown in Fig. 1) and are not transposed. Under such conditions the impedance voltage-drop along each conductor is made up of two parts, one due to the simple a.c. resistance (of an isolated conductor under the conditions assumed) and the other due to combined effects of the self-inductance of the phase considered and of the mutual inductance effects of the other two conductors. Thus an expression for the voltage-drop involves only the conductor currents, the dimensions of the conductors and the geometry of their arrangement. Symbolically, in Phase 1 we have

$$\Delta E_1 = I_1 R_K + j\omega(L_1 I_1 + M_{2,1} I_2 + M_{3,1} I_3) \text{ vector volt/cm} \quad . \; . \; . \; . \; . \; . \; . \quad (1)$$

Similar expressions may be obtained for the other two phases by permuting the suffixes.

The values of the coefficients of self and mutual inductance depend only upon the geometry of the spacing and have the following values:—

$$L_1 = \left(0\cdot5 + 2\,\text{logh}\,\frac{l}{b}\right)10^{-9} \text{ henry per cm} \quad . \; . \; . \; . \; . \; . \; . \quad (2)$$

$$M_{2,1} = \left(2\,\text{logh}\,\frac{l}{S_{1,2}}\right)10^{-9} \text{ henry per cm} \quad . \; . \; . \; . \; . \; . \; . \quad (3)$$

$$M_{3,1} = \left(2\,\text{logh}\,\frac{l}{S_{1,3}}\right)10^{-9} \text{ henry per cm} \quad . \; . \; . \; . \; . \; . \; . \quad (4)$$

Substituting these values in equation (1) and writing I_2 and I_3 in terms of I_1, we have

$$\Delta E_1 = I_1 R_K + j\omega I_1 10^{-9}\left[\left(0\cdot5 + 2\,\text{logh}\,\frac{l}{b}\right) + (-0\cdot5 + 0\cdot866j)\left(2\,\text{logh}\,\frac{l}{S_{1,2}}\right) + (-0\cdot5 - 0\cdot866j)\left(2\,\text{logh}\,\frac{l}{S_{1,3}}\right)\right] \quad . \quad (5)$$

---

* Skin-effect is neglected, as calculation shows the effect is less than 1 per cent in cases of the kind dealt with herein.

Thus the impedance of Phase 1 is given by*

$$\frac{\Delta E_1}{I_1} = R_K + j\omega 10^{-9}\left[\left\{0\cdot 5 + 2\,\text{logh}\,\frac{(S_{1,2}\times S_{1,3})^{\frac{1}{2}}}{b}\right\} - \left(\sqrt{3}j\,\text{logh}\,\frac{S_{1,2}}{S_{1,3}}\right)\right] \quad \ldots \quad (6)$$

$$= \left(R_K + \sqrt{3}\omega 10^{-9}\,\text{logh}\,\frac{S_{1,2}}{S_{1,3}}\right) + j\omega 10^{-9}\left(0\cdot 5 + 2\,\text{logh}\,\frac{(S_{1,2}\,S_{1,3})^{\frac{1}{2}}}{b}\right) \text{ ohm/cm to neutral} \quad \ldots \quad (7a)$$

Similarly,

$$\frac{\Delta E_2}{I_2} = \left(R_K + \sqrt{3}\omega 10^{-9}\,\text{logh}\,\frac{S_{2,3}}{S_{1,2}}\right) + j\omega 10^{-9}\left(0\cdot 5 + 2\,\text{logh}\,\frac{(S_{2,3}\,S_{1,2})^{\frac{1}{2}}}{b}\right) \text{ ohm/cm to neutral} \quad \ldots \quad (7b)$$

$$\frac{\Delta E_3}{I_3} = \left(R_K + \sqrt{3}\omega 10^{-9}\,\text{logh}\,\frac{S_{1,3}}{S_{2,3}}\right) + j\omega 10^{-9}\left(0\cdot 5 + 2\,\text{logh}\,\frac{(S_{1,3}\,S_{2,3})^{\frac{1}{2}}}{b}\right) \text{ ohm/cm to neutral} \quad \ldots \quad (7c)$$

The absolute value of the impedance of Phase 1

$$= 10^{-9}\sqrt{\left[\left(R_K\times 10^{-9} + \sqrt{3}\omega\,\text{logh}\,\frac{S_{1,2}}{S_{1,3}}\right)^2 + \omega^2\left(0\cdot 5 + 2\,\text{logh}\,\frac{(S_{1,2}\,S_{1,3})^{\frac{1}{2}}}{b}\right)^2\right]} \text{ ohm/cm to neutral} \quad . \quad (7d)$$

In equation (7*a*) the term in the first bracket is the apparent resistance and that in the second bracket the reactance to neutral of Phase 1. The term

$$\left(\sqrt{3}\omega 10^{-9}\,\text{logh}\,\frac{S_{1,2}}{S_{1,3}}\right)$$

in the apparent resistance is due to a transference of power between the conductors through the magnetic field. A similar phenomenon has already been noted in connection with three single-conductor cables.† For a given configuration and axial separation of the conductors, the direction of the phase transference depends on the sequence of the currents in the conductors. For example, if the currents in the conductors were in the following sequence:—

$$\text{Phase } 1 = I_1$$
$$\text{Phase } 2 = I_1 e^{4\pi j/3}$$
$$\text{Phase } 3 = I_1 e^{2\pi j/3}$$

then the first term of equation (7*a*) would be

$$\left(R_K + \sqrt{3}\omega 10^{-9}\,\text{logh}\,\frac{S_{1,3}}{S_{1,2}}\right) = \left(R_K - \sqrt{3}\omega 10^{-9}\,\text{logh}\,\frac{S_{1,2}}{S_{1,3}}\right) \quad \ldots \quad (8)$$

The sign of the second term in equations (7*b*) and (7*c*) for the apparent resistance of Phases 2 and 3 would be similarly changed. Again, for a given phase sequence of currents the magnitude and sign of the term

$$\left(\sqrt{3}\omega 10^{-9}\,\text{logh}\,\frac{S_{1,2}}{S_{1,3}}\right)$$

clearly depend on the relative magnitudes of $S_{1,2}$ and $S_{1,3}$. In general, the apparent resistance and reactance in asymmetrical spacing without transposition are different in all three phases.

---

* These three unit voltage-drops are not spaced 120° apart in time phase except in equilateral triangular spacing. The angle between the vector voltage drop of Phase 1 and the Current I_1:—

$$= \text{Arc tan}\,\frac{\text{Apparent Reactance}}{\text{Apparent Resistance}}$$

$$= \text{Arc tan}\left[\frac{\omega\left(0\cdot 5 + 2\,\text{logh}\,\frac{(S_{1,2}\,S_{1,3})^{\frac{1}{2}}}{b}\right)}{10^{-9}R_K + \sqrt{3}\omega\,\text{logh}\,\frac{S_{1,2}}{S_{1,3}}}\right] = \phi \text{ (say)}$$

Angle between vector voltage-drop of Phase 2 and Current I_2:—

$$= \text{Arc tan}\left[\frac{\omega\left(0\cdot 5 + 2\,\text{logh}\,\frac{(S_{2,3}\,S_{1,2})^{\frac{1}{2}}}{b}\right)}{\left(R_K 10^{-9} + \sqrt{3}\omega\,\text{logh}\,\frac{S_{2,3}}{S_{1,2}}\right)}\right] = \theta \text{ (say)}$$

Angle between vector voltage-drops of Phases 1 and 2 = $2\pi/3 + (\theta - \phi)$.

† See Bibliography, Ref. No. 36, page 367. This transference of power does not affect the heating of the conductors which is the same in all conductors and is equal to the square of the absolute value of the current multiplied by R_K. The power transferred to Phase 1 from the other two conductors is:—

$$= \left(\sqrt{3}\omega 10^{-9}\,\text{logh}\,\frac{S_{1,2}}{S_{1,3}}\right) I^2 \text{ watts per cm length} \quad \ldots \quad (7e)$$

where I is the absolute (or measured) value of the current.

(ii) *Effect of symmetry.*

(*a*) *Triangular spacing.*—In equilateral triangular spacing

$$S_{1,2} = S_{1,3} = S_{2,3}$$

Thus, both with or without transposition, equation (7*a*) becomes

$$\frac{\Delta E_1}{I_1} = R_K + j\omega 10^{-9}\left(0\cdot5 + 2 \operatorname{logh}\frac{S_{1,2}}{b}\right) \text{ ohm/cm to neutral} \quad \ldots \ldots \quad (9a)$$

$$= (0\cdot161 \times 10^6 R_K) + j\left(0\cdot0253 + 0\cdot233 \log_{10}\frac{S_{1,2}}{b}\right) \text{ ohm/mile to neutral at 50 cycles} \quad \ldots \quad (9b)$$

Under such conditions the numerical values of the resistance and reactance are equal in all three phases, though vectorially the voltage-drops are 120° apart in phase.

(*b*) *Transposition.*—If the conductors are regularly transposed, the above-mentioned effects of asymmetry balance out over an integral multiple of three transpositions.* The resistance of any phase will then be R_K and the reactance will be the average of the values in equations (7*a*), (7*b*) and (7*c*); that is,

$$\text{Vector reactance per phase} = j\omega 10^{-9}\left(0\cdot5 + 2 \operatorname{logh}\frac{(S_{1,2} \times S_{1,3} \times S_{2,3})^{\frac{1}{3}}}{b}\right) \text{ ohm/cm to neutral} \quad . \quad (10a)$$

Numerically,

$$\text{Reactance per phase} = 0\cdot0253 + 0\cdot233 \log_{10}\frac{(S_{1,2} \times S_{1,3} \times S_{2,3})^{\frac{1}{3}}}{b} \text{ ohm/mile to neutral at } 50 \sim \quad . \quad (10b)$$

(D) DOUBLE CIRCUIT TOWERS.

(i) *General considerations.*

In the following treatment it is assumed that the conductors of each circuit are asymmetrically spaced, but that the two circuits are symmetrically arranged about the vertical centre line of the tower. The loads on the two circuits are assumed to be equal and separately balanced. When neither circuit is transposed, there are then six ways of permuting the time phase of the currents in one circuit for a given time-phase sequence of currents in the other (see Figs. 3 (*a*), (*b*), (*c*), (*d*), (*e*), (*f*)); while if the currents in both circuits are permuted, there are twelve possible arrangements (see Figs. 3 (*a*) to 3 (*l*)).† There are, however, only thirty-six different impedance equations for all the conductors for the reasons given below. In ten of the arrangements, each involving six impedance equations, five involve the same thirty equations as the other five, the only difference being that the values for the two circuits are interchanged. Corresponding arrangements are Figs. 3 (*a*) and 3 (*j*), 3 (*b*) and 3 (*k*), 3 (*c*) and 3 (*l*), 3 (*e*) and 3 (*f*), 3 (*h*) and 3 (*i*).

In addition, for Figs. 3 (*d*) and 3 (*g*), we shall show later that the three impedance equations of each circuit are equal in each figure (though the three equations of Fig. 3 (*d*) are different from those of Fig. 3 (*g*)). Thus, as in the other ten arrangements, there are only half as many impedance equations as conductor positions.

In the following sub-section a simple rule is deduced by which the impedance in any arrangement may be written down directly, and a discussion is given of the characteristics of the various arrangements both with and without transposition.

(ii) *Derivation of impedance equations* (*conductors not transposed*).

Take as a typical example the sequence of currents shown in Fig. 3 (*l*).
Let

$$\text{Current in conductor Position 1} = \text{current in conductor Position 4} = I_1$$

$$\text{Current in conductor Position 2} = \text{current in conductor Position 5} = I_2 = I_1 e^{2\pi j/3}$$

$$\text{Current in conductor Position 3} = \text{current in conductor Position 6} = I_3 = I_1 e^{4\pi j/3}$$

---

[*] Regular transposition makes the voltage-drop vectors 120° apart in phase.

[†] It may be noted that in any of the 12 arrangements the phase impedances remain unaltered if the time phase of *all* the currents is altered by, say, $2\pi/3$ or $4\pi/3$.

The voltage-drop per unit length along any conductor is equal to the sum of the drop due to the simple a.c. resistance of an isolated conductor and a reactance-drop due to the self-inductance of the conductor considered and five mutual inductance effects due to the other five conductors. Thus the voltage-drop along the conductor in Position 1,

$$\Delta E_1 = I_1 R_K + j\omega(L_1 I_1 + M_{2,1} I_2 + M_{3,1} I_3 + M_{4,1} I_1 + M_{5,1} I_2 + M_{6,1} I_3) \text{ vector volts/cm} \quad . \quad . \quad (11)$$

$$= I_1 R_K + j\omega I_1(L_1 + M_{4,1}) + I_2(M_{2,1} + M_{5,1}) + I_3(M_{3,1} + M_{6,1}) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

Writing I_2 and I_3 in terms of I_1 and putting

$$M_{4,1} = \left(2 \operatorname{logh} \frac{l}{S_{4,1}}\right)10^{-9}$$

$$M_{5,1} = \left(2 \operatorname{logh} \frac{l}{S_{5,1}}\right)10^{-9}$$

$$M_{6,1} = \left(2 \operatorname{logh} \frac{l}{S_{6,1}}\right)10^{-9}$$

the vector impedance of Phase 1,

$$\frac{\Delta E_1}{I_1} = R_K + j\omega 10^{-9}\left(0 \cdot 5 + 2 \operatorname{logh} \frac{(S_{2,1}\, S_{3,1}\, S_{5,1}\, S_{6,1})^{\frac{1}{4}}}{b S_{4,1}} + \sqrt{3} j \operatorname{logh} \frac{S_{3,1}\, S_{6,1}}{S_{2,1}\, S_{5,1}}\right) \text{ ohm/cm to neutral} \quad . \quad . \quad . \quad (13)$$

$$= \left(R_K + \sqrt{3}\omega 10^{-9} \operatorname{logh} \frac{S_{2,1}\, S_{5,1}}{S_{3,1}\, S_{6,1}}\right) + j\omega 10^{-9}\left(0 \cdot 5 + 2 \operatorname{logh} \frac{(S_{2,1}\, S_{3,1}\, S_{5,1}\, S_{6,1})^{\frac{1}{4}}}{b S_{4,1}}\right) \text{ ohm/cm to neutral} \quad . \quad (14a)$$

$$= (P_1 + jQ_1), \text{ say.}$$

From this equation we see that the *apparent resistance* of any conductor is equal to

$$\left[R_K + \sqrt{3}\omega 10^{-9} \operatorname{logh} \frac{\text{(Product of axial distances from conductor to other two carrying current } 2\pi/3 \text{ later in time phase)}}{\text{(Product of axial distances from conductor to two others carrying current } 4\pi/3 \text{ later in time phase)}}\right] \text{ ohm/cm}$$

Similarly, the *apparent reactance* is equal to

$$j\omega 10^{-9}\left[0 \cdot 5 + 2 \operatorname{logh} \frac{\text{(Product of axial distances from conductor considered to four others carrying current of different time phase)}^{\frac{1}{4}}}{(b \times \text{axial distance from conductor considered to other carrying current of same time phase)}}\right] \text{ ohm/cm to neutral.}$$

Using these two rules, we may write directly the impedances of the remaining five conductors in Fig. 3 (*l*) as follows:—

$$\frac{\Delta E_2}{I_2} = \left(R_K + \sqrt{3}\omega 10^{-9} \operatorname{logh} \frac{S_{3,2}\, S_{6,2}}{S_{1,2}\, S_{4,2}}\right) + j\omega 10^{-9}\left(0 \cdot 5 + 2 \operatorname{logh} \frac{(S_{1,2}\, S_{3,2}\, S_{4,2}\, S_{6,2})^{\frac{1}{4}}}{b S_{5,2}}\right) \text{ ohm/cm to neutral} \quad . \quad (14b)$$

$$= (P_2 + jQ_2), \text{ say.}$$

$$\frac{\Delta E_3}{I_3} = \left(R_K + \sqrt{3}\omega 10^{-9} \operatorname{logh} \frac{S_{1,3}\, S_{4,3}}{S_{2,3}\, S_{5,3}}\right) + j\omega 10^{-9}\left(0 \cdot 5 + 2 \operatorname{logh} \frac{(S_{1,3}\, S_{2,3}\, S_{4,3}\, S_{5,3})^{\frac{1}{4}}}{b S_{6,3}}\right) \text{ ohm/cm to neutral}^* \quad . \quad (14c)$$

$$= (P_3 + jQ_3), \text{ say.}$$

$$\frac{\Delta E_4}{I_4} = \left[\left(R_K + \sqrt{3}\omega 10^{-9} \operatorname{logh} \frac{S_{2,4}\, S_{5,4}}{S_{3,4}\, S_{6,4}}\right) + j\omega 10^{-9}\left(0 \cdot 5 + 2 \operatorname{logh} \frac{(S_{2,4}\, S_{3,4}\, S_{5,4}\, S_{6,4})^{\frac{1}{4}}}{b S_{1,4}}\right)\right] \text{ ohm/cm to neutral} \quad (14d)$$

$$\frac{\Delta E_5}{I_5} = \left[\left(R_K + \sqrt{3}\omega 10^{-9} \operatorname{logh} \frac{S_{3,5}\, S_{6,5}}{S_{1,5}\, S_{4,5}}\right) + j\omega 10^{-9}\left(0 \cdot 5 + 2 \operatorname{logh} \frac{(S_{1,5}\, S_{3,5}\, S_{4,5}\, S_{6,5})^{\frac{1}{4}}}{b S_{2,5}}\right)\right] \text{ ohm/cm to neutral} \quad (14e)$$

$$\frac{\Delta E_6}{I_6} = \left[\left(R_K + \sqrt{3}\omega 10^{-9} \operatorname{logh} \frac{S_{1,6}\, S_{4,6}}{S_{2,6}\, S_{5,6}}\right) + j\omega 10^{-9}\left(0 \cdot 5 + 2 \operatorname{logh} \frac{(S_{1,6}\, S_{2,6}\, S_{4,6}\, S_{5,6})^{\frac{1}{4}}}{b S_{3,6}}\right)\right] \text{ ohm/cm to neutral} \quad (14f)$$

---

* These vector voltage-drops are not 120° apart in phase.

The angle between the voltage-drops of Phases 1 and 2 $= \frac{2\pi}{3} + \left(\text{arc tan} \frac{Q_1}{P_2} - \text{arc tan} \frac{Q_2}{P_2}\right)$

Angle between voltage-drops of Phases 2 and 3 $= \frac{2\pi}{3} + \left(\text{arc tan} \frac{Q_2}{P_2} - \text{arc tan} \frac{Q_3}{P_3}\right)$

Numerical value of impedance of Phase 1 $= \sqrt{(P_1^2 + Q_1^2)}$ ohm per cm

In the particular case when the two outers of each circuit are symmetrical about their middle phase conductors

(i.e. $S_{1,4} = S_{6,3}$; $S_{5,1} = S_{6,2} = S_{4,2} = S_{5,3}$; $S_{1,2} = S_{6,5} = S_{2,3} = S_{5,4}$; $S_{1,3} = S_{6,4}$; $S_{1,6} = S_{3,6}$),

the above expressions become

$$\frac{\Delta E_1}{I_1} = \frac{\Delta E_4}{I_4}$$

as in equation (14*a*).

$$\frac{\Delta E_2}{I_2} = \frac{\Delta E_5}{I_5} = R_K + j\omega 10^{-9}\left(0\cdot 5 + 2\,\mathrm{logh}\,\frac{S_{1,2}\,S_{4,2}}{bS_{5,2}}\right) \quad . \; . \; . \; . \; . \; . \; . \; . \quad (14g)$$

$$\frac{\Delta E_3}{I_3} = \frac{\Delta E_6}{I_6} = \left[R_K + \sqrt{3}\omega 10^{-9}\,\mathrm{logh}\left(\frac{S_{3,1}\,S_{6,1}}{S_{2,1}\,S_{5,1}}\right)\right] + j\omega 10^{-9}\left(0\cdot 5 + 2\,\mathrm{logh}\,\frac{(S_{2,1}\,S_{3,1}\,S_{5,1}\,S_{6,1})^{\frac{1}{4}}}{bS_{4,1}}\right) \quad . \quad (14h)$$

The remaining thirty impedance equations may be written down in a similar way.

(iii) *Characteristics of different current permutations* (*without transposition*).

It is usual to transpose long and important power lines primarily to reduce inductive interference with communication circuits. On double circuit lines this involves the use of special and expensive transposition towers, and if transposition could be avoided, say, on short lines where also the power and communication circuits are widely separated, a considerable saving would result. It is desirable, therefore, to examine the impedance equation for a non-transposed double circuit line from the standpoint of the power supply engineer, the most important aspects of the problem being:—

(1) The obtaining of equal phase impedances in the two circuits. (This ensures that when operated in parallel the load is equally divided between them.)

(2) Reduction in phase impedance so as to decrease the impedance voltage-drop in the line.

Considering item (1), investigation shows that out of all the twelve possible arrangements (see Figs. 3 (*a*) to 3 (*l*)) here are only two, viz. Figs. 3 (*d*) and 3 (*g*), in which the six impedance equations are not all different. For these two arrangements the impedances of conductors carrying currents of the same time phase (those in the same horizontal plane) in the two circuits are equal, and thus either of these methods may be adopted for parallel operation. It may be noted that in all arrangements without transposition there is transformer action between conductors differing in time phase, and Figs. 3 (*d*) and 3 (*g*) are no exceptions.

Respecting power transference between conductors *of the same circuit* (which it is desirable to keep as low as possible from a practical standpoint), there is nothing to choose between Fig. 3 (*d*) and Fig. 3 (*g*), because the three terms in the apparent resistances due to this effect have the same numerical values in both cases and differ only in sign.

Consider now the question of power transference between the two circuits, each considered as a unit. The power transferred to or from circuit A by circuit B

= I^2 [Sum of three apparent phase resistances per cm — Sum of three a.c. resistances per cm of isolated phase conductor] watts/cm

where I = R.M.S. phase current (in amperes).

In the case of Figs. 3 (*d*) or 3 (*g*), this is equal to

$$\left[\sqrt{3}\omega 10^{-9} I^2\,\mathrm{logh}\left(\frac{S_{3,1}\,S_{4,1}\,S_{1,2}\,S_{6,2}\,S_{2,3}\,S_{5,3}}{S_{2,1}\,S_{5,1}\,S_{3,2}\,S_{4,2}\,S_{1,3}\,S_{6,3}}\right)\right] \text{watt/cm} \quad . \; . \; . \; . \; . \; . \; . \quad (14j)$$

$$= \text{zero.}$$

Thus for these arrangements there is no transference of power between the two circuits.

Respecting item (2) above, investigation shows that the effect of mutal inductance of the second circuit may increase or decrease the apparent phase reactance compared with that of a single circuit at similar spacings, and we have therefore to deduce what phase sequence of currents gives the lowest reactances.

In all the twelve possible impedance equations applying to any one conductor position, there are only *three* different reactance values, i.e. there are only *nine* different reactance values in all the thirty-six impedance equations. This is evident if we consider the rule given below equation (14*a*) for writing down the apparent reactance of any conductor. The denominator of the logarithmic term in the apparent reactance involves the dimension from the conductor position considered to the other of the same time phase, which is necessarily in the opposite circuit in one of three possible positions. Thus for any given conductor position in circuit A there are only three possible dimensions to conductors in circuit B, and, therefore only three possible reactance values, which, by using the rule already given, can be written down directly. As an example, we give the values for conductor Position 1 in Figs. 3 (*a*) to 3 (*l*) as follows:—

$$\text{Figs. 3 }(a),\ 3\ (d),\ 3\ (g)\text{ and }3\ (j) = j\omega 10^{-9}\left(0\cdot 5 + 2\ \text{logh}\,\frac{(S_{2,1}\,S_{3,1}\,S_{4,1}\,S_{5,1})^{\frac{1}{2}}}{bS_{6,1}}\right)\ \text{ohm/cm.}$$

$$\text{Figs. 3 }(b),\ 3\ (e),\ 3\ (h)\text{ and }3\ (k) = j\omega 10^{-9}\left(0\cdot 5 + 2\ \text{logh}\,\frac{(S_{2,1}\,S_{3,1}\,S_{4,1}\,S_{6,1})^{\frac{1}{2}}}{bS_{5,1}}\right)\ \text{ohm/cm}$$

$$\text{Figs. 3 }(c),\ 3\ (f),\ 3\ (i)\text{ and }3\ (l) = j\omega 10^{-9}\left(0\cdot 5 + 2\ \text{logh}\,\frac{(S_{2,1}\,S_{3,1}\,S_{5,1}\,S_{6,1})^{\frac{1}{2}}}{bS_{4,1}}\right)\ \text{ohm/cm}$$

We next observe that while the numerator of the logarithmic term involves the square root of any dimension, the denominator involves the dimension itself, so it is probable that the lowest reactance value will occur when the biggest of the three possible dimensions (i.e. $S_{1,4}$ for conductor Position 1) appears in the denominator, and this is actually the case. By applying the same method to conductor Positions 2 and 3, we find that the lowest reactances occur when the top conductor of either circuit carries current of the same time phase as the bottom of the other, i.e. as in Figs. 3 (*c*) or 3 (*l*),* which are, therefore, the most favourable arrangements from this standpoint.

It may be noted that for the above figures there is a transference of power between the circuits given by

$$\left[\sqrt{3}\omega 10^{-9}I^2\ \text{logh}\left(\frac{S_{3,1}\,S_{6,1}\,S_{1,2}\,S_{4,2}\,S_{2,3}\,S_{5,3}}{S_{2,1}\,S_{5,1}\,S_{3,2}\,S_{6,2}\,S_{1,3}\,S_{4,3}}\right)\right]\ \text{watts/cm} = \left[\sqrt{3}\omega 10^{-9}I^2\ \text{logh}\left(\frac{S_{6,1}\,S_{4,2}\,S_{5,3}}{S_{5,1}\,S_{6,2}\,S_{4,3}}\right)\right]\ \text{watts/cm} \quad (14k)$$

(iv) *Effects of transposition.*

(*a*) *Circuits transposed at same frequency.*—Regular transposition equalizes the impedances of all three phases of each circuit over an integral multiple of three transpositions, provided the two circuits are transposed in such directions as to maintain the same relative positions of conductors carrying currents of the same time phase.

As in the untransposed case, for ten of the twelve possible current permutations the impedances of one half are the same as for the other half, with the values for the two circuits interchanged in any instance. The corresponding arrangements of current sequence for the transposed case are the same as already given for the untransposed case, and give ten different impedance equations. For the remaining two cases the four impedances are all equal, as we shall see later, so that the total number of impedance equations is eleven.

Calculation of impedance of Circuits B, Fig. 3 (*c*) *and A, Fig.* 3 (*l*).

Taking as a typical case the arrangement of Fig. 3 (*c*) over an integral multiple of three transpositions, the impedance per unit length of any phase of the right-hand circuit will be equal to one-third of the sum of the separate impedances of conductor positions 4, 5 and 6; that is,

$$= \left[\left\{R_K + \sqrt{3}\omega 10^{-9}\ \text{logh}\left(\frac{S_{5,1}\,S_{6,2}\,S_{4\,3}}{S_{5,3}\,S_{6,1}\,S_{4,2}}\right)^{\frac{1}{3}}\right\} + j\omega 10^{-9}\left(0\cdot 5 + 2\ \text{logh}\,\frac{(S_{1,2}\,S_{1,3}\,S_{2,3})^{\frac{1}{3}}}{b}\,\frac{(S_{5,1}\,S_{6,1}\,S_{4,2}\,S_{6,2}\,S_{4,3}\,S_{5,3})^{\frac{1}{3}}}{(S_{4,1}\,S_{5,2}\,S_{6,3})^{\frac{1}{3}}}\right)\right]\ \text{ohm/cm to neutral} \quad . \quad (15a)$$

Similarly,

Impedance of Circuits A, Fig. 3 (*c*) *and B, Fig.* 3 (*l*).

$$= \left[\left\{R_K + \sqrt{3}\omega 10^{-9}\ \text{logh}\left(\frac{S_{2,4}\,S_{3,5}\,S_{1,6}}{S_{3,4}\,S_{1,5}\,S_{2,6}}\right)^{\frac{1}{3}}\right\} + j\omega 10^{-9}\left(0\cdot 5 + 2\ \text{logh}\,\frac{(S_{1,2}\,S_{1,3}\,S_{2,3})^{\frac{1}{3}}}{b}\,\frac{(S_{5,1}\,S_{6,1}\,S_{4,2}\,S_{6,2}\,S_{4,3}\,S_{5,3})^{\frac{1}{3}}}{(S_{4,1}\,S_{5,2}\,S_{6,3})^{\frac{1}{3}}}\right)\right]\ \text{ohm/cm to neutral} \quad . \quad (15b)$$

In view of the practical importance of transposed circuits, it is useful for reference to enumerate all the remaining possible impedance equations as follows:—

Circuits A, Fig. 3 (*a*) *and B, Fig.* 3 (*j*).

$$\text{Impedance} = \left[\left\{R_K + \sqrt{3}\omega 10^{-9}\ \text{logh}\left(\frac{S_{5,1}\,S_{6,2}\,S_{4,3}}{S_{4,1}\,S_{5,2}\,S_{6,3}}\right)^{\frac{1}{3}}\right\} + j\omega 10^{-9}\left(0\cdot 5 + 2\ \text{logh}\,\frac{(S_{1,2}\,S_{1,3}\,S_{2,3})^{\frac{1}{3}}}{b} \times \frac{(S_{4,1}\,S_{5,1}\,S_{5,2}\,S_{6,2}\,S_{4,3}\,S_{6,3})^{\frac{1}{3}}}{(S_{6,1}\,S_{5,3}\,S_{4,2})^{\frac{1}{3}}}\right)\right]\ \text{ohm/cm to neutral} \quad . \quad (15c)$$

---

* The six reactance values of Fig. 3 (*c*) are the same as those of Fig. 3 (*l*), and the terms in the apparent resistances due to power transference are numerically equal but of opposite sign for corresponding conductor positions.

Circuits B, Fig. 3 (*a*) *and A, Fig.* 3 (*j*).

Same as equation (15*c*) except that sign of second term in apparent resistance is reversed.

Circuits A, Fig. 3 (*b*) *and B, Fig.* 3 (*k*).

$$\text{Impedance} = \left[\left\{R_K + \sqrt{3}\omega 10^{-9} \operatorname{logh}\left(\frac{S_{4,1}\,S_{5,2}\,S_{6,3}}{S_{6,1}\,S_{4,2}\,S_{5,3}}\right)^{\frac{1}{3}}\right\} + j\omega 10^{-9}\left(0\cdot 5 + 2\operatorname{logh}\frac{(S_{1,2}\,S_{2,3}\,S_{1,3})^{\frac{1}{3}}}{b} \times \frac{(S_{4,1}\,S_{6,1}\,S_{4,2}\,S_{5,2}\,S_{5,3}\,S_{6,3})^{\frac{1}{6}}}{(S_{5,1}\,S_{6,2}\,S_{4,3})^{\frac{1}{3}}}\right)\right] \text{ ohm/cm to neutral} \quad . \quad (15d)$$

Circuits B, Fig. 3 (*b*) *and A, Fig.* 3 (*k*).

Same as equation (15*d*) except that sign of second term in apparent resistance is reversed.

Circuits A and B for both Figs. 3 (*d*) *and* 3 (*g*).

$$\text{Impedance} = \left[R_K + j\omega 10^{-9}\left\{0\cdot 5 + 2\operatorname{logh}\frac{(S_{1,2}\,S_{1,3}\,S_{2,3})^{\frac{1}{3}}}{b}\left(\frac{S_{4,1}\,S_{5,1}\,S_{4,2}}{S_{6,1}\,S_{5,2}\,S_{4,3}}\right)^{\frac{1}{3}}\right\}\right] \text{ ohm/cm to neutral} \quad . \quad (15e)$$

Circuits A, Fig. 3 (*e*) *and B, Fig.* 3 (*f*).

$$\text{Impedance} = \left[\left\{R_K + \sqrt{3}\omega 10^{-9} \operatorname{logh}\left(\frac{S_{6,1}\,S_{5,2}\,S_{4,3}}{S_{4,1}\,S_{6,2}\,S_{5,3}}\right)^{\frac{1}{3}}\right\} + j\omega 10^{-9}\left\{0\cdot 5 + 2\operatorname{logh}\frac{(S_{1,2}\,S_{2,3}\,S_{1,3})^{\frac{1}{3}}}{b}\left(\frac{S_{6,1}\,S_{5,2}\,S_{4,3}}{S_{6,3}\,S_{5,1}\,S_{4,2}}\right)^{\frac{1}{3}}\right\}\right] \text{ ohm/cm to neutral} \quad . \quad (15f)$$

Circuits B, Fig. 3 (*e*) *and A, Fig.* 3 (*f*).

Apparent resistance same as equation (15*f*) with sign of second term reversed.

$$\text{Apparent reactance} = j\omega 10^{-9}\left[0\cdot 5 + 2\operatorname{logh}\frac{(S_{1,2}\,S_{2,3}\,S_{1,3})^{\frac{1}{3}}}{b}\left(\frac{S_{6,1}\,S_{5,2}\,S_{4,3}}{S_{4,1}\,S_{6,2}\,S_{5,3}}\right)^{\frac{1}{3}}\right] \text{ ohm/cm to neutral} \quad . \quad (15g)$$

Circuits A, Fig. 3 (*h*) *and B, Fig.* 3 (*i*).

Apparent resistance same as equation (15*g*). and apparent reactance same as equation (15*f*).

Circuits B, Fig. 3 (*h*) *and A, Fig.* 3 (*i*).

Apparent resistance as in equation (15*f*), and apparent reactance as in equation (15*g*).

There are thus eleven possible impedance equations, the total number of different reactances and resistances involved in all the equations being six and nine respectively for all arrangements of both circuits. From the standpoint of impedance (when transposed), we may classify Figs. 3 (*a*) to 3 (*l*) into three groups:—

Group 1, comprising Figs. 3 (*a*), 3 (*b*), 3 (*c*), 3 (*j*), 3 (*k*), 3 (*l*).
Group 2, comprising Figs. 3 (*d*), 3 (*g*).
Group 3, comprising Figs. 3 (*e*), 3 (*h*), 3 (*f*), 3 (*i*).

Group 1.

The characteristics of this group are that the apparent reactances of both circuits (in any figure) are the same, while the terms in their apparent resistances due to power transference are numerically equal but of opposite sign.

This group includes Figs. 3 (*c*) and 3 (*l*), which have the lowest reactances of any of the arrangements (less than that of a single circuit at similar spacings). In all cases there is a power transference between the two circuits, but it is least for Figs. 3 (*c*) and 3 (*l*).

Group 2.

In this group there is no power transference between the circuits, i.e. the apparent resistances are equal to the a.c. resistance of an isolated conductor. The reactances of both circuits are equal (and for the "grid" lines about 2 per cent higher than that of a single circuit at similar spacings).

Group 3.

In this group the apparent reactances of the two circuits are different, while the terms in their apparent resistances due to power transference are numerically equal and of opposite sign. There is a power transference between the circuits.*

From a practical aspect the amount of power transferred between the circuits is negligible, the greatest value on the "grid" lines being only 2·5 kW per mile (for Figs. 3 (*e*) and 3 (*j*)), and the smallest values (except for Figs. 3 (*d*) and 3 (*g*), in which no power is transferred) 0·28 kW per mile (for Figs. 3 (*c*) and 3 (*l*)). Thus the most useful practical arrangements are the same as those for non-transposed circuits, viz. Figs. 3 (*c*) and 3 (*l*), which have the lowest impedance, and Figs. 3 (*d*) and 3 (*g*), in which the circuits have equal impedances.

(*b*) *Circuits transposed at different frequencies.*—There is only one case of practical importance, namely, when the second circuit is transposed at one-third the frequency of the first. Under such conditions it is obvious † from symmetry that over an integral multiple of three transpositions of the circuit B all mutual inductance effects balance out, and the resistance and reactance of all six phases are the same as for a single circuit (see equation (10*a*)) at similar spacing and with the same phase sequence (provided the two circuits are symmetrical about the centre line of the pole).

In practice it will not always be possible to arrange that the distance between the sending and receiving ends of the line is an integral multiple of three transpositions of the circuit having the lesser frequency of transposition (i.e. circuit B). Under such conditions the unbalanced portion of the line may be reduced to a length not exceeding two transpositions of circuit A by transposing the two circuits at the same frequency over the odd portion of the line. The unbalance then remaining would be negligible in practice.

(E) MODIFICATIONS ON LONG LINES.

In the foregoing theory the impedance voltage-drop along a conductor has been taken as numerically equal to the absolute value of the current multiplied by the absolute value of the impedance. Actually the impedance voltage-drop is the absolute value of the vector difference between the sending- and receiving-end voltages. On short lines up to, say, fifty miles, the above assumption leads to an error of a few per cent, but on long lines the effects of the charging current must be taken into account.

For long lines electrically balanced either by regular transposition or equilateral triangular spacing of the conductors, the method of obtaining the impedance-drop is given in text-books on the subject, and need not be repeated here. The solution is as follows:—

Let E_s = sending-end voltage to neutral (volts).
E_r = receiving-end voltage to neutral (volts).
I_r = receiving-end current to neutral (amperes).
$Z = R_{KM} + jx$ = vector impedance per unit length of line (ohm/mile).
$Y = g + jc$ = vector admittance per unit length of line (mho/mile).

Then the impedance voltage-drop over a length l_1 miles,

$$E_s - E_r = E_r(\cosh\sqrt{(YZ)}l_1 - 1) + I_r\sqrt{\frac{Z}{Y}}\sinh\sqrt{(YZ)}l_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (18)$$

---

* The power transferred to circuit A from circuit B in a typical case such as Fig. 3 (*e*):—

$$= \left[\sqrt{3}\omega 10^{-9}\, 2\,\text{logh}\left(\frac{S_{6,1}S_{5,2}S_{4,3}}{S_{4,1}S_{6,2}S_{5,3}}\right)\right]I^2 \text{ watt/cm} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (16)$$

where I = absolute value of current in amps.

† This may be proved if desired as follows: Taking the arrangement in Fig. 3 (*l*), let the frequency of transposition of circuit A be three times that of B. Then keeping the right-hand circuit as in the diagram, let the left-hand circuit be transposed a complete turn of the lay. Over this length the impedance of any phase of circuit A will be given by

$$\frac{\Delta E_1}{I_1} = \left[R_K + \sqrt{3}\omega 10^{-9}\,\text{logh}\left(\frac{S_{5,1}S_{5,2}S_{5,3}}{S_{6,1}S_{6,2}S_{6,3}}\right)^{\frac{1}{3}} + j\omega 10^{-9}\left\{0\cdot 5 + 2\,\text{logh}\frac{(S_{2,1}S_{3,1}S_{2,3})^{\frac{1}{3}}}{b}\frac{(S_{5,1}S_{5,2}S_{5,3}S_{6,1}S_{6,2}S_{6,3})^{\frac{1}{3}}}{(S_{4,1}S_{4,2}S_{4,3})^{\frac{1}{3}}}\right\}\right] \text{ ohm/cm to neutral} \qquad (17a)$$

Over this length the left-hand circuit is transposed three times.

Now let the right-hand circuit be transposed one-third of a turn and maintained fixed while the left-hand circuit is transposed three times. Over this length the impedance is equal to

$$\frac{\Delta E_1}{I_1} = \left[R_K + \sqrt{3}\omega 10^{-9}\,\text{logh}\left(\frac{S_{6,1}S_{6,2}S_{6,3}}{S_{4,1}S_{4,2}S_{4,3}}\right)^{\frac{1}{3}} + j\omega 10^{-9}\left(0\cdot 5 + 2\,\text{logh}\frac{(S_{2,1}S_{3,1}S_{2,3})^{\frac{1}{3}}}{b}\frac{(S_{4,1}S_{4,2}S_{4,3}S_{6,1}S_{6,2}S_{6,3})^{\frac{1}{3}}}{(S_{5,1}S_{5,2}S_{5,3})^{\frac{1}{3}}}\right)\right] \text{ ohm/cm to neutral} \qquad (17b)$$

Repeat the last-named operation, and over this length we have

$$\frac{\Delta E_1}{I_1} = \left[R_K + \sqrt{3}\omega 10^{-9}\,\text{logh}\left(\frac{S_{4,1}S_{4,2}S_{4,3}}{S_{5,1}S_{5,2}S_{5,3}}\right)^{\frac{1}{3}} + j\omega 10^{-9}\left(0\cdot 5 + 2\,\text{logh}\frac{(S_{2,1}S_{3,1}S_{2,3})^{\frac{1}{3}}}{b}\frac{(S_{4,1}S_{4,2}S_{4,3}S_{5,1}S_{5,2}S_{5,3})^{\frac{1}{3}}}{(S_{6,1}S_{6,2}S_{6,3})^{\frac{1}{3}}}\right)\right] \text{ ohm/cm to neutral} \qquad (17c)$$

The impedance per length over an integral multiple of nine transpositions of the left-hand circuit is obtained by taking ⅓ of the sum of (17*a*), (17*b*) and (17*c*). This gives

$$\frac{\Delta E_1}{I_1} = \left[R_K + j\omega 10^{-9}\left(0\cdot 5 + 2\,\text{logh}\frac{(S_{2,1}S_{3,1}S_{2,3})^{\frac{1}{3}}}{b}\right)\right] \text{ ohm/cm to neutral} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (17d)$$

which is the same (cf. equation (10*a*)) as that of a single circuit. Similar remarks apply to circuit B, since if the mutual effect of B on A is nil, the reverse is also true.

This gives $E_s - E_r$ as a complex quantity, the absolute value of which is the numerical impedance voltage-drop. The impedance Z to be used in equation (18) is the value calculated by the methods given in sections (*c*) and (*d*) of this Appendix. For long lines not transposed (i.e. not electrically balanced) the impedance and admittance per unit length vary all along the line. Although it is theoretically possible to obtain a solution for this case, the result when obtained would be of great complexity and has no practical application, as all long lines must be transposed to avoid interference with other circuits. For this reason no attempt has been made to calculate this case.

(F) POWER LOSSES.

(i) *Introduction.*

On a short line the power losses are equal to the product of the square of the absolute value of the current and the line resistance. This method assumes that the capacity current may be neglected and also that leakage and corona losses are negligible. On a long line, the capacity current cannot be neglected, as it causes the absolute value of the current, upon which the heating depends, to vary all along the line. It is usual in such cases to evaluate the power losses as the difference between the sending- and receiving-end powers. If the leakage and corona loss are negligible or can be separately evaluated, this is an exact method, but it has the disadvantage that the losses are evaluated as the difference between two much greater quantities, so that the accuracy is not very great. For this reason we have deduced an expression for the power losses by integrating the I^2R losses all along the line, by which the losses may be directly evaluated. The method applies only when the line is electrically balanced either by regular transposition or equilateral spacing. This is the only case of practical interest.

(ii) *Losses on a long line.*

Take the voltage at the receiving-end E_r as the reference vector. Let the receiving-end current $I_r = (\mathfrak{J}_1 - j\mathfrak{J}_2)$. Then it is shown in text-books that at a distance l_1 miles from receiving end, the vector current

$$I_{l_1} = (\mathfrak{J}_1 - j\mathfrak{J}_2)\cosh\sqrt{(YZ)}l_1 + E_r\sqrt{\frac{Y}{Z}}\sinh\sqrt{(YZ)}l_1 \quad . \; . \; . \; . \; . \; . \; . \; . \qquad (19a)$$

Put

$$\sqrt{(YZ)} = \alpha + j\beta \quad \text{and} \quad \sqrt{\frac{Y}{Z}} = \gamma + j\delta$$

Thus

$$\begin{aligned} I_{l_1} &= (\mathfrak{J}_1 - j\mathfrak{J}_2)(\cosh \alpha l_1 \cos \beta l_1 + j \sinh \alpha l_1 \sin \beta l_1) + E_r(\gamma + j\delta)(\sinh \alpha l_1 \cos \beta l_1 + j \cosh \alpha l_1 \sin \beta l_1 \\ &= \Big[\mathfrak{J}_1 \cosh \alpha l_1 \cos \beta l_1 + \mathfrak{J}_2 \sinh \alpha l_1 \sin \beta l_1 + E_r(\gamma \sinh \alpha l_1 \cos \beta l_1 - \delta \cosh \alpha l_1 \sin \beta l_1) \\ &\qquad + j\big\{\mathfrak{J}_1 \sinh \alpha l_1 \sin \beta l_1 - \mathfrak{J}_2 \cosh \alpha l_1 \cos \beta l_1 + E_r(\delta \sinh \alpha l_1 \cos \beta l_1 + \gamma \cosh \alpha l_1 \sin \beta l_1)\big\}\Big] \quad . \; . \qquad (19b) \end{aligned}$$

The absolute (numerical) value of the current at a distance l_1 from the receiving end is given by the absolute value of equation (19*b*). This is as follows:—

$$\begin{aligned} |I_{l_1}|^2 &= (\mathfrak{J}_1^2 + \mathfrak{J}_2^2)(\cosh^2 \alpha l_1 \cos^2 \beta l_1 + \sinh^2 \alpha l_1 \sin^2 \beta l_1 + E_r^2(\gamma^2 + \delta^2)(\sinh^2 \alpha l_1 \cos^2 \beta l_1 + \cosh^2 \alpha l_1 \sin^2 \beta l_1) \\ &\quad + 2\mathfrak{J}_1 E_r(\gamma \sinh \alpha l_1 \cosh \alpha l_1 - \delta \sin \beta l_1 \cos \beta l_1) - 2\mathfrak{J}_2 E_r(\gamma \sin \beta l_1 \cos \beta l_1 + \delta \sinh \alpha l_1 \cosh \alpha l_1) \qquad (20) \end{aligned}$$

The power loss on a small length dl_1 of the line over which the current is sensibly constant

$$= |I_{l_1}|^2 R_K dl_1$$

and the total loss over a length l_1

$$= \int_0^{l_1} |I|^2 R_K dl_1$$

By integrating the right-hand side of equation (20) between the limits "0" and "l_1" we obtain

$$\begin{aligned} \int_0^{l_1} |I|^2 R_K dl_1 = \frac{R_K}{2}\Bigg[&(\mathfrak{J}_1^2 + \mathfrak{J}_2^2)\left(\frac{\sinh 2\alpha l_1}{2\alpha} + \frac{\sin 2\beta l_1}{2\beta}\right) + E_r^2(\gamma^2 + \delta^2)\left(\frac{\sinh 2\alpha l_1}{2\alpha} - \frac{\sin 2\beta l_1}{2\beta}\right) \\ &+ 2\mathfrak{J}_1 E_r\left\{\frac{\gamma}{2\alpha}(\cosh 2\alpha l_1 - 1) + \frac{\delta}{2\beta}(\cos 2\beta l_1 - 1)\right\} \\ &- 2\mathfrak{J}_2 E_r\left\{\frac{\delta}{2\alpha}(\cosh 2\alpha l_1 - 1) - \frac{\gamma}{2\beta}(\cos 2\beta l_1 - 1)\right\}\Bigg] \quad . \; . \; . \; . \; . \; . \; . \; . \qquad (21) \end{aligned}$$

This is the required expression for the power losses in a line of length "l_1," and it will be noted that the losses depend on the power factor at the receiving end. At unity power factor $\mathfrak{J}_2 = 0$ and the last term disappears. In its present form the expression applies when the power factor is lagging, because it was assumed in the beginning that $I_r = \mathfrak{J}_1 - j\mathfrak{J}_2$. For a leading power factor the sign of $\mathfrak{J}_2$ must be reversed and the last term made positive, thus increasing the losses.*

(G) EFFECTS DUE TO STRANDING.

It is well known that the self-inductance of a stranded conductor (of non-magnetic material) is less than that of a solid conductor having the same cross-sectional area, owing to the greater diameter. The amount of this reduction varies with the number of strands, and decreases as the number of strands increases, since when the number of strands is indefinitely large the inductance is the same as for a single conductor of the same total cross-section. The self-inductance of a stranded conductor is, however, less than for a single conductor of diameter equal to the maximum diameter of the stranded conductor. It is usual to work with this maximum diameter rather than with the diameter of the conductor of equivalent area. Accordingly, when the effect of stranding is taken into account in a single formula, the term due to internal self-inductance increases with number of strands in order to take into account the fact that the maximum diameter approaches the diameter of the equivalent conductor as the number of strands is increased. The problem has been solved by Dwight, who has shown that in the formula

$$L = \left(0 \cdot 5 + 2 \operatorname{logh} \frac{l}{b}\right) 10^{-9} \text{ henry/cm}$$

(b = overall radius, l = distance of return circuit), the effect of stranding may be taken into account by replacing the first term (0·5) by the following:—

For Single conductor, constant term = 0·5
61-strand ,, ,, = 0·517
37-strand ,, ,, = 0·528
19-strand ,, ,, = 0·555
7-strand ,, ,, = 0·642
3-strand ,, ,, = 0·777

When the spacing between the conductors is small (of the order of two or three feet), taking account of stranding alters the reactance by an amount in the region of one or two per cent, and this refinement may be justifiable. At the large spacings (12 to 25 feet and upwards) used on high-voltage lines, however, the alteration is less than 1 per cent (becoming decreasingly important as the spacing increases) and the effect may be neglected, bearing in mind the practical variations in the conductor spacings, the unknown effect of the steel towers, etc. For these reasons, no account is taken of stranding in the working formulæ given (Appendix IV).

For cables of non-magnetic material, the effect of spiralling of strands in giving an axial magnetic field may be neglected.

(H) CONDUCTORS WITH STEEL CORES.†

Effect on inductance.

The spiralling of the strands of a conductor tends to increase the self-inductance by producing a solenoid effect. In non-magnetic conductors this effect is quite negligible. In aluminium conductors with steel cores there arises a second effect due to the core, which operates in the reverse direction to the solenoid effects. The current carried by the steel core is smaller than would be carried if the conductor were homogeneous, thus reducing the linkages. When there is only one layer of aluminium over the steel core, the solenoid effect is found to preponderate, and the net result is an increase of inductance over that of a non-magnetic conductor of similar stranding and overall diameter, the amount of increase at 3-feet spacing varying up to about 17 per cent with the current carried, being greater at higher current densities.

With two or more layers of aluminium round the core, the solenoid effect more or less cancels out, since the spiralling is in opposite directions for alternate layers. In this instance, the effect of the low-current density in the core becomes apparent, and the net result is a slight decrease in the inductance of the order of 5 per cent at 3-feet spacing compared with that of a non-magnetic conductor of the same stranding and overall diameter. This inductance is, moreover, constant, and independent of the current flowing.

For long-distance transmission the conductors used will almost invariably have two or more layers of aluminium over the steel, and under such conditions it is sufficiently accurate to take the inductance of a steel-cored conductor as being equal to that of a homogeneous non-magnetic conductor of the same stranding and overall diameter. The error introduced thereby is unimportant at practical spacings of conductors, but for single-layer conductors, however, this method is too inaccurate.

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* When two or more power circuits are in close proximity, equation (21) is only strictly true when the conditions are such that the effect of mutual inductance between them is balanced out. As already mentioned, this is not always the case when both circuits are transposed at the same frequency, but depends on the phase sequence of the conductor currents. For the "grid" lines the effect is, however, very small and may be neglected. It is to be noted that the above limitation applies also when the power losses are estimated from the difference between the sending- and receiving-end powers, as it is inherent in the ordinary hyperbolic theory of long lines upon which the method usually employed and the authors' method (see equation (21)) are both based.

† This information is based on the experiments of Prof. W. Work, of Pittsburg, on standard sizes of American conductors. See Bib. Ref. No. 1, Chapter II and Tables.

Effect on resistance.[*]

The addition of a steel core reduces the resistance of a conductor, as the core carries part of the current. The reduction is, however, only about 1 or 2 per cent. A much more important effect is that due to the spiralling of the aluminium wires, which produces an axial field along the conductor, giving rise to hysteresis and eddy-current losses in the steel. These losses vary both with frequency and current density, and depend also on the number of layers of aluminium over the steel. When only one layer of aluminium wire is used, the losses are greatest; with two layers spiralled in opposite directions the net effect is negligible, as the axial field is substantially eliminated. With three layers, the losses lie between those for a single layer and those for a double layer, due to the unbalanced effect of the outer layer.

For a conductor with a single layer of aluminium the increase in a.c. resistance with increasing current density may be as much as 25 per cent at practical current densities, while for a three-layer conductor the maximum increase is about 20 per cent.

APPENDIX III.—THE IMPEDANCE OF A LINE WITH EARTH RETURN.

(A) INTRODUCTION.

In Appendix II the problem of the impedance of three-phase overhead systems was dealt with. It has been assumed throughout this report that in normal operation the phase currents are balanced, i.e. the vector sum is zero, as will be the case in the systems with which the authors are particularly concerned. Under exceptional circumstances the currents may become unbalanced, and in the present Appendix it is proposed to deal with the most important case of this kind, namely, when there is a short-circuit to earth on one phase.

The solution of this problem involves a knowledge of the effective resistance and inductance of an earth return. This problem has been considered by many investigators, and a number of different solutions are available which, however, usually give similar numerical results for earth impedance. Since a consideration of each of these in detail would be too lengthy, the authors have decided to give one in detail, that due to Rüdenberg,[†] which they have themselves tested experimentally and found to be reasonably accurate. The methods in the others will be briefly indicated and a table of formulæ will be given.

(B) IMPEDANCE OF A SIMPLE LINE AND EARTH RETURN.

According to Rüdenberg, it is assumed that the line conductor can be taken as located along the axis of a semi-cylindrical trench of which the radius is the height of the conductor above earth. It is also assumed that the current flow is uniformly parallel to the line, that is, the crowding of lines of current flow due to finite earth plates is neglected.

Let ρ = distance of any point from the line, measured normal to the axis.
B = magnetic induction, the lines of which are presumed to be circles with the line as axis.
E = electric force assumed parallel to the line.
t = time co-ordinate.
i = current density at any point in the earth in absolute units.

Then, if the law of electromagnetic induction

$$\int B dl = 4\pi \int_S i dS$$

is applied to a toroid bonded by the cylinders ρ and $\rho + d\rho$, we have the standard equation

$$\frac{1}{\rho}\frac{\partial}{\partial\rho}(\rho B) = 2\pi i \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22a)$$

But from the law of electric induction

$$\int E dl = \frac{\partial}{\partial t}\int_S B dS$$

If this is applied to a circuit formed by two filaments parallel to the axis and distant ρ and $\rho + d\rho$ from it we have

$$\frac{\partial E}{\partial \rho} = \frac{\partial B}{\partial t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (22b)$$

But if u = specific resistance of the earth in absolute units

$$E = ui$$

whence

$$\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial i}{\partial\rho}\right) = \frac{2\pi}{u}\frac{\partial i}{\partial t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

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[*] Skin-effect is negligible for commercial conductor sizes and frequencies.

[†] Bib. Ref. No. 24.

It is now assumed that the current density i is sinusoidal with the same frequency as the current in the line so that (23) becomes

$$\frac{1}{\rho}\frac{d}{d\rho}\left(\rho\frac{di}{d\rho}\right) = \frac{2\pi j\omega i}{u} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (24)$$

This is Bessel's equation, and since i must be zero when ρ is very large, i is proportional to a Bessel's function of second kind and zero order. Again, the integral of the current from $\rho = h$ to $\rho = \infty$ is equal to the current in the line (I), since the latter entirely returns by the earth. Thus

$$i = \frac{\sqrt{jK}H_0(\sqrt{jK}\rho)Ie^{j\omega t}}{\pi h H_1(\sqrt{jK}h)} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (25)$$

where H_0 and H_1 are Hankel functions of the zero and first orders, that is, Kelvin's functions $ker_0 + jkei_0$ and $ker_1 + jkei_1$, and

$$K = 2\pi\sqrt{f/u},$$
$$Ie^{j\omega t} = \text{total current, and}$$
$$f = \text{frequency.}$$

For $\rho = h$ immediately under the line,

$$\begin{aligned} E &= ui \\ &= \frac{u\sqrt{jK}H_0(\sqrt{jK}h)Ie^{j\omega t}}{\pi h H_1(\sqrt{jK}h)} \\ &= \omega Ie^{j\omega t}\left[\frac{\pi}{2} + j2\,\mathrm{logh}\left(\frac{2}{\gamma Kh}\right)\right] \end{aligned} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (26)$$

since Kh is generally very small. γ = Bessel's constant = 1·781 . . .

The potential drop in the earth is El, where l is the length of the line. Thus the effective resistance R and inductance L of the earth in absolute units for a length of line l are given by

$$\left.\begin{aligned} R &= \frac{\pi\omega l}{2} = \pi^2 fl \\ L &= 2l\,\mathrm{logh}\left(\frac{2}{\gamma Kh}\right) \end{aligned}\right\} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (27)$$

In actual practice the crowding of the lines of current flow at the earth plates must be taken into account by an added resistance and inductance R' and L'.

The self-inductance of the aerial lines of force of the line is given by

$$l(A_1 + 2\,\mathrm{logh}\,h/b) \text{ absolute units} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (28)$$

where A_1 is a constant depending on the stranding of the line conductor, b is the outside radius of the conductor in cm. The effect of the field of the wire in the earth is shown by Rüdenberg to die away rapidly at fairly short distances from the line.

Thus the total inductance of line and earth return is

$$L' + l\left(A_1 + 2\,\mathrm{logh}\,\frac{2}{\gamma Kb}\right) \text{ C.G.S. units} \quad . \; . \; . \; . \; . \; . \; . \; . \; (29)$$

and the total resistance

$$R' + \pi^2 fl + R_{Ka}l \text{ C.G.S. units} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (30)$$

all the quantities being measured in electromagnetic C.G.S. units, and where R_{Ka} = resistance of the conductor per unit length in absolute units.

Rüdenberg's formulæ were recommended by the Comité Consultatif International des Communications Téléphoniques à Grande Distance,* but recently Pollaczek's formulæ have been preferred. Other formulæ, however, have been given, the most important of which are discussed below.

Breisig † uses the method of the energy of the magnetic field in order to deduce self-inductance and mutual inductance coefficients of an earth return. He considers the conductor as surrounded on all sides by the earth, but the conductor is taken as of finite length. The inductance so calculated should be too low on account of the overestimate of the attenuation of the aerial field by the assumption of earth on all sides.

Pollaczek ‡ makes somewhat the same assumptions as Rüdenberg, but takes the earth as a semi-infinite solid and the wire parallel to the surface and applies boundary conditions. He assumes that the electric force and current flow are parallel to the wire and uniform, and that the height of the line is small compared with other quantities. He obtains a Bessel's differential equation, as Rüdenberg, but develops some of the formulæ by means of series and integrals.

* Bib. Ref. No. 29.

† *Ibid.*, No. 22.

‡ *Ibid.*, No. 27.

Mayr * deals only with mutual inductance of earth currents, not self-inductance. He assumes that the earth is a conducting stratum 300–500 metres in thickness, with a perfect dielectric of unit permeability and specific inductive capacity above and below.

Carson † obtains a solution by means of periodic functions and Fourier integrals. With Rüdenberg and Pollaczek he assumes that the electric force is parallel to the line conductor and that the earth is a semi-infinite solid with finite conductivity. He determines the unknown functions by means of the condition that at the surface of the earth both the magnetic fields due to the line and due to the earth currents are continuous. His treatment differs from Pollaczek's only in the form of functions used.

When the impedance of an earth return is considered there is little difference between the formulæ of Rüdenberg, Pollaczek and Carson in practice. When the current distribution at wider separations is required, as in inductive interference, the formulæ of Pollaczek and Carson seem superior. It is hoped to treat this latter aspect in a future report.

A simple, practical method for estimating the effect of earth currents is to assume that the earth return current is located in an equivalent conductor below the surface of the earth. With a perfectly conducting earth this depth would be equal to the height of the line, but owing to the high resistivity it is actually much lower. For 50 cycles per second a depth of 500 or 600 metres has been suggested for earth of average resistivity. The depth of the image conductor decreases with increase of frequency and increase of earth conductivity.

Formulæ for impedance of line and earth return.

The resistance of the conductor and earth plates and the effect of stranding are neglected in the formulæ given below, proposed by the following authorities:—

RÜDENBERG—

Inductance (henrys/cm).

$$\left[1 + 2\,\text{logh}\left(\frac{2}{\gamma K b}\right)\right]10^{-9}$$

Resistance (ohms/cm).

$$\pi^2 f 10^{-9}$$

POLLACZEK—

Inductance (henrys/cm).

$$\left[1 + 2\,\text{logh}\left(\frac{2}{\gamma K_1 b}\right) + \frac{4\sqrt{2K_1 h}}{3}\right]10^{-9} \text{ if } K_1 h < 1$$

$$\left[2\,\text{logh}\left(\frac{2h}{b}\right) + \frac{\sqrt{2}}{K_1 h} - \frac{1}{2\sqrt{2K_1^3 h^3}}\right]10^{-9} \text{ if } K_1 h > 1{\cdot}25$$

Resistance (ohms/cm).

$$10^{-9}\omega\left[\pi/2 - \frac{4\sqrt{2K_1 h}}{3} + 4K_1^2 h^2(5/4 - \text{logh}\,\gamma K_1 h)\right] \text{ if } K_1 h < 1/4$$

$$10^{-9}\omega\sqrt{2}\left[\frac{1}{K_1 h} - \frac{1}{\sqrt{2K_1^2 h^2}} + \frac{1}{4K_1^3 h^3}\right] \text{ if } K_1 h > 1{\cdot}25$$

BREISIG—

Inductance (henrys/cm).

$$2\left[\text{logh}\left(\frac{\pi}{Kb}\right) - 1\right]10^{-9}$$

Resistance (ohms/cm).

$$\pi^2 f 10^{-9}$$

CARSON—

The total impedance of the earth return is given by

$$Z_0 + 4\omega(P + jQ)10^{-9} \text{ ohms/cm}$$

where Z_0 = impedance with perfectly conducting earth, i.e. with image conductor for earth return.

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* Bib. Ref. No. 23.

† *Ibid.*, No. 25.

The impedance due to finite conductivity then gives:—

$$\textit{Inductance} = 4Q10^{-9} \text{ henrys/cm}$$
$$= -\,0\cdot 0386 + \tfrac{1}{2}\operatorname{logh}\left(\frac{1}{x}\right) + \frac{x}{3\sqrt{2}}10^{-9} \text{ henrys/cm}$$
$$\textit{Resistance} = 4\omega P$$
$$= 4\omega\left[\frac{\pi}{8} + \frac{x}{3\sqrt{2}} + \frac{x^2}{16}\left(0\cdot 6728 + \operatorname{logh}\frac{2}{x}\right)\right]10^{-9} \text{ ohm/cm}$$

where $x = 2hK < 1/4$

When $x > 1/4$ the formulæ are rather more complicated, being in the form of series, which, however, converge rapidly.

The following symbols are used in the above formulæ:—

$$K = 2\pi\sqrt{\frac{f}{u}}$$
$$K_1 = 2\pi\sqrt{\frac{2f}{u}}$$

f = frequency
s = specific resistance of earth in C.G.S. units
b = radius of line conductor (cm)
h = height of line conductor (cm)
$\gamma = 1\cdot 781 \ldots$ = Bessel's constant
$\omega = 2\pi f$

(C) Short-Circuit with other Conductors Present.

The previous calculations refer only to a single-phase current with a return path through the earth. In recent practice and on the proposed "grid" system the towers are joined together with a continuous earth wire, the conductivity of which is comparable with that of the phase wires (actually about one-half the phase wires). A considerable portion of the return current travels along the earth wire in parallel with the earth. For the purposes of calculation it is assumed that the earth wire is insulated from the earth except at the two ends of the section of line considered. In practice the earth wire is bonded at every tower, but there is not much exchange of current between earth and earth wire at intermediate towers, owing to the fact that when the earth current has spread out from the fault the earth plate at the tower generally acts as a high-resistance bond. The authors' experiments on the "grid" lines show that usually the "multiple" earths affect the current in the earth wire only at the ends of the section under short-circuit, and the average current is increased only by a small amount. With short lines the effect may be large. The matter is discussed more fully later.

Let Δe_1 = potential-drop per cm along Phase 1 assumed earthed at distance l cm from the earthed neutral of the generator.
Let J_1 = short-circuit current in Phase 1.

Then

$$\Delta e_1 = \left[R_{Ka} + j\omega\left\{A_1 + 2\operatorname{logh}\left(\frac{h_1}{b}\right)\right\}\right]J_1 + 2j\omega I_2\operatorname{logh}\left(\frac{h_2}{S_{2,1}}\right) + 2j\omega I_3\operatorname{logh}\left(\frac{h_3}{S_{3,1}}\right) - 2j\omega I_4\operatorname{logh}\left(\frac{h_4}{S_{4,1}}\right) \quad (31)$$

In this expression all quantities are in absolute c.g.s. units.

Where I_2 and I_3 are the currents in Phases 2 and 3.
I_4 and I_5 are the currents in earth conductor and earth respectively.
h_1, h_2, h_3, h_4 are the heights above earth (cm) of conductors 1, 2, 3 and earth wire respectively.
$S_{2,1}, S_{3,1}, S_{4,1}$ are the distances (cm) of Phases 2, 3 and earth wire respectively from Phase 1.
A_1 = a constant to take account of internal self-inductance of Phase conductor 1.

Let Δe = potential-drop per cm in the earth.

Then

$$\Delta e = \left[\frac{R'}{l} + R + j\omega\left(\frac{L'}{l} + L\right)\right]I_5$$
$$= \left[\frac{R'}{l} + R_4 + j\omega\left(A_4 + 2\operatorname{logh}\frac{h_4}{r_4}\right)\right]I_4 - J_1 2j\omega\operatorname{logh}\frac{h_1}{S_{1,4}} - 2j\omega I_2\operatorname{logh}\left(\frac{h_2}{S_{2,4}}\right) - I_3 2j\omega\operatorname{logh}\left(\frac{h_3}{S_{3,4}}\right) \quad . \quad . \quad (32)$$

In the above equations

$$J_1 = I_4 + I_5$$

(I_2 and I_3 being neglected in comparison with J_1, I_4 and I_5), and

R_4 = resistance of earth conductor per cm in absolute ohms.
R_4' = contact resistance in earth wire connections in absolute ohms.
A_4 = a constant to take account of internal self-inductance of earth wire.*
R = resistance of earth per cm length in absolute units.
L = inductance of earth per cm length in absolute units.
R' = resistance of earth plate and fault connection in absolute units.
L' = inductance in henrys of earth plate and fault connection in absolute units.
$S_{1,4}$, $S_{2,4}$, $S_{3,4}$ = distances in cm of phase conductors from earth wire.
I_5 = total current in earth.
r_4 = outside radius of earth wire in cm.

The convention adopted is that the positive direction of currents in the phases is in the direction of J_1, while the positive direction for I_4 and I_5 is opposite to J_1.

The potential V applied to the fault is given by

$$\frac{V}{l} = \Delta e_1 + \Delta e \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)$$

If the specific resistance of the earth is known and also the frequency, then R and L can be found from equation (27). The values of R', R_4', and L' must be estimated or assumed. When these quantities are known, and also I_2 and I_3, the values of

$$\frac{I_5}{J_1} \text{ and } \frac{I_4}{J_1}$$

can be calculated from equation (32). If these values are substituted in (31), Δe_1 is obtained as a factor times J_1, and Δe may also be obtained in similar form. Thus the total impedance V/J_1 can be found. In deriving the above equations the effect of I_2, I_3 and I_4 on the earth current has been neglected. Calculation shows that this is justifiable owing to the large attenuation of their magnetic fields in the earth. Further, the effect of the earth currents on the self-inductance of the earth wire has been neglected. This matter is difficult of approach since theories are least rigorous near the conductors, but the assumption is to some extent justified from Rüdenberg's point of view, though not from the position adopted by Pollaczek and Carson. Experimental evidence on currents in earth wires is difficult to obtain, but the authors' tests indicate that the above theory would, if anything, underestimate the earth wire current, whereas a mutual inductance effect due to the earth current would be expected to decrease the earth wire current. The matter would repay further study, but the authors are of opinion from experimental and theoretical considerations that, bearing in mind the magnitude of the earth wire current, serious errors are not involved.

Simpler expressions are obtained if the effect of the current in the insulated phases and stray resistances, etc., are neglected. On large interconnected systems the former assumption will be valid. The correction for the latter depends on particular cases and the resistance of the fault connection and earth plate may vary from a fraction of an ohm to several ohms. Under the above conditions, the above equations reduce to

$$\left.\begin{aligned} \Delta e_1 &= \left[R_{Ka} + j\omega\left(A_1 + 2\,\text{logh}\,\frac{h_1}{b}\right)\right] J_1 - 2I_4 j\omega\,\text{logh}\,\frac{h_4}{S_{1,4}} \\ \Delta e &= (R + j\omega L)I_5 \\ &= \left[R_4 + j\omega\left(A_4 + 2\,\text{logh}\,\frac{h_4}{r_4}\right)\right] I_4 - 2J_1\omega j\,\text{logh}\,\frac{h_1}{S_{4,1}} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

To simplify, let

$$\begin{aligned} \lambda &= (R + j\omega L)10^{-9} \\ &= \left[\pi^2 f + j\omega\left(2\,\text{logh}\,\frac{2}{\gamma K h_1}\right)\right] 10^{-9} \text{ ohm/cm} \end{aligned}$$

$$\lambda_4 = \left[R_4 + j\omega\left(A_4 + 2\,\text{logh}\,\frac{h_4}{r_4}\right)\right] 10^{-9} \text{ ohm/cm}$$

$$\lambda_1 = \left[R_{Ka} + j\omega\left(A_1 + 2\,\text{logh}\,\frac{h_1}{b}\right)\right] 10^{-9} \text{ ohm/cm}$$

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* The effect of stranding is unimportant at practical conductor spacings and is neglected in the working formulæ. This also applies to symbol A_1.

$$\left.\begin{aligned} L_1 &= 2j\omega 10^{-9} \operatorname{logh} \frac{h_1}{S_{4,1}} \text{ ohm/cm} \\ L_4 &= 2j\omega 10^{-9} \operatorname{logh} \frac{h_4}{S_{4,1}} \text{ ohm/cm} \end{aligned}\right\}$$ where $S_{4,1}$ means the axial distance from phase 1 to earth wire, see Fig. 7

Then equation (34) becomes

$$\Delta e_1 = \lambda_1 J_1 - L_4 I_4 \quad \ldots \ldots \quad (35a)$$

$$\Delta e = \lambda I_5 = \lambda_4 I_4 - L_1 J_1 \quad \ldots \ldots \quad (35b)$$

In these expressions Δe_1 and Δe are in volts/cm; J_1, I_4, I_5 are in amperes.

Also we have

$$J_1 = I_4 + I_5 \quad \ldots \ldots \quad (35c)$$

from which

$$\frac{I_4}{J_1} = \frac{\lambda + L_1}{\lambda + \lambda_4}$$

and

$$\frac{I_5}{J_1} = \frac{\lambda_4 - L_1}{\lambda + \lambda_4}$$

The impedance per cm is given by

$$\frac{V}{lJ_1} = \frac{\Delta e_1 + \Delta e}{J_1} = \lambda_1 J_1 + L_4 I_4 + \lambda I_5 = \lambda_1 - L_4 \frac{(\lambda + L_1)}{\lambda + \lambda_4} + \frac{\lambda(\lambda_4 - L_1)}{\lambda + \lambda_4}$$

$$= \left[\lambda_1 + \frac{\lambda(\lambda_4 - L_4) - L_1(\lambda + L_4)}{(\lambda + \lambda_4)}\right] \text{ ohm/cm} \quad \ldots \quad (35d)$$

The following figures may be of interest as indicating the measure of agreement to be obtained in practice. Some short-circuit tests were carried out by the authors upon a steel tower line * about 16 metres high and bearing a three-phase overhead system in vertical flat spacing with a normal voltage of 33 kV. The line was about 10 kilometres long. A steel earth wire, of low conductivity compared with the phase wires but of steel having a rather higher conductivity than usual, connected all the towers, an earth plate being provided at every other tower. Tests were made with a fault on one phase:—

(1) With a phase wire bonded at every fourth tower to simulate a multiple earthed earth wire.
(2) With a phase wire bonded only at each end of the line.
(3) With the steel earth wire alone.

Theoretical values were obtained assuming no local fault resistance or other stray effects. The earth resistance was taken as 1 000 ohms/cm cube from measurements on interference with telephone lines. The frequency was 50 cycles.

The measured values for the impedance and power factor for the three cases were:—

	(1)	(2)	(3)
Impedance	0·702 ohm/km	0·695 ohm/km	0·795 ohm/km
Power factor	51·8 per cent	53·5 per cent	49·9 per cent

The calculated values for cases (2) and (3), treated as above, were:—

	(2)	(3)
Impedance	0·683 ohm/km	0·760 ohm/km
Power factor	48·4 per cent	45·8 per cent

It is seen that " multiple " earths did not have a very great effect upon the impedance with a high conductivity earth wire ((1) and (2)). The general agreement is fairly close considering the uncertain nature of several of the dimensions and quantities involved, and a large part of the discrepancy can be explained by the neglect of earth plate and local fault resistance. For example, if a stray resistance (at fault or earth plate) of 0·2 ohm were taken as included in the measurement, the test values would have been modified to the following for comparison with theory:—

	(1)	(2)	(3)
Impedance	0·679 ohm/km	0·675 ohm/km	0·774 ohm/km
Power factor	50·2 per cent	51·9 per cent	48·5 per cent

---

* The Runcorn-Ellesmere Port Line of the Mersey Power Co., Ltd.

The conductivity of the earth does not have a very great effect upon the impedance, within fairly wide limits. To illustrate this, some figures are taken from some calculated for the proposed grid system for England and Scotland. The cases taken are for double and single circuit towers with a short-circuit on the lowest phase.

Resistivity of earth, ohms/cm cube	Impedance, ohm/km	Power factor, per cent	Tower
20 000	0·666	34·6	Single circuit
500	0·609	34·9	
20 000	0·676	33·4	Double circuit
500	0·616	33·9	

Dimensions are given in the worked examples, see later.

(D) THE EFFECT OF MULTIPLE EARTHS ON THE EARTH WIRE.

In practice the earth wire is connected to earth at every tower, so that the earth conductor and earth in parallel form a repeated network except at the ends of the section. Here the effective scheme of connections depends upon how exactly the fault occurs. The simplest assumption and one fulfilled in tests by the authors is that the fault takes place to the tower, so that the earth wire is directly connected to the current-carrying phase at the fault, and to the return conductor or pole or neutral of generator at the other end of the section. The earth current must, however, spread out before attaining uniform flow, and this interposes an " earth plate resistance " at each end in the path of the earth current proper. The effect of this is to produce a non-uniform potential distribution in the earth, with the result that there is an exchange of current between earth wire and earth, the earth wire current being large at the end of the line and decreasing to a constant value as the centre of the section is approached. If the earth plate resistance is large the increase of earth wire current at the ends will be correspondingly large, while if the earth plate resistance is very small the current in the earth wire will be constant, and it will behave as if there were no intermediate earths; for in this case the potential-drop is uniform both in the earth and earth wire, and there can be no exchange of current between them. If, on the other hand, there is an initial resistance in the connection between the earth wire and fault which is much higher than the earth plate resistance, then the earth wire current will increase from the ends to the centre of the line; formulæ for this case are not given in the present report but can be derived in the same manner as for the case considered.

Assume that the fault is to a tower so that the earth wire is directly connected to the fault phase, and also that the earth wire is connected to the other pole of the supply. Let the earth plate resistance at the fault and at the return pole be R', and let R_i' be the resistance of the intermediate earth plates, supposed uniform along the line. In the average case $R' = R_i'$, but since the effect depends largely upon the value R' it is desirable for illustration of the theory not to make this simplification. The problem can be solved as a repeated network, but this method leads to complicated formulæ if a finite number of towers is considered. Much simpler expressions are obtained if the earths at each tower are treated as a uniformly distributed " leakage " G, where

$$G = \frac{1}{R_i' l_0} \quad \text{and} \quad l_0 = \text{distance in cm between consecutive towers.}$$

It may be shown that *

$$\frac{I_4}{J_1} = \frac{R'(\lambda_4 - L_4)a_1 \cosh a_1 x}{(\lambda + \lambda_4)\left[(\lambda + \lambda_4)\sinh a_1 \frac{l}{2} + R' a_1 \cosh a_1 \frac{l}{2}\right]} + \frac{L_4 + \lambda}{\lambda + \lambda_4} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (36a)$$

where I_4 = current in earth wire.
J_1 = total current in short-circuited phase.
λ_4 = self-impedance of earth wire as above.
λ = self-impedance of earth per cm as above.
L_4 = mutual impedance between fault phase and earth wire.
$a_1 = G(\lambda + \lambda_4)$.
x = distance in cm from centre of fault section.
l = length of line between ends of short-circuited section. See Fig. 7.

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[*] As mentioned later, the net effect of the "multiple" earths on the average percentage of short-circuit current passing through the earth wire and on the impedance of line and earth return is only a few per cent for the grid system, except on very short lines, say, about 1 mile long, and is therefore unimportant from a practical aspect, and has been neglected in the "working formulæ." For this reason the derivation of equations (36a) to (36f) (which is lengthy) is not given in detail herein, but will be published later in a paper dealing with the methods of test, etc., employed and the induced voltages, etc., observed in telephone circuits, in the authors' tests.

In the majority of cases $\alpha_1\frac{l}{2}$ is large, so that

$$\cosh \alpha_1\frac{l}{2} = \sinh \alpha_1\frac{l}{2}$$

Thus

$$\frac{I_4}{J_1} = \frac{(\lambda_4 - L_4)}{(\lambda + \lambda_4)\left[1 + (\lambda + \lambda_4)/\alpha_1 R'\right]}\,\frac{\cosh \alpha_1 x}{\cosh \alpha_1\frac{l}{2}} + \frac{L_4 + \lambda}{\lambda + \lambda_4} \quad \ldots\ldots \tag{36b}$$

As R' increases the fraction of total current in the earth wire approaches a limiting maximum value given by

$$\frac{I_4}{J_1} = \frac{\lambda_4 - L_4}{\lambda + \lambda_4}\,\frac{\cosh \alpha_1 x}{\cosh \alpha_1\frac{l}{2}} + \frac{L_4 + \lambda}{\lambda + \lambda_4} \quad \ldots\ldots \tag{36c}$$

Again, as R' decreases or as x decreases, I_4 tends to the value for an insulated earth wire as already treated, namely

$$\frac{I_4}{J_1} = \frac{L_4 + \lambda}{\lambda + \lambda_4} \quad \ldots\ldots \tag{36d}$$

Actually the first term is not usually of importance until x is nearly equal to $l/2$, owing to the rapid variation of $\cosh \alpha_1 x$. Fig. 9 shows a curve calculated for some tests on the Bedford–Little Barford Grid Line. Tests were made of earth resistivity by surface methods and also of earth plate resistance and tower resistances. The last were negligible, being of the order of 0·01 ohm at 50 cycles. The earth resistivity was taken as 2 000 ohms per cm cube, the intermediate earth plates as 2·5 ohms, and the terminal earth plates as 1·25 ohms; i.e.

$$u = 2 \times 10^{12}$$
$$R' = 1{\cdot}25 \text{ ohms}$$
$$R'_i = 2{\cdot}5 \text{ ohms}$$

All these values were averages from the tests made. The dimensions, etc., of the towers were similar to those given in Fig. 2 for single circuit " grid " lines. The line was transposed one complete turn of the " lay " in the length tested so that the effect of different heights of the phase wires was averaged. From Fig. 9 it is clear that most of the variation in current occurs in the kilometre adjacent to the end of the line. The value of I_4/J_1 observed at the end of the line was approximately 74 per cent as a mean for several observations, thus giving satisfactory agreement with the theoretical value of 72 per cent. The phase displacement between the total current and the earth wire current was small, the theoretical value being 3° 29′ in a positive direction, that is towards the voltage vector. The average of a number of observations at different short-circuit currents was 3° 20′, which is a remarkably close agreement.

The effect of the intermediate earths and consequent increase of earth wire current at the ends of the line was to increase the average value of the earth wire current from about 31 per cent of the total for the " insulated " case, i.e. without intermediate earths, at the centre of the line, to 34 per cent, an amount which may be ignored in practice.

The earth wire current at the end of the line is given by

$$\frac{I_4}{J_1} = \frac{\lambda_4 - L_4}{(\lambda + \lambda_4)\left[1 + (\lambda + \lambda_4)/\alpha_1 R'\right]} + \frac{L_4 + \lambda}{\lambda + \lambda_4} \quad \ldots\ldots \tag{36e}$$

and in the limiting case when R' is very large, $I_4 = J_1$ which is otherwise obvious. It is also clear that if $l/2$ is small $\cosh \alpha_1 x$ does not become negligible in comparison with $\cosh \alpha_1\frac{l}{2}$ even when $x = 0$, and the earth wire current will be greater than in the absence of intermediate earths, at all parts of the line. The initial current is, however, independent of the length of the line as is also, except for short lines, the current in the middle of the line.

The overall impedance of the line and earth return is given by

$$Z = \lambda_1 + \frac{\lambda\lambda_4}{\lambda + \lambda_4} - \frac{L_4(L_4 + 2\lambda)}{\lambda + \lambda_4} + \frac{2}{\lambda l}\,\frac{(\lambda_4 - L_4)^2}{(\lambda + \lambda_4)\left(1 + \frac{\lambda + \lambda_4}{R'\alpha_1}\right)} \text{ ohms/cm} \quad \ldots\ldots \tag{36f}$$

where λ_1 = self-impedance of fault phase as above, in ohms/cm.

On the " grid " lines at Bedford for the section tested, about 14 km, the total impedance was 9·0 ohms by equation (36*f*) (or 1·03 ohm per mile). Experiment gave an average impedance of 9·04 ohms and a power factor of about 39·1 per cent; theory giving a power factor of about 41·0 per cent.

The theory given above considers the leakage to earth due to the towers as distributed over the whole of the line. A possible variation of this scheme is to assume the distributed leakage as extending only to the middle of the end spans, treating the terminal sections as ordinary conductors. The effect of this assumption can approximately be included in the above expressions, merely by replacing R' by

$$\frac{R'}{\left(1+\frac{a_1 l_0}{2}\right)}$$

and the modification so introduced is usually small.

As an additional check on the theory the voltage induced in the two free (i.e. insulated) phase wires by the short-circuit current was calculated, the values so obtained for the Bedford tests being about 3 or 4 per cent higher than the experimental values.

If the present theory is applied to the authors' test results on the Runcorn–Ellesmere Port Line for the "multiple" earthed-phase wire and the steel earth wire, the values of earth plate resistances necessary to give agreement with observation are found to be consistent with each other and of the order of magnitude which experience in that locality suggests. No measurements could, however, be taken owing to the difficulty of insulating the steel earth wire for an earth plate test. Accordingly, actual figures are not given here.

APPENDIX IV.—WORKING FORMULÆ AND WORKED NUMERICAL EXAMPLES.

1. LINE IMPEDANCES WITH BALANCED THREE-PHASE CURRENTS.

(*a*) *Introduction.*—For single circuit towers working formulæ are given only for transposed circuits,* this being the only practical case. For double circuit towers formulæ are given for *one* time-phase sequence of currents (viz. that giving the minimum phase impedances, see Fig. 3 (*l*)) when the circuits are transposed at the same frequency, and for *two* phase sequences when not transposed. Of the latter, one phase sequence (the same as that for transposed circuits) gives minimum phase impedance, and the other (see Fig. 3 (*d*)) equal impedances for corresponding conductors (in the same horizontal plane) of the two circuits. All resistances are in ohms per mile and all reactances in ohms per mile to neutral at 50 ∼.

(*b*) *Single circuit towers.*—The resistance and reactance are equal in all phases.

$$\textit{Apparent resistance} = R_{KM} \text{ ohm/mile} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (37)$$

$$\textit{Apparent reactance}\,\dagger = \left[0{\cdot}0253 + 0{\cdot}233 \log_{10}\left\{\frac{\sqrt[3]{(S_{1,2}\,S_{1,3}\,S_{2,3})}}{b}\right\}\right] \text{ ohm/mile to neutral} \quad . \; . \quad (38)$$

(*c*) *Double circuit towers.*—(It is assumed that the two circuits are symmetrical about the vertical centre line of the tower and are transposed in such directions of spiral as to maintain the same relative positions of conductors carrying currents of the same time phase. For Fig. 3 (*l*) the directions are the same.)

(i) *Transposed circuits.*

Time-phase sequence of currents as shown in 2 (*l*).

$$\begin{aligned}
\text{The current in Conductor 1} &= \text{current in Conductor 4} = I_1\\
\text{The current in Conductor 2} &= \text{current in Conductor 5} = I_2\\
&= I_1(-\,0{\cdot}5 + 0{\cdot}866j)\\
\text{The current in Conductor 3} &= \text{current in Conductor 6} = I_3\\
&= I_1(-\,0{\cdot}5 - 0{\cdot}866j)
\end{aligned}$$

Circuit A.

The resistance and reactance of all phases of circuit A are equal.

$$\textit{Apparent resistance} = \left[R_{KM} + 0{\cdot}201 \log_{10}\sqrt[3]{\left(\frac{S_{5,1}\,S_{6,2}\,S_{4,3}}{S_{5,3}\,S_{6,1}\,S_{4,2}}\right)}\right] \text{ ohm/mile} \quad . \; . \; . \; . \quad (39a)$$

$$\textit{Apparent reactance} = \left[0{\cdot}0253 + 0{\cdot}233 \log_{10}\left\{\frac{\sqrt[3]{(S_{1,2}\,S_{2,3}\,S_{1,3})}}{b} \times \sqrt[6]{\frac{(S_{5,1}\,S_{6,1}\,S_{4,2}\,S_{6,2}\,S_{4,3}\,S_{5,3})}{(S_{4,1}\,S_{5,2}\,S_{6,3})^2}}\right\}\right] \text{ ohm/mile to neutral} \quad . \quad (39b)$$

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* All formulæ for transposed circuits apply to a length of line containing an integral multiple of three transpositions

† For equilateral triangular spacing with or without transposition this expression reduces to

$$\text{Reactance} = \left[0{\cdot}0253 + 0{\cdot}233 \log_{10} \frac{S_{1,2}}{b}\right] \text{ ohm/mile to neutral} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (38a)$$

Circuit B.

The resistance and reactance of all phases of circuit B are equal.

$$\textit{Apparent resistance} = \left[R_{KM} + 0{\cdot}201 \log_{10} \sqrt[3]{\left(\frac{S_{2,4}\,S_{3,5}\,S_{1,6}}{S_{3,4}\,S_{1,5}\,S_{2,6}}\right)}\right] \text{ohm/mile} \quad \ldots \quad (40)$$

Apparent reactance:—same as equation (39*b*) above

(ii) *Non-transposed circuits.*

Time-phase sequence of currents as given above for Fig. 3 (*l*).

Circuit A.

$$\text{Phase 1: } \textit{Apparent resistance} = \left[R_{KM} + 0{\cdot}201 \log_{10} \left(\frac{S_{2,1}\,S_{5,1}}{S_{3,1}\,S_{6,1}}\right)\right] \text{ohm/mile} \quad \ldots \quad (41a)$$

$$\textit{Apparent reactance} = \left[0{\cdot}0253 + 0{\cdot}233 \log_{10} \frac{\sqrt[2]{(S_{2,1}\,S_{3,1}\,S_{5,1}\,S_{6,1})}}{bS_{4,1}}\right] \text{ohm/mile to neutral} \quad . \quad (41b)$$

$$\text{Phase 2: } \textit{Apparent resistance} = \left[R_{KM} + 0{\cdot}201 \log_{10} \left(\frac{S_{3,2}\,S_{6,2}}{S_{1,2}\,S_{4,2}}\right)\right] \text{ohm/mile} \quad \ldots \quad (41c)$$

$$\textit{Apparent reactance} = \left[0{\cdot}0253 + 0{\cdot}233 \log_{10} \frac{\sqrt[2]{(S_{1,2}\,S_{3,2}\,S_{4,2}\,S_{6,2})}}{bS_{5,2}}\right] \text{ohm/mile to neutral} \quad . \quad (41d)$$

$$\text{Phase 3: } \textit{Apparent resistance} = \left[R_{KM} + 0{\cdot}201 \log_{10} \left(\frac{S_{1,3}\,S_{4,3}}{S_{2,3}\,S_{5,3}}\right)\right] \text{ohm/mile} \quad \ldots \quad (41e)$$

$$\textit{Apparent reactance} = \left[0{\cdot}0253 + 0{\cdot}233 \log_{10} \frac{\sqrt[2]{(S_{1,3}\,S_{2,3}\,S_{4,3}\,S_{5,3})}}{bS_{6,3}}\right] \text{ohm/mile to neutral} \quad . \quad (41f)$$

Circuit B.

Phase 4: *Apparent resistance*:—as equation (41*e*) with sign of second term reversed.
Apparent reactance:—same as equation (41*f*).

Phase 5: *Apparent resistance*:—as equation (41*c*) with sign of second term reversed.
Apparent reactance:—same as equation (41*d*).

Phase 6: *Apparent resistance*:—as equation (41*a*) with sign of second term reversed.
Apparent reactance:—same as equation (41*b*).

Time-phase sequence of currents as in Fig. 3 (*d*).

Current in Conductor 1 = current in Conductor 6 = I_1
Current in Conductor 2 = current in Conductor 5 = I_2
= $I_1(-\,0{\cdot}5 + 0{\cdot}866j)$
Current in Conductor 3 = current in Conductor 4 = I_3
= $I_1(-\,0{\cdot}5 - 0{\cdot}866j)$

Phases 1 *and* 6.

$$\textit{Apparent resistance} = \left[R_K = 0{\cdot}201 \log_{10} \left(\frac{S_{3,1}\,S_{4,1}}{S_{2,1}\,S_{5,1}}\right)\right] \text{ohm/mile} \quad \ldots \quad (41g)$$

$$\textit{Apparent reactance} = \left[0{\cdot}0253 + 0{\cdot}233 \log_{10} \frac{\sqrt[2]{(S_{2,1}\,S_{3,1}\,S_{4,1}\,S_{5,1})}}{bS_{6,1}}\right] \text{ohm/mile to neutral} \quad . \quad . \quad (41h)$$

Phases 2 *and* 5.

$$\textit{Apparent resistance} = \left[R_K + 0{\cdot}201 \log_{10} \left(\frac{S_{1,2}\,S_{6,2}}{S_{3,2}\,S_{4,2}}\right)\right] \text{ohm/mile} \quad \ldots \quad (41j)$$

$$\textit{Apparent reactance} = \left[0{\cdot}0253 + 0{\cdot}233 \log_{10} \frac{\sqrt[2]{(S_{1,2}\,S_{3,2}\,S_{4,2}\,S_{6,2})}}{bS_{5,2}}\right] \text{ohm/mile to neutral} \quad . \quad . \quad (41k)$$

Phases 3 *and* 4.

$$\textit{Apparent resistance} = \left[R_K + 0\cdot201 \log_{10}\left(\frac{S_{2,3}\,S_{5,3}}{S_{1,3}\,S_{6,3}}\right)\right] \text{ ohm/mile} \quad \ldots \quad (41l)$$

$$\textit{Apparent reactance} = \left[0\cdot0253 + 0\cdot233 \log_{10} \frac{\sqrt[4]{(S_{1,3}\,S_{2,3}\,S_{5,3}\,S_{6,3})}}{bS_{4,3}}\right] \text{ ohm/mile to neutral} \quad \ldots \quad (41m)$$

2. POWER LOSSES WITH BALANCED THREE-PHASE CURRENTS.

The power loss in a "short" line (in watts/mile) = (R.M.S. current)^2 × R_{KM} × length of line in miles

The power loss on a "long" line of length l_1 miles (in watts)

$$= \frac{R_{KM}}{2}\left[(\mathfrak{J}_1^2 + \mathfrak{J}_2^2)\left(\frac{\sinh 2al_1}{2a} + \frac{\sin 2\beta l_1}{2\beta}\right) + E_r^2(\gamma^2 - \delta^2)\left(\frac{\sinh 2al_1}{2a} - \frac{\sin 2\beta l_1}{2\beta}\right)\right.$$
$$\left. + 2\mathfrak{J}_1 E_r\left\{\frac{\gamma}{2a}(\cosh 2al_1 - 1) + \frac{\delta}{2\beta}(\cos 2\beta l_1 - 1)\right\} - 2\mathfrak{J}_2 E_r\left\{\frac{\delta}{2a}(\cosh 2al_1 - 1) - \frac{\gamma}{2\beta}(\cos 2\beta l_1 - 1)\right\}\right] \quad (42)$$

where $a + j\beta = \sqrt{(cZ)}$.

c = capacity susceptance of line in mhos per mile,

Z = vector impedance per mile,

$= (R_{KM} + jx)$,

x = reactance in ohms/mile of line to neutral,

$\gamma + j\delta = \sqrt{\frac{c}{Z}}$.

$\mathfrak{J}_1$ = component of receiving-end current in phase with receiving-end voltage.

$\pm\,\mathfrak{J}_2$ = component of receiving-end current in quadrature with receiving-end voltage.

(NOTE.—Equation (42) refers to the case when the power factor at the receiver is *lagging*. For unity power factor the last term in (42) is zero, while for a *leading* power factor its sign is reversed from that given above.)

3. IMPEDANCE OF LINE WITH EARTH RETURN.

Assumptions. (*Refer to Fig.* 7.)

The short-circuit is assumed to occur from Conductor 1 to earth at Z at a distance "l" cm from the earthed neutral of the generator. The phase voltage V causes the current to flow along the phase conductor MP and to return partly through the earth along PZON and partly along the earth wire PKON. The earth wire is assumed earthed where the fault occurs, and at the supply end (see Fig. 7), but the effect of intermediate (or multiple) earthing of the towers is neglected. The frequency assumed is 50~.

Impedance of phase conductor and return path via earth and earth wire in parallel

$$= \left\{\lambda_1 + \frac{\lambda(\lambda_4 - L_4) - L_1(\lambda + L_4)}{(\lambda + \lambda_4)}\right\} \times 0\cdot161 \times 10^6 \text{ ohm/mile} \quad . \quad (43a)$$

$$\frac{\text{Current in earth wire}}{\text{Current in earthed phase}} = \frac{I_4}{J_1} = \frac{I_4}{I_4 + I_5} = \frac{\lambda + L_1}{\lambda + \lambda_4} \quad \ldots \quad (43b)$$

$$\frac{\text{Current in earth}}{\text{Current in earthed phase}} = \frac{I_5}{J_1} = \frac{I_5}{I_4 + I_5} = \frac{\lambda_4 - L_1}{\lambda + \lambda_4} \quad \ldots \quad (43c)$$

where

$$\lambda = \left\{(\pi^2 f) + j\omega\left(0\cdot5 + 4\cdot6 \log_{10}\frac{2}{\gamma K h_1}\right)10^{-9}\right\} \text{ ohm/cm}$$

$$\lambda_1 = \left\{R_{Ka} + j\omega\left(0\cdot5 + 4\cdot6 \log_{10}\frac{h_1}{b}\right)\right\}10^{-9} \text{ ohm/cm}$$

$$\lambda_4 = \left\{R_4 + j\omega\left(0\cdot5 + 4\cdot6 \log_{10}\frac{h_4}{r_4}\right)\right\}10^{-9} \text{ ohm/cm}$$

$$L_1 = \left\{4\cdot6 j\omega 10^{-9} \log_{10}\left(\frac{h_1}{S_{4,1}}\right)\right\} \text{ ohm/cm}$$

$$L_4 = \left\{4\cdot6 j\omega 10^{-9} \log_{10}\left(\frac{h_4}{S_{4,1}}\right)\right\} \text{ ohm/cm}$$

For meaning of other symbols, see Appendix I.

If there is no earth wire, i.e. all the short-circuit current returns through the earth, the total impedance is the sum of the phase conductor and earth in series

$$= \{\lambda + \lambda_1\} \times 0\cdot161 \times 10^6 \text{ ohm/mile} \qquad \ldots\ldots\ldots\ldots \quad (44)$$

4. Numerical Examples.

(*a*) *Line impedance* (*without earth return*).—As a typical example evaluate the line constants for the "grid" system, double circuit tower, both circuits transposed at same frequency and in same direction. Phase sequence as in Fig. 3 (*l*).

Dimensions of line conductor and axial spacings of cables as on Fig. 2.

Outside diameter of conductor over strands = 0·77 in. = 1·955 cm.

Number of strands = 37.

A.C. resistance of isolated conductor = 0·2505 ohm/mile.

Circuit A.

(Over an integral multiple of three transpositions.)

From equation (39*a*):—

$$\textit{Apparent resistance of any phase} = \left[0\cdot2505 + 0\cdot201 \log_{10}\left(\frac{875 \times 875 \times 774}{935 \times 636 \times 935}\right)^{\frac{1}{3}}\right] \text{ohm/mile}$$

$$= (0\cdot2505 + 0\cdot0018) = 0\cdot252 \text{ ohm/mile}$$

By equation (39*b*):—

$$\textit{Apparent reactance of any phase} = \left[0\cdot0253 + 0\cdot233 \log_{10}\left\{\frac{(398 \times 735 \times 398)^{\frac{1}{3}}}{0\cdot977} \times \frac{(875 \times 636 \times 935 \times 875 \times 774 \times 935)^{\frac{1}{6}}}{(1\,013 \times 951 \times 1\,013)^{\frac{1}{3}}}\right\}\right] \text{ohm/mile to neutral}$$

$$= [0\cdot0253 + (0\cdot233 \times 2\cdot6219)] = 0\cdot637 \text{ ohm/mile to neutral}$$

Circuit B

Apparent resistance of any phase = (0·2505 − 0·0018) = 0·248 ohm/mile

Apparent reactance of any phase:—same as Circuit A given above.

(*b*) *Evaluation of power losses.*—As an example we will calculate the power losses on the "grid" system for a line 500 miles long having a load current of 220 amperes for three values of power factor at the receiving end, namely unity power factor, and 0·8 leading and lagging. Assume voltage to neutral

$$= \frac{132}{\sqrt{3}} 10^3 = 76\,300 \text{ volts}$$

Before applying equation (42) it is necessary to calculate the values of the quantities $\mathfrak{J}_1$, $\mathfrak{J}_2$, c, Z, α, β, γ, δ, 2α, l_1, $2\beta l_1$.

(i) $\mathfrak{J}_1$ and $\mathfrak{J}_2$.

At 0·8 power factor lagging $\mathfrak{J}_1 = 0\cdot8 \times$ load current $= 0\cdot8 \times 220 = 176$ amperes. Similarly

$$\mathfrak{J}_2 = \sqrt{(220^2 - 176^2)} = 132 \text{ amperes}$$

(ii) c, Z.

$$Z = \text{impedance per mile} = R_{KM} + jx$$

From Table 2

Reactance x = 0·667 ohm/mile

Resistance R_{KM} = 0·251 ohm/mile

$$\therefore\ Z = 0\cdot251 + j0\cdot667 \text{ in cartesian co-ordinates}$$

$$= \sqrt{(0\cdot251^2 + 0\cdot667^2)} \arctan\frac{0\cdot667}{0\cdot251} = 0\cdot709 \underline{/69^\circ\,16'} \text{ in polar co-ordinates.}$$

By the ordinary text-book formulæ capacity susceptance

$$c = 4\cdot 4 \times 10^{-6} \text{ mho/mile}$$

Thus $c = j4\cdot 4 \times 10^{-6}$ in cartesian co-ordinates

$$= 4\cdot 4 \times 10^{-6}\,\underline{|90^\circ} \text{ in polar co-ordinates}$$

(iii) α, β

$$\text{By definition } \alpha + j\beta = \sqrt{(cZ)}$$

Therefore

$$\begin{aligned} cZ &= 4\cdot 4 \times 10^{-6}\,\underline{|90^\circ} \times 0\cdot 709\ \underline{/69^\circ\ 16'} \\ &= 3\cdot 115 \times 10^{-6}\,\underline{\backslash 159^\circ\ 16'} \\ \therefore\quad \sqrt{(cZ)} &= 1\cdot 765 \times 10^{-3}\ \underline{/79^\circ\ 38'} \\ &= 1\cdot 765 \times 10^{-3}\,(\cos 79^\circ\ 38' + j \sin 79^\circ\ 38') \\ &= (0\cdot 319 + j1\cdot 7355)10^{-3} = \alpha + j\beta \end{aligned}$$

(iv) γ, δ.

$$\text{By definition } \gamma + j\delta = \sqrt{\frac{c}{Z}}$$

$$\begin{aligned} &= \sqrt{\frac{4\cdot 4 \times 10^{-6}}{0\cdot 709}}\ \frac{\underline{|90^\circ} - \underline{/69^\circ\ 16'}}{2} \\ &= 10^{-3} \times 2\cdot 49\ \ \underline{/10^\circ\ 22'} \\ &= 10^{-3}\,(2\cdot 455 + 0\cdot 448j) \end{aligned}$$

(v) $2\alpha l_1$, $2\beta l_1$.

$$l_1 = 500 \text{ miles}$$

$$\therefore\quad 2\alpha l_1 = 2 \times 500 \times 0\cdot 319 \times 10^{-3} = 0\cdot 319 \text{ radian}$$

Similarly

$$2\beta l_1 = 2 \times 500 \times 1\cdot 7355 \times 10^{-3} = 1\cdot 7355 \text{ radians}$$

From tables of hyperbolic and circular functions we have

$$\begin{aligned} \sinh 2\alpha l_1 &= 0\cdot 3244 \qquad & \sin 2\beta l_1 &= 0\cdot 9855 \\ \cosh 2\alpha l_1 &= 1\cdot 0513 \qquad & \cos 2\beta l_1 &= -\ 0\cdot 1700 \end{aligned}$$

(vi) *First term in bracket in equation* (42).

$$\begin{aligned} (\mathfrak{J}_1^2 + \mathfrak{J}_2^2)\left(\frac{\sinh 2\alpha l_1}{2\alpha} + \frac{\sin 2\beta l_1}{2\beta}\right) &= (176^2 + 132^2) \times \left(\frac{0\cdot 3244}{2 \times 0\cdot 319 \times 10^{-3}} + \frac{0\cdot 9855}{2 \times 1\cdot 7355 \times 10^{-3}}\right) \\ &= 48\cdot 4 \times 10^6(0\cdot 508 + 0\cdot 284) = 38\cdot 4 \times 10^6 \end{aligned}$$

(vii) *Second term in bracket in equation* (42).

$$E_r^2(\gamma^2 + \delta^2)\left(\frac{\sinh 2\alpha l_1}{2\alpha} - \frac{\sin 2\beta l_1}{2\beta}\right)$$

$$\begin{aligned} &= 76\ 300^2(2\cdot 455^2 \times 10^{-6} + 0\cdot 448^2 \times 10^{-6})(0\cdot 508 - 0\cdot 284) \\ &= 5\ 830 \times 6\cdot 232 \times 0\cdot 224 \times 10^3 = 8\cdot 13 \times 10^6 \end{aligned}$$

(viii) *Third term in bracket in equation* (42).

$$\begin{aligned} &= 2\mathfrak{J}_1 E_r\left\{\frac{\gamma}{2\alpha}(\cosh 2\alpha l_1 - 1) + \frac{\delta}{2\beta}(\cos 2\beta l_1 - 1)\right\} \\ &= 2 \times 176 \times 76\ 300\left\{\frac{2 \times 0\cdot 455 \times 10^{-3}}{2 \times 0\cdot 319 \times 10^{-3}}(1\cdot 0513 - 1) + \frac{0\cdot 448 \times 10^{-3}}{2 \times 1\cdot 7355 \times 10^{-3}}(-\ 0\cdot 1700 - 1)\right\} \\ &= 27\cdot 85 \times 10^6(0\cdot 1975 - 0\cdot 1515) = 1\cdot 271 \times 10^6 \end{aligned}$$

(ix) *Fourth term in bracket in equation* (42).

$$= -2\mathfrak{J}_2E_r\left\{\frac{\delta}{2\alpha}(\cosh 2\alpha l_1 - 1) - \frac{\gamma}{2\beta}(\cos 2\beta l_1 - 1)\right\}$$

$$= -2 \times 132 \times 76\,300\left\{\frac{0\cdot448 \times 10^{-3}}{2 \times 0\cdot319 \times 10^{-3}}(0\cdot0513) - \frac{2\cdot455 \times 10^{-3}}{2 \times 1\cdot7355 \times 10^{-3}}(-1\cdot17)\right\}$$

$$= -17\cdot5 \times 10^6$$

(x) *Total power losses.*

0·8 *power factor lagging at receiver.*

$$\text{Losses} = \frac{0\cdot251}{2} \times 10^6\{38\cdot4 + 8\cdot13 + 1\cdot27 - 17\cdot5\}$$

$$= 3\cdot80 \times 10^6 \text{ watts}$$

Power losses neglecting capacitance (i.e. load losses alone) $= 220^2 \times 500 \times 0\cdot251 = 6\cdot075 \times 10^6$ watts

Thus $$\frac{\text{Power losses at 0·8 power factor lagging}}{\text{Load losses alone}} = \frac{3\cdot80}{6\cdot075} = 62\cdot5 \text{ per cent}$$

0·8 *power factor leading at receiver.*

$$\text{Losses} = \frac{0\cdot251}{2} \times 10^6\{38\cdot4 + 8\cdot13 + 1\cdot27 + 17\cdot5\}$$

$$= 8\cdot2 \times 10^6 \text{ watts}$$

Therefore $$\frac{\text{Power losses at 0·8 power factor leading}}{\text{Load losses alone}} = \frac{8\cdot2}{6\cdot075} = 135 \text{ per cent}$$

Unity power factor.

$$\text{Losses} = \frac{0\cdot251}{2} \times 10^6\{38\cdot4 + 8\cdot13 + 1\cdot27 + 0\}$$

$$= 6\cdot0 \times 10^6$$

Therefore $$\frac{\text{Power losses at unity power factor}}{\text{Load losses alone}} = \frac{6\cdot0}{6\cdot075} = 98\cdot8 \text{ per cent}$$

(*c*) *Impedance with earth return.*

(i) *With earth wire.*

Take the case of a short-circuit to earth from the middle phase on a single circuit tower (see Fig. 2) of the "grid" lines, distant 1 mile from the generating station. The earth conductor on the tower is not shown in Fig. 2, but is taken as on the vertical centre line of the tower 60 ft. above ground at a tower. For dimensions of earth conductor, see Fig. 2.

Assume resistivity of earth $u = 20\,000$ ohms/cm cube $= 20 \times 10^{12}$ absolute units.

Take mean height of fault phase above earth $h_1 = 1\,190$ cm (to allow for sag).

Take mean height of earth conductor above earth $h_4 = 1\,645$ cm (to allow for sag).

Take distance from axis of earth conductor to fault phase $S_{1,4} = 567$ cm.

We have $$K = 2\pi\sqrt{\frac{f}{u}} = 2\pi\sqrt{\frac{50}{20 \times 10^{12}}} = 9\cdot91 \times 10^{-6}$$

$$\lambda = 10^{-9}\left\{(\pi^2 50) + j10^2\pi\left(0\cdot5 + 4\cdot6\log_{10}\frac{2}{1\cdot781 \times 9\cdot91 \times 10^{-6} \times 1\,190}\right)\right\}$$

$$= (0\cdot492 + 2\cdot86j)10^{-6} \text{ ohm/cm}$$

$$R_{Ka} = 1\cdot56 \times 10^3 \text{ absolute ohms/cm}$$

$$R_4 = 3\cdot90 \times 10^3 \text{ absolute ohms/cm *}$$

$$b = 0\cdot98 \text{ cm}; \; r_4 = 0\cdot7 \text{ cm}$$

$$\lambda_1 = \left\{1\cdot56 \times 10^{-6} + j10^2\pi 10^{-9}\left(0\cdot5 + 4\cdot6\log_{10}\frac{1\,190}{0\cdot98}\right)\right\}$$

$$= \left\{1\cdot56 \times 10^{-6} + j0\cdot314 \times 10^{-6}(0\cdot5 + 14\cdot2)\right\}$$

$$= (1\cdot56 + 4\cdot62j)10^{-6} \text{ ohm/cm}$$

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* 1 absolute ohm $= 10^9$ ohm.

$$\lambda_4 = \left\{3 \cdot 90 \times 10^{-6} + j10^2\pi 10^{-9}\left(0 \cdot 5 + 4 \cdot 6 \log_{10} \frac{1\,645}{0 \cdot 7}\right)\right\}$$
$$= (3 \cdot 90 + 5 \cdot 04j)10^{-6} \text{ ohm/cm}$$
$$L_1 = \left\{4 \cdot 6j10^2\pi 10^{-9} \log_{10}\left(\frac{1\,190}{567}\right)\right\}$$
$$= 0 \cdot 466j \times 10^{-6} \text{ ohm/cm}$$
$$L_4 = \left\{4 \cdot 6j10^2\pi 10^{-9} \log_{10}\left(\frac{1\,645}{567}\right)\right\}$$
$$= 0 \cdot 668j \times 10^{-6} \text{ ohm/cm}$$

Then from equation (43*b*)

$$\frac{\text{Current in earth wire}}{\text{Current in earthed phase}} = \frac{I_4}{J_1} = \frac{I_4}{I_4 + I_5}$$
$$= \frac{(0 \cdot 492 + 2 \cdot 86j) + (0 \cdot 466j)}{(0 \cdot 492 + 2 \cdot 86j) + (3 \cdot 90 + 5 \cdot 04j)}$$
$$= 0 \cdot 35 + 0 \cdot 137j$$

Numerically $$\frac{I_4}{I_4 + I_5} = \sqrt{(0 \cdot 35^2 + 0 \cdot 137^2)} = 0 \cdot 374$$

Thus 37·4 per cent of the short-circuit current in the line conductor returns through the earth wire.

From equation (43*c*)

$$\frac{\text{Current in earth}}{\text{Current in earthed phase}} = \frac{I_5}{J_1} = \frac{I_5}{I_4 + I_5}$$
$$= \frac{(3 \cdot 90 + 5 \cdot 04j) - 0 \cdot 466j}{(0 \cdot 492 + 2 \cdot 86j) + (3 \cdot 90 + 5 \cdot 04j)}$$
$$= 0 \cdot 652 - 0 \cdot 131j$$

Numerically $$\frac{I_5}{I_4 + I_5} = \sqrt{(0 \cdot 652^2 + 0 \cdot 131^2)} = 0 \cdot 665$$

(NOTE.—Numerically

$$\frac{I_5}{I_4 + I_5} + \frac{I_4}{I_4 + I_5} = 0 \cdot 374 + 0 \cdot 665 = 1 \cdot 039 = \text{Greater than unity}$$

This is because I_5 and I_4 are out of phase.)

From equation (43*a*)

Impedance of phase conductor and return path via earth and earth wire in parallel

$$= \left\{(1 \cdot 56 + 4 \cdot 62j)10^{-6} + \frac{(0 \cdot 492 + 2 \cdot 86j)10^{-6}(3 \cdot 90 + 4 \cdot 37j) - 0 \cdot 466j10^{-6}(0 \cdot 492 + 3 \cdot 53j)}{4 \cdot 39 + 7 \cdot 9j}\right\} \times 0 \cdot 161 \times 10^6 \text{ ohm/mile to neutral}$$
$$= (2 \cdot 36 + 6 \cdot 19j) \times 0 \cdot 161 \text{ ohm/mile to neutral}$$

Numerically, impedance $= \sqrt{(2 \cdot 36^2 + 6 \cdot 19^2)} \times 0 \cdot 161$ ohm/mile
$= 1 \cdot 06$ ohms/mile to neutral

Power factor of short-circuit $= \cos\left(\text{arc tan}\,\frac{6 \cdot 19}{2 \cdot 36}\right) = \cos 69° = 0 \cdot 358$

(ii) *Without earth wire.*

By equation (44)

$$\text{Impedance} = (\lambda + \lambda_1) \times 0 \cdot 161 \times 10^6 \text{ ohm/mile to neutral}$$
$$= \left\{(0 \cdot 492 + 2 \cdot 86j) + (1 \cdot 56 + 4 \cdot 62j)\right\}0 \cdot 161 \text{ ohm/mile to neutral}$$
$$= (2 \cdot 05 + 7 \cdot 48j)0 \cdot 161$$

Numerically $= \sqrt{(2 \cdot 05^2 + 7 \cdot 48^2)}0 \cdot 161 = 1 \cdot 25$ ohms/mile to neutral

Power factor $= \cos\left(\text{arc tan}\,\frac{7 \cdot 48}{2 \cdot 05}\right) = \cos 75° = 0 \cdot 26$

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DISCUSSION ON

"A CRITICAL STUDY OF A THREE-PHASE SYSTEM OF UNARMOURED SINGLE-CONDUCTOR CABLES."*

Dr. H. B. Dwight: In equations (118) and (119), formulæ are given for the sheath eddy-loss for cables in one plane, and these are credited to a paper by Dr. F. W. Carter published in 1928 in the *Proceedings of the Cambridge Philosophical Society*. While the omission of the reference to the earlier publication was doubtless made inadvertently, these formulæ (118) and (119) are the same as the first terms of formulæ for cable sheaths in Section V of my paper on "Proximity Effect in Wires and Thin Tubes," published in the *Transactions of the American Institute of Electrical Engineers* (1923, vol. 42, p. 856).

Messrs. E. B. Wedmore, P. D. Morgan and **S. Whitehead** (*in reply*): Mention should have been made of Dr. Dwight's earlier work in the portion of our paper to which he refers. The purpose of Appendix V of the paper was to show the application of Dr. Carter's method to the particular problem concerned, and reference to Dr. Dwight's work in which the same result was obtained by a different method was unfortunately omitted.

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* Paper by Messrs. E. B. Wedmore, P. D. Morgan and S. Whitehead (see vol. 67, page 359).

DISCUSSION ON

"NOTE ON SHEATH LOSSES IN SINGLE-CORE SINGLE-PHASE CABLES." *

Dr. H. B. Dwight: In the first paragraph of this paper the authors discuss the calculation of the loss and e.m.f. in cable sheaths, and state that it is unlikely for the loss and voltage conditions to change suddenly when contact is made between the sheaths. On the contrary, when two points in an electrical network are suddenly connected, any e.m.f. which previously existed between them becomes zero and may be said to be used up in driving an additional current through the network. This is a well-known principle and is useful in solving some network problems. Thus, the open-circuit voltage between sheaths is not zero just before they touch, and need not be expected to be zero. Reference is also made in the same paragraph to the question of a discrepancy in the tests published by Mr. Dunsheath† in 1927. These tests, however, seem to have been made originally as commercial tests, and no claim for precise accuracy appears to have been made by Mr. Dunsheath. This is borne out by the fact that the mutual inductance of certain non-magnetic cables computed from Table D (vol. 65, p. 493 and Fig. 17) shows 30 per cent variation, whilst the only change reported is that the current increased from 150 to 300 amperes. This can be seen by dividing each value of measured e.m.f. by the corresponding current. A serious discrepancy in this set of measurements is thereby shown, for the mutual inductance of non-magnetic conductors is a constant for constant frequency and varying current. Another similar set of measurements given in Table A and Fig. 5, which have been used in the discussion of conflicting calculations, also shows internal evidence of inaccuracy, since it is impossible to plot the readings as a smooth curve. Much more consistent tests will be found in the paper by Messrs. W. S. Clark and G. B. Shanklin in the *Transactions* of the American Institute of Electrical Engineers (1919, vol. 38, p. 917). In view of the discussion as to the correct formula for the open-circuit e.m.f. between cable sheaths, it is noteworthy that a complete formula including proximity and shielding effects has apparently not been published. I have recently derived such a formula which is comparatively short and yet practically complete. The zero-frequency inductance of a sheath in the single-phase case can be taken directly from it, and is $2 \log_e (d/r)$. The terms involving frequency to higher powers have a slight effect on the result, but even in the case of 2 000 000-circular-mil cables at 60 cycles and 10 cm spacing, their effect is only 0·16 per cent, which is practically negligible. This can be said to prove the case for the expression $2 \log_e (d/r)$ as against any expression of the form $\log_e [(d-r)/r]$.

Prof. W. Cramp and **Mr. G. M. Harvey** (*in reply*): It is with great pleasure that we take this opportunity of acknowledging the work of Clark and Shanklin, published in 1919, and of Dr. Dwight himself, which appeared in 1924. The former was published before our own early work, but we did not see it until long afterwards. We have definitely said that, in the absence of any new evidence to the contrary, the use of $\log (d/r)$ is satisfactorily established for all practical purposes and requires no further proof. Clearly, Dr. Dwight fully endorses also our conclusions (*a*) and (*b*) on page 336 (vol. 67) of the *Journal*. It is true, as he points out, that in an electrical network a potential difference often exists between two points, and that this disappears when contact is made, causing a corresponding change or re-distribution of current and of losses. A change of this kind is precisely what we sought but (for reasons given) failed to find; and we know of no published figures which give definite information on the matter. Clark and Shanklin afford no help, since they do not appear to have used a spacing less than 3 in. with cables having an overall diameter of 2·47 in. We agree with Dr. Dwight's declaration that no complete formula has yet been published, and we look forward to his new solution, which we hope will complete the theory of this problem. We confess to a certain feeling of trepidation when we see that he only describes his new formula as "practically" complete; but we shall continue to hope for the elimination of the adverb.

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* Paper by Prof. W. Cramp and Mr. G. M. Harvey (see vol. 67, page 335).

† *Journal I.E.E.*, 1927, vol. 65, p. 469.

DISCUSSION ON
"DIRECT GENERATION OF ALTERNATING CURRENT AT HIGH VOLTAGES."*

EAST MIDLAND SUB-CENTRE, AT LEICESTER, 29TH OCTOBER, 1929.

Mr. B. A. M. Boyce: In spite of the ingenuity spent on the design of this alternator, I do not consider it to be the best solution for a modern machine. The authors have not given any winding temperatures, and I feel that, however easily the conductors are rated, the temperature of the bull will be very high as there are three temperature gradients in series above the tooth iron before the bull is reached, and differential expansions must take place. The insulation is impregnated; hence the insulation has something besides mica in its composition which may cause air pockets due to the temperatures and expansions mentioned above, with the consequent formation of ozone. If this occurs, serious trouble will follow. The authors have carefully explained the low voltage between the outer conductors and earth; but if, as I understand to be the case, the neutral is not earthed, I contend that it is necessary to insulate the whole winding equally from earth if the same factor of safety is desired. I cannot see how the efficiency of the author's machine can compare with that of a low-voltage machine coupled to transformers. I also feel that the presence of transformers is a distinct advantage in the event of surges taking place, as they act as buffers. I suggest that the best design for any turbo-alternator is one having 1 bar per slot, and that the voltages should be chosen to meet this condition and then stepped up to the required value by transformers. The firm with which I am associated has made several sets, using 1 bar per slot, in which the current per set is from 8 000 to 10 000 amperes. The insulation is mica 0·08 in. thick, so that the temperature gradient is small. The breakdown voltage on these bars was 26 000 volts.

Mr. E. A. Mills: There has been a gradual increase in generator voltage, extending over a number of years, the higher voltages being mainly due to the increase in generator capacities. Factors contributing towards the use of larger machines are the increased efficiency obtainable, which is of far greater importance in the larger machines than with the smaller units, and the difficulties experienced in dealing with the machine leads. The authors have produced a machine to generate at a pressure of 33 000 volts. This pressure has been in use in this country for the interlinking of systems and, on some of the larger systems, as a distribution pressure, and, as the authors point out, in certain areas a saving would be effected by direct generation at this pressure. The success of generating direct at a pressure of 33 000 volts will depend entirely on reliability being assured, and on the achievement of an efficiency at least equal to that obtainable with lower-voltage machines.

Mr. L. H. L. Badham: By means of a novel development of the intersheath principle, the authors have obtained a stator winding such that, in the core portion, the electrostatic conditions do not differ appreciably from those of machines of normal voltages. This, however, has necessitated a weak arrangement of joints at the overhang. The right-angle joints appear to be such that they would have to be made with clips or soft solder, in order to avoid damaging the insulation; also, these joints do not lend themselves to effective sealing. As regards the overhang, this is practically a standard arrangement and it would be interesting to know whether any corona was visible when the machine was completely erected. Experiment shows that corona may be visible when a machine is stationary and that this disappears when the machine is running and consequently the windings are in a strong draught of air. I recently inspected in India the 22 000-volt synchronous condensers which were built at Rugby, after they had been in commission for 2½ years. These were of special design to eliminate corona and were quite successful. There was no smell of ozone and no sign of marking on the insulation. The damaging effect of corona is due to the formation of nitrous compounds from combination with the air, which attack the insulation. If, therefore, the machines were designed to be ventilated and cooled with some other gas, the ill effects of corona could be reduced. Hydrogen has been found to be a satisfactorily medium for rotatory machines, since the windage losses are considerably reduced, its cooling properties are very superior to those of air, and corona effects are very small. For very-high-voltage machines it seems that development will involve the use of some cooling agent other than air.

Mr. C. A. Brearley: Some of the critics of direct generation at high voltages with direct coupling to the line have expressed doubts as to the wisdom of eliminating the transformer because of the effect of the latter in reducing short-circuit currents. May not the elimination of the transformer, where, as in this case, the generator appears to have ample inherent reactance and mechanical strength to cope with short-circuits, be of direct advantage in eliminating one piece of apparatus where higher harmonics may be introduced or accentuated? Do the authors think that this may be one of the causes helping to account for the very satisfactory operation of the 33 000-volt generator at Brimsdown in dealing with line disturbances? Perhaps useful information on this point might be obtained if oscillograph records could be taken on both sides of the transformer coupled to the 11 000-volt set, and studied in conjunction with oscillograph curves of the 33 000-volt set.

Mr. R. H. Wilmot: The authors have certainly advanced a strong case for the 33 000-volt alternator, and it must be admitted that this is a very definite step forward in the history and knowledge of electrical generation. Certain electrical engineers have questioned the possibility of satisfactory insulation at such a voltage. Surely, apart from the generally recognized success of 33 000-volt underground-cable insulation and practice, the use of concentric conductors and the method of insulation put forward by the authors, together with its admitted practical success at Brimsdown, should be a sufficient guarantee of security and reliability for even the most sceptical critic. Assuming that the reliability of the 33 000-volt alternator is equal to that of the 11 000-volt alternator and transformer, the next question to be faced is that of initial cost, and closely linked with this is operation efficiency and running cost. The authors have shown that the approximate reduction in initial cost, using the 33 000-volt alternator scheme, is £10 000 (for a 75 000-kW plant). Assuming capital charges at 15 per cent (to cover interest, depreciation, maintenance, repairs, rent, rates and taxes), the extra annual running cost with the 11 000-volt alternator and transformer scheme is £1 500. This represents an additional cost of 0·00109d. per kWh, assuming 50 per cent load factor. With regard to the question of efficiency, it would appear that the full-load efficiency of a 25 000-kW 11 000-volt alternator would not exceed 97·5 per cent. The efficiency of 11 000/33 000-volt transformers could not be taken at much more than 99 per cent, which makes the overall electrical efficiency of the 11 000-volt scheme 96·53 per cent. From Fig. E (vol. 67, page 1136) of the authors' reply, the full-load efficiency of the 25 000-kW 33 000-volt alternator is given as 97 per cent. Hence the additional losses with the 11 000-volt scheme would appear to be $97 - 96{\cdot}53 = 0{\cdot}47$ per cent of 75 000 kW = 350 kW. This represents £640, or an additional cost of 0·00047d. per kWh, assuming 50 per cent load factor and taking losses at 0·1d. per unit (as assumed in the paper). It would therefore appear, taking into account the initial and running costs for the 75 000-kW plant considered, that the annual running cost of the 11 000-volt alternator and transformer scheme is £1 500 + £640 = £2 140 (representing 0·00156d. per kWh) more than that of the 33 000-volt direct-generation scheme. Surely this in itself, particularly at the present time when power station engineers are searching for every possible means of improving station efficiency, would commend the 33 000-volt direct-generation scheme for serious consideration. Direct generation would therefore seem to be very advantageous in cases where distribution at 33 000 volts is being carried out. At higher transmission voltages, such as 150 000 volts, it is essential to use a transformer, and for such cases it would appear that there is no advantage to be gained by generating at 33 000 volts rather than at 11 000 volts, as step-up transformers would be required in either instance.

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* Paper by the Hon. Sir CHARLES A. PARSONS and Mr. J. ROSEN (see vol. 67, page 1065).

Sir Charles Parsons and **Mr. J. Rosen** (*in reply*): Replying to Mr. Boyce, the heat to be dissipated per unit area from the conductors is lower than that in a conductor of normal design, so giving low losses, low temperature-rises and high efficiency. This was explained in reply to previous discussions. No difficulty has been experienced with ozone.

We are glad to have Mr. Mills's views. The fact that the high-voltage alternator at Brimsdown continues to run very satisfactorily at 34 500 volts indicates that machines of this voltage can be designed to be equally as reliable as low-voltage plant.

In reply to Mr. Badham, the wires from the conductors are stemmed into the loops formed in the end-connections in a very similar manner to that adopted in our standard alternator construction. This joint has proved to be sound. There has been no sign of corona on any occasion with the alternator excited up to its full voltage. We agree that hydrogen might be used with advantage, but it is at present unnecessary to depart from the usual method of air circulation.

We are in agreement with Mr. Brearley on the question of elimination of transformers, so avoiding the danger of accentuating harmonics which might then become a source of trouble. The wave-forms of the high- and low-voltage alternators are practically the same, but it has not yet been possible to obtain oscillograms so as to ascertain the effect of step-up transformers on the wave-form of the low-voltage machine.

We are glad to have the figures which have been submitted by Mr. Wilmot. On the whole they agree very closely with our own figures and show clearly the advantage, both in initial outlay and in operating costs, of direct generation at high voltages. The method of calculation adopted demonstrates very clearly the economic advantages of the high-voltage generator.

PROCEEDINGS OF THE INSTITUTION.

792ND ORDINARY MEETING, 21ST NOVEMBER, 1929.

(Joint Meeting with the Institute of Fuel.)

Colonel Sir T. F. Purves, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 7th November, 1929, were taken as read and were confirmed and signed.

A list of candidates for election and transfer approved by the Council for ballot was taken as read and was ordered to be suspended in the Hall.

A general discussion took place on the subject of "Low-Temperature Carbonization of Fuel, with special reference to its Combination with the Production of Electricity" (see page 229), with introductory papers by Mr. S. McEwen (see page 205), Prof. P. Rosin, Dr. Ing. (see page 212), and Messrs. E. H. Smythe and E. G. Weeks (see page 219).

On the motion of the President a vote of thanks to the authors was carried with acclamation, and the meeting terminated at 7.45 p.m.

793RD ORDINARY MEETING, 28TH NOVEMBER, 1929.

Captain J. M. Donaldson, M.C., Vice-President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 21st November, 1929, were taken as read and were confirmed and signed.

A paper by Mr. H. W. Taylor, Member, entitled "Voltage Control of Large Alternators" (see page 317), was read and discussed.

On the motion of the Chairman a vote of thanks to the author was carried with acclamation, and the meeting terminated at 7 p.m.

INSTITUTION NOTES.

Faraday Medal.

The Council have made the ninth award of the Faraday Medal to Sir Ernest Rutherford, O.M., F.R.S.

Lending Library.

A new edition of the Lending Library Catalogue has been published. Copies can be had on application to the Secretary.

The Benevolent Fund.

The Committee of Management desire to draw the attention of the members to the appeal for funds which will be found on the last page of the cover of this issue of the *Journal*.

Informal Meetings.

115TH INFORMAL MEETING (28TH OCTOBER, 1929).

Chairman: Colonel Sir Thomas F. Purves, O.B.E.

Subject of Discussion: "Systematic Research by Industrial Undertakings" (introduced by the President, Col. Sir Thomas F. Purves, O.B.E.).

Speakers: Messrs. J. R. Bedford, W. A. Erlebach, E. S. Ritter, J. F. Shipley, A. F. Harmer, P. Dunsheath, O.B.E., W. Day, W. A. Gillott, A. N. D. Kerr, W. Lang, T. Wadsworth, W. E. Warrilow, J. G. Hines, C. G. Garton, T. N. Riley, H. Craske, F. Ockenden.

116TH INFORMAL MEETING (4TH NOVEMBER, 1929).

Chairman: Mr. J. R. Bedford.

Subject of Discussion: "Paris and the Pyrenees: Notes on some of the Technical Features of the I.E.E. 1929 Visit" (introduced by Mr. R. Borlase Matthews).

Speakers: Mr. Ll. B. Atkinson, Major T. Rich, Mr. A. F. Harmer, Mrs. H. E. Hall, Messrs. A. J. Cridge, E. S. Ritter, W. R. Rawlings, Miss Atkinson, Messrs. W. G. C. Jackson, R. S. Downe, A. C. Brown, J. R. Bedford.

117TH INFORMAL MEETING (11TH NOVEMBER, 1929).

Chairman: Mr. W. Lang.

Subject of Discussion: "Temporary Expedients in Engineering" (introduced by Mr. W. E. Highfield).

Speakers: Messrs. J. F. Shipley, A. Morgan, M. Whitgift, W. J. Minton, G. F. Bedford, A. F. Harmer, N. Prentice, E. S. Ritter, L. J. Gooch, T. H. Dennis, W. A. Erlebach, G. C. Allingham, A. N. D. Kerr, A. J. N. Kennett, S. B. Jackson, D. J. Watkins, W. Lang.

118TH INFORMAL MEETING (25TH NOVEMBER, 1929).

Chairman: Mr. R. Grierson.

Subject of Discussion: "Wooden Poles for Overhead Transmission Lines and their Preservation" (introduced by Mr. C. Wade.)

Speakers: Messrs. R. Grigg, G. V. Twiss, A. F. Harmer, R. H. Herford, E. S. Ritter, S. C. Bartholomew, R. G. Bennett, N. Prentice.

119TH INFORMAL MEETING (9TH DECEMBER, 1929).

Chairman: Mr. W. E. Bradshaw.

Subject of Discussion: "To Earth or Not to Earth" (introduced by Messrs. T. C. Gilbert and W. R. Rawlings).

Speakers: Messrs. A. H. Dykes, A. F. Harmer, Dr. K. Ekstrom, Messrs. H. W. Ellis, E. S. Ritter, C. J. Banister, S. W. Melsom, A. J. Bousfield, F. E. Phillips, D. J. Watkins, B. Higgs, W. Lang, W. A. Ritchie, A. Morgan, A. Edwards, W. E. Bradshaw.

THE ELECTRICAL PLANT AND NETWORK OF THE SOCIÉTÉ ÉLECTRIQUE DE LA SIDÉRURGIE LORRAINE.

By L. A. E. SÉKUTOWICZ and A. EVAIN.

(*Paper received 12th September, and read at the Joint Meeting of* THE INSTITUTION *and the* BRITISH SECTION *of the* SOCIÉTÉ DES INGÉNIEURS CIVILS DE FRANCE, *12th December*, 1929.)

SUMMARY.

The history and development to 1929 of the pooling arrangement by which some 60 per cent of all the electric generating plant in the Lorraine steelworks is regulated and the electricity sold is generally described. Of the 3 600 000 cubic metres of blast-furnace gas available, half is used for processes in the various works and the other half for generating electricity. Most of this electricity is used in the works. Nominally some 100 000 kW are available for export sale.

An overhead network interconnects, through substations, 10 power stations with an output of 125 000 kW, all working in parallel. Some 65 per cent of the power is developed by gas engines whose want of overload capacity throws too much of the inevitable load fluctuation on the gas-fired steam-turbine sets. These latter are being increased to a capacity of 74 000 kW distributed in 7 works, and some of the boilers are not being fired only with blast-furnace gas but, if desired, also with pulverized fuel. The whole working is controlled by telephone by a load dispatcher.

TABLE OF CONTENTS.

Introduction. Historical note; object.
Part 1. Description of the installations.
  Technical basis.
  Stability of the interconnected stations.
  Development of the company's installations.
  Present position and schemes in hand.
Part 2. Operation of the network; parallel running and utility of the new steam units.
  Operation of the company.
  Role of the load dispatcher.
  New power stations of the company.
Conclusion.

INTRODUCTION.

As far back as 1918, and therefore during the course of the War, the Mining and Metallurgical Technical Commission of France foresaw the necessity for the reconstruction of the mines and works which had been devastated in the Lorraine region and for the construction of a network to transmit electrical energy to them during the period of reconstruction.

Apart from the provisional help that could be given to the victimized companies by constructing a transmission network coupling their installations together, the ultimate aim of the promoters of the scheme was the realization of a permanent pooling of the means of production of electrical energy by running the metallurgical power stations in parallel in order to ensure the regularity and continuity of the supply of energy to the works; the transmission lines were also to be designed to allow of the sale of the energy generated in the power houses by surplus blast-furnace gas.

The firms which were brought under consideration comprise, at the present time, excluding the Belgian and Luxembourg works:—

8 pig-iron foundries (excluding steelworks), with 30 blast furnaces; and
12 complete works, with blast-furnaces, steel-producing plant and rolling mills, comprising 70 blast furnaces.

These works are capable of supplying annually 7 million tons of cast iron, which corresponds to a total output of 3·6 million m^3 of blast-furnace gas per hour.

Deducting from the above the needs of the blast-furnace services proper (the heating of the cowpers, blowers and accessories), it should theoretically be possible to dispose of 1·8 million cubic metres of gas per hour for purposes other than blast furnaces, which is equivalent to 240 tons of coal per hour of a calorific value of 7 000 calories per kg. This should produce from 300 000 to 400 000 kW according to the system employed, i.e. gas engines or turbines.

If we take into account the amount of energy required for the purposes of the central stations themselves, we can estimate a surplus amount of energy available for sale of up to 100 000 kW.

The installations that have so far been completed comprise 10 works, which include 60 blast furnaces.

In order to carry out this programme the principal metallurgical companies and the Omnium Lyonnais (a firm which specializes in the industrial applications of electrical energy and which would provide the technical service of the future company) grouped together to form a technical department for the construction of future schemes and in 1920 created the Société Électrique de la Sidérurgie Lorraine, with a capital of 8 million francs.

Negotiations with the Government which were commenced in 1920 were only successfully concluded in 1924. The concession to transmit applied to the creation of an overhead ring-main at 65 000 volts tied-in to the State station at Landres, which was built earlier by the State on the 120 000-volt line which connected some Swiss works and the works in the French Ardennes and the network at 65 000 volts from the mines of La Houve (Fontoy substation). These two distribution concessions gave rights for a ring main at 30 000 volts to connect the mines (and the less important works) to 65 000/30 000-volt substations which were connected to the high-tension network.

The network and an outline of the distribution area of the Société are shown in Fig. 1. This indicates the geographical position of the installations of the company between the super-power stations, either built or under consideration, of La Houve, Strasbourg, Kembs and Vincey, and is designed to allow of large interchanges of energy.

The initial programme, which is still being carried out, should be completed very shortly by the installation of new power stations designed to utilize the surplus gas products in each of the metallurgical works forming part of the group.

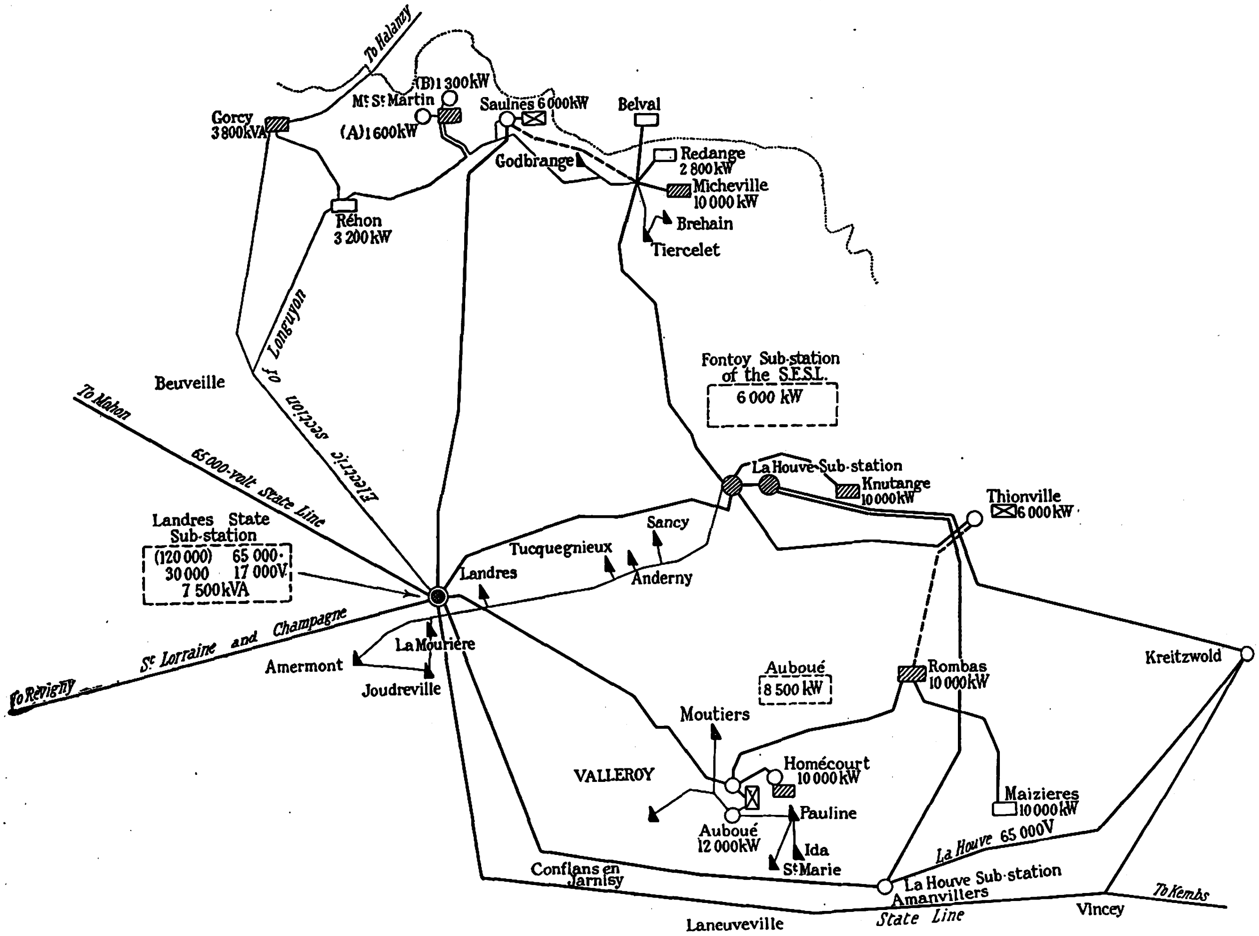
To Halanzy
(B) 1 300kW
Mt St Martin
(A) 1 600kW
Gorcy 3 800kVA
Saulnes 6 000kW
Belval
Redange 2 800kW
Micheville 10 000kW
Brehain
Tiercelet
Godbrange
Réhon 3 200kW
Electric section of Longuyon
Beuveille
To Mahon
65 000-volt State Line
Fontoy Sub-station of the S.E.S.L.
6 000 kW
La Houve Sub-station
Knutange 10 000kW
Thionville 6 000kW
Sancy
Tucquegnieux
Anderny
Landres
Landres State Sub-station
(120 000) 65 000-30 000 17 000V
7 500kVA
St Lorraine and Champagne
To Revigny
Amermont
La Mourière
Joudreville
Auboué 8 500 kW
Rombas 10 000kW
Kreitzwold
Moutiers
Homécourt 10 000kW
VALLEROY
Pauline
Auboué 12 000kW
Ida
St Marie
Maizieres 10 000kW
La Houve 65 000V
Conflans en Jarnisy
La Houve Sub-station
Amanvillers
State Line
Laneuveville
Vincey
To Kembs

FIG. 1.—Plan of network.

☒ Ordinary blast furnaces.

▨ Complete steelworks.

☐ Transformer stations.

▲ Iron mines.

◍ Substations belonging to the company.

○ Independent substations.

● State substation.

—— 65 000-volt lines constructed or under constructon.

– – – 65 000-volt lines projected.

—— 30 000-volt lines constructed or under construction.

All lines comprise 6 conductors. Capacities indicated in kW are only those of the machines actually supplying the network.

Part (1). Description of the Installations.

(1) *Technical Basis of the Scheme.*—The first detailed examination in 1919 showed that the company would be able to dispose of surplus energy which to all intents and purposes would increase and develop in proportion to the technical progress made in the metallurgical works. It was expected, however, that new processes (electro-metallurgical, electro-chemical, etc.) would perhaps create such a large local demand for power in the works that they might in time even absorb the increasing surplus of power, and this would be detrimental to the financial efficiency of the undertaking. It was therefore necessary to consider the technical part of the programme very cautiously, and in such a way that the whole scheme would be particularly elastic not only from the commercial but also from the technical point of view. On the other hand, the company could only bring in its constituent members successively, and certain of those who subscribed to the undertaking in its initial stages hesitated when it approached fruition.

From the technical point of view the idea of the general parallel running of interconnected power stations involved difficulties and objections which do not seem to be overcome everywhere, even to-day, for in 1928 a German technical journal stated that central stations driven by blast-furnace gas engines cannot run satisfactorily under these conditions.

Now it was only by adopting the programme as a whole that the advantages of this system could be fully realized. In order to appreciate this, the basis of operation of these works must be remembered. The number of blast furnaces in operation in a works only varies over a relatively long period in such a way that their cycle is relatively constant. If we leave out of consideration for the moment the inevitable variation of quantity and quality due to ordinary running troubles, the repercussion of which diminishes as the number of blast furnaces in use increases, the daily and annual production of gas is sufficiently constant. The amount of gas used for heating the cowpers may momentarily upset this regularity. On the other hand, it has been noticed that this type of apparatus is relatively elastic; they act as heat accumulators and can be used to regulate to a certain extent the amount of gas available for power purposes. These gases are always surplus in pig-iron works that do not produce steel.

At the present time, in complete works comprising steelworks and rolling-mills the last-named work in two or three shifts during the 24 hours. During the change-over periods there is a surplus of gas because the gas blowers of the steelworks and gas-heating appliances are more or less completely shut down. The rolling-mill and accessory motors are also out of service. Therefore a complete works disposes of a surplus amount of power and energy during at least a part of each day of the week. During the whole of Sunday, when the steel production is at a standstill, the total amount of gas production is available.

During the working periods there is also surplus energy, but this surplus varies considerably during the course of an 8-hour shift, as it represents the difference between a relatively constant total production and the extremely variable needs of the steel-producing plant and of the rolling-mills.

The steelworks blower takes from 1 800 to 2 000 kW and is only worked intermittently. An electric rolling mill may absorb 12 000 kW instantaneously and 4 000 kW practically constantly. The running-up of gas engines corresponds to an increase in the available power of from 2 000 to 4 000 kW, and their shutting down to a corresponding decrease. These sudden peaks are a very serious problem for an isolated metallurgical power station, the continuous rating of which may be 10 000 kW, with 15 000-kW peaks and a total installed capacity of, say, 18 000 kW. The shape of the load curve resembles rather closely that of a traction supply. On account of the small amount of elasticity in gas engines, which cannot take an overload without slowing up, and which consequently cause a large variation in the voltage and frequency of the network, all the apparatus connected to the network is adversely affected.

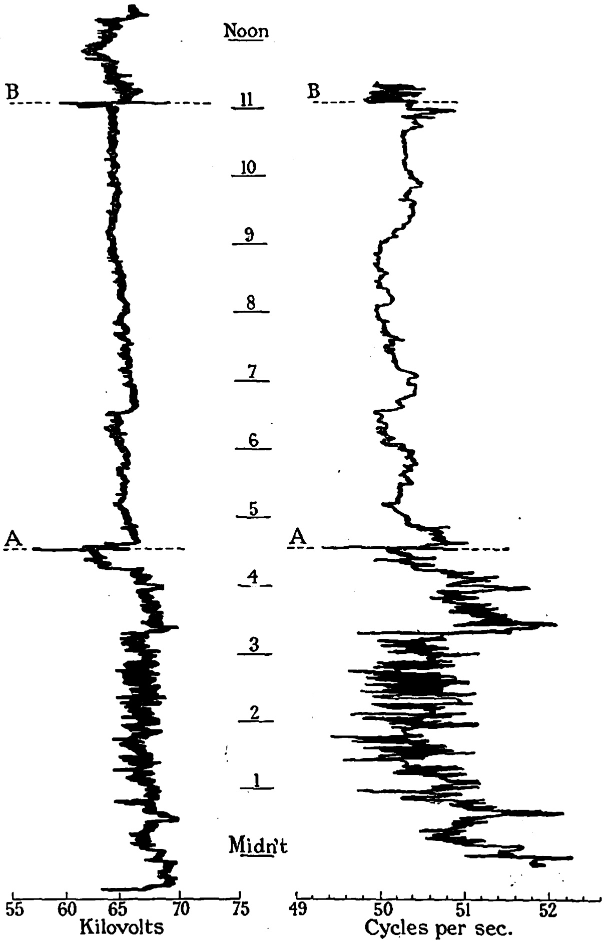

Fig. 2.—Voltage and frequency charts of the company's network for the 5th August, 1929.

General parallel running attenuates very considerably the relative importance of these peaks and regularizes the voltage and frequency (see Fig. 2). Experience has shown that this allows of a considerable increase in the production of rolled steel; this has given much advantage to the steelworks connected to the network of the company. On the other hand, when these stations are not interconnected power peaks give rise to loss of gas and general inefficiency in utilizing the product, for there are practically no gas reserves in works at the present day. Furthermore, the running in parallel of a number of power stations allows a reduction in the amount of stand-by plant which has to be installed in each one of them, as at any time and nearly everywhere at certain hours there is a surplus amount of gas. This method of running produces further energy at no cost other than that which corresponds to a reinforcement of the gas-washing plant.

All the above advantages, including the very great advantage of being able to dispose of the total number of generators and to run on light load only those whose efficiency is satisfactory under these conditions, have been known for a long time [*] and have not been lost sight of by the promoters of the company. The possibility of mutual interchange of power in the case of accident is of further advantage to the system.

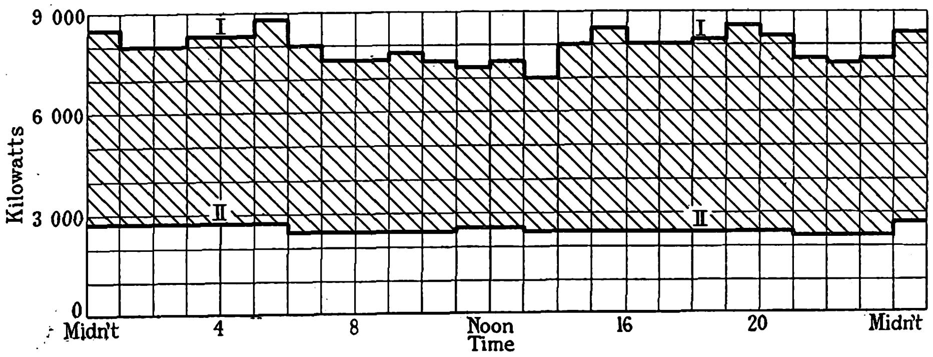

FIG. 3.—Load curve of a pig-iron works without steel manufacturing or rolling-mills.

Curve I = Total output of machines. Curve II = Power utilized in the Company's works.

The area between Curves I and II represents the output supplied to the network.

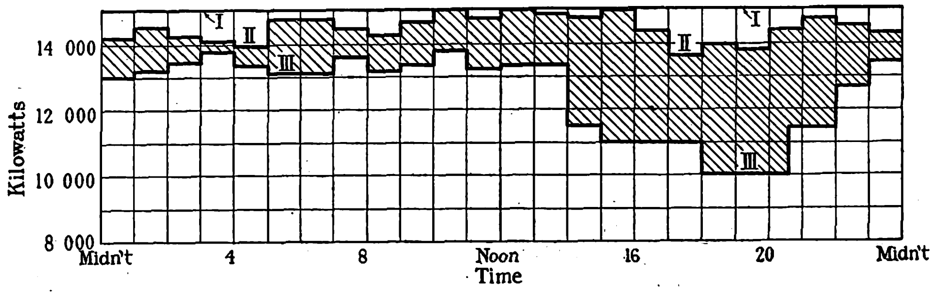

FIG. 4.—Load curve of a complete metallurgical works.

Curve I = Capacity of machines in service. Curve II = Total power supplied. Curve III = Power utilized in the Company's works.

The area between Curves II and III represents the output supplied to the network.

But however advantageous the recuperation of energy during working hours may be, the utilization of the energy which can be produced by employing waste gas, particularly during the change-over periods, is even more important.

Figs. 3 and 4 show the means available in a works, (*a*) without steelworks or rolling-mills; and (*b*) with steel plant and rolling-mills.

On account of labour difficulties the off-periods are grouped during the night hours when the available energy is unfortunately difficult to utilize on the neighbouring distribution networks. In order to obtain a market for the surplus it is necessary to feed a very large area in such a way that some steam power stations may close down entirely during the night.

Another method of overcoming the difficulty would be by shifts rotating with respect to each other. For instance, a rotation covering several complete works each having two shifts would allow practically constant production in the 24 hours and of energy being supplied to electric furnaces, for instance. It is even possible to arrange this rotation in such a way that when the peak load comes on to the distribution company's station the amount of surplus energy available in the steelworks would be the maximum, and this is very important from the commercial point of view.

Such methods as these are only possible in practice if, when all the stations are running in parallel, the works production, and therefore the consumption, can be regulated at will.

The incorporation in such a general scheme of a stand-by coal station, or even a hydro-electric station with a large reservoir, would be of very great advantage, but could only produce its full effect if the parallel running were general. This point will be dealt with later in the paper.[*]

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[*] See in particular the work of Mr. Courtoy, the promoter of the Union des Centrales de Liége.

[*] The late Mr. de Loisy showed in particular that there is no practical economic means of storing either blast-furnace gas or steam, or even their heat or their energy, in order to overcome peaks or to store available quantities produced during the off-periods. However, one of the works of the group which has a coking plant has just installed a gasometer for coke-furnace gas which will hold the equivalent of 10 000 kW, but in order to reap the best advantage it is necessary at certain times to substitute blast-furnace gas for coke gas for heating. The use of the lower levels of the mines, in order to vary artificially the amount of pumping required, only provides, when it can be adopted, an insufficient palliative.

Up to the present time the construction of steam power stations as general reserves has been postponed, and a call has been made on the turbo-alternator sets of the various members of the company and on the neighbouring steam power stations. This is now being remedied by installing in the power stations of several of the members of the company a number of turbo-alternators having a total capacity of 74 000 kW with gas-heated boilers, one of these being so designed that pulverized coal may also be used. If the general parallel-running scheme is in operation the sets will be able to run at their full efficiency. To illustrate this point, Fig. 5 gives a curve showing the hourly output available at the present time, and Fig. 6 the shape of the load curve of a large distribution company.

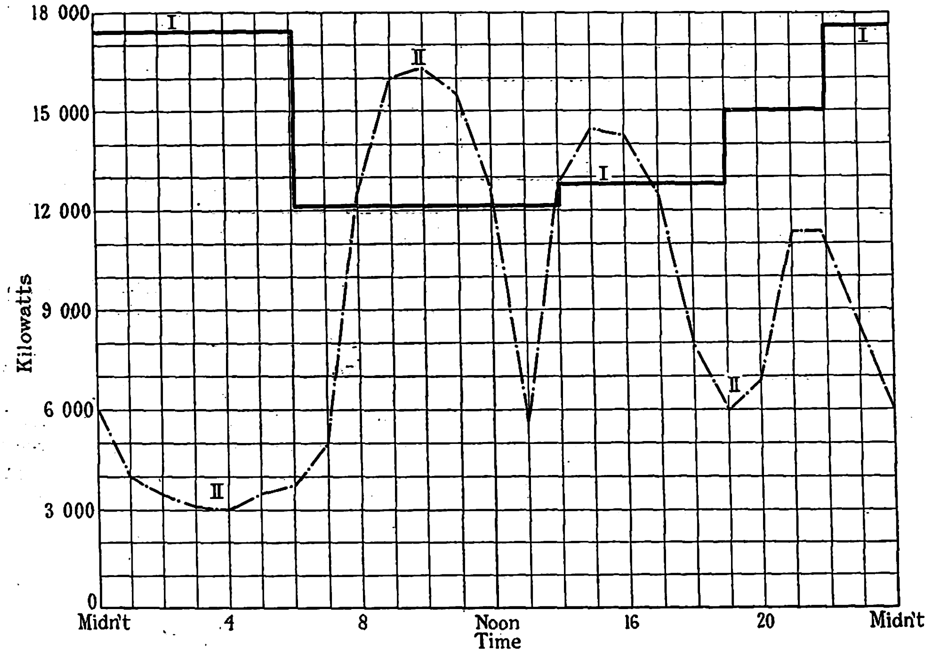

FIG. 5.—Diagram showing the power available on the company's network throughout the day.

Curve I = Power available for disposal. Curve II = Typical load curve of distribution network.

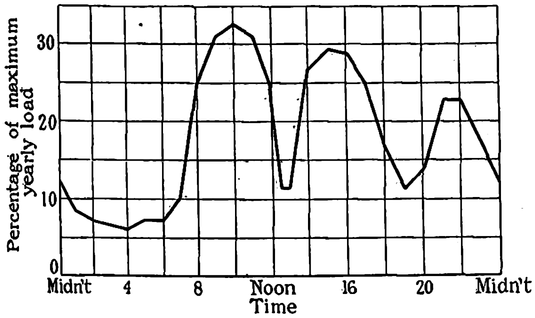

FIG. 6.—Summer load curve of a steam power station.

The advantages of general parallel-running as between works and with neighbouring distribution companies were well established from the beginning, but objections were always raised by those who feared that operation would be difficult or impossible in practice. These fears were based on the irregularity of the generating sets (4-stroke blast-furnace gas engines with either 2 or 4 single or double tandem cylinders).

The relative importance of peaks decreases with the number of interconnected production centres as and when developed. In regard to gas engines, the possibility of running them in parallel in some works when subjected to heavy peaks was well known. It was therefore sufficient to connect them together by a sufficiently small impedance and to run the machines under conditions which would approach parallel running with short connections from terminal to terminal. The impedance of the company's 65 000-volt lines is of the order of 0·42 ohm per km.

Two further difficulties remain. On the one hand steam power stations of neighbouring distribution companies would become connected to the metallurgical power stations by a network of lines and substations, the total impedance of which is not negligible and, on the other hand, gas engines would have to run in parallel with powerful steam-turbine stations which have a practically fixed frequency and would work under conditions slightly different from those which existed formerly. This difficulty will be referred to again later in the paper.

It appeared that the installation of steam sets in metallurgical stations would simplify the problem. It was thought that the adoption of a pressure of 65 000 volts * was sufficient to allow the first condition to be satisfied, and experience has confirmed this view. A higher voltage would have resulted in stations being too expensive in relation to their power, whereas a lower

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* Although not standard in France this voltage has been adopted because it is that of the nearest distribution company which agreed to serve as the first stand-by, and because at that time this voltage could have been used for single-core underground cables if the latter had to be employed at certain points.

voltage would have given rise to regulation difficulties and a greatly increased amount of copper. It would also have made the development of the network more difficult.

For the secondary networks, after a period of indecision as to whether to adopt voltages of between 15 000 and 17 000 volts, and on account of the amount of power required by certain mines, the company decided to adopt a voltage of 30 000. This was the highest voltage that could be used at that time, and if it was proved necessary in certain places to use 3-phase cables, such a voltage allowed the design of economical transformer stations, and well-designed and well tried-out gear at this voltage was obtainable. It was also felt that certain supporters of the scheme might be tempted to employ second-rate 10 000- or 15 000-volt plant which would not be sufficiently good for the service, whereas it is practically impossible to obtain second-rate 30 000-volt plant.

Practice has entirely justified the choice of these two voltages. Furthermore, it is only in very rare cases that the company has had to employ underground cables (generally at 6 000 volts) for connecting the works substations to the corresponding generators, which in general are at a distance of less than 200 metres. In some cases very short lengths of 30 000-volt cables are utilized at the ends of lines inside certain substations.

The adoption of 65 000 volts also allowed the use of rigid insulators. This type of insulator was chosen for reasons of economy. These insulators have had to be reinforced, and on the last line, erected in 1929, the suspension type was employed.

Rigid insulators, as such, have not really given rise to any trouble (with the exception of the breakage of a number of petticoats), but numerous short-circuits have ruptured a number of insulators and have even fused the line. This difficulty has been overcome by gradually and carefully earthing the neutral at a certain number of points on the network.

The results of this protection have not yet been sufficiently definitely established, but up to the present no disadvantages which can be traced to the earthing of the neutral have become apparent.

The interruptions to the supply caused by the above troubles would very probably have been avoided if from the outset a balanced selective protection scheme had been adopted, more particularly as all the company's poles were designed to carry six conductors and two earth wires.

It was for reasons of economy and on account of the high cost of the necessary outdoor transformers for operating the relays that the installation of this selective protection scheme was provisionally postponed. Since then the supply has utilized the two circuits separately, for reasons which are probably of a transient nature and which will be explained later. As a consequence the company is experimenting with impedance relays.

The factor of safety of the insulators in so far as puncture voltage is concerned was made sufficiently high to avoid the risks of perforation even for a voltage much in excess of the flash-over voltage. In the substations, surge protective gear was limited to the adoption of shunted inductance coils connected to each outgoing feeder,* and the transformers were so designed that their insulation to earth was very high (sufficient for 3 times the working voltage) and the insulation between turns was designed to withstand the full working voltage. Thus the insulators work rather effectively as voltage-limiting devices, although this is not their role. However, the lack of selective protection has made itself felt, as mentioned above. This question is now under consideration, as are also the questions of the general earthing of the neutral and the methodical reinforcement of the insulators in the more exposed regions, the data for which have been collected with the experience of the last few years of operation. The company is also examining very closely the effect of a recent theory which has been put forward to see whether these sections do actually correspond to zones in which the geological formation of the earth's sub-strata shows peculiarities.

With regard to the substations, the outdoor system was adopted from the beginning, not only from the point of view of economy but also to facilitate any reorganization or extensions to the network, as it was difficult to foresee what method of development would be adopted. In spite of the production by certain works of conducting dust in very large quantities, this system has given rise to no accidents in operation and has effected certain economies in building up the network which might have been paralysed at its inception by the financial crisis of the franc.

The works substations (65 000/6 000 volts) are simply liaison substations for the network and at the same time serve as disconnecting or by-passing substations. They are designed for one incoming and one outgoing feeder, each having 6 conductors. Each station is connected across the general ring main and can be disconnected from the circuit without interrupting the continuity of the ring.

The interconnecting station at Fontoy is a substation transforming the voltage from 65 000 to 30 000 for feeding the mines network, and at the same time for four 65 000-volt 6-conductor lines connecting the Micheville--Thionville and Landres stations, and has a local outgoing 65 000-volt feeder to a local station.

In all these substations the transformers are of the outdoor type with forced oil circulation of the external-tube water-cooled type. The first transformers were designed for 6 000 kW and were of the 3-phase core type. The later transformers were of the 3-phase shell type designed for 10 000 kW. Although the first transformers have given entire satisfaction the company is experimenting with the shell type, which appears to be stronger and to be better able to withstand the effects of short-circuits.

The whole of the control is operated by means of batteries from a small board placed in a shelter. The rupturing capacity of the circuit breakers was chosen to be very large on account of the great amounts of power available.

STABILITY OF THE INTERCONNECTED STATIONS.

The interconnected stations run along the frontier (Chiers Valley) and in the valleys of the rivers Fentsch and Orne, which are tributaries of the Moselle. The distance between the furthest stations does not exceed 60 km. This distance is small on account of the large amount of power interconnected, the voltage adopted and the cross-section of the lines.

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* The capacity of the substation constitutes a certain measure of protection against surges.

Of the 15 stations situated in the French part of the mining area, 10 are connected to the network. The total amount of power of the latter is of the order of 125 000 kW, but all the units are not permanently connected to the network.

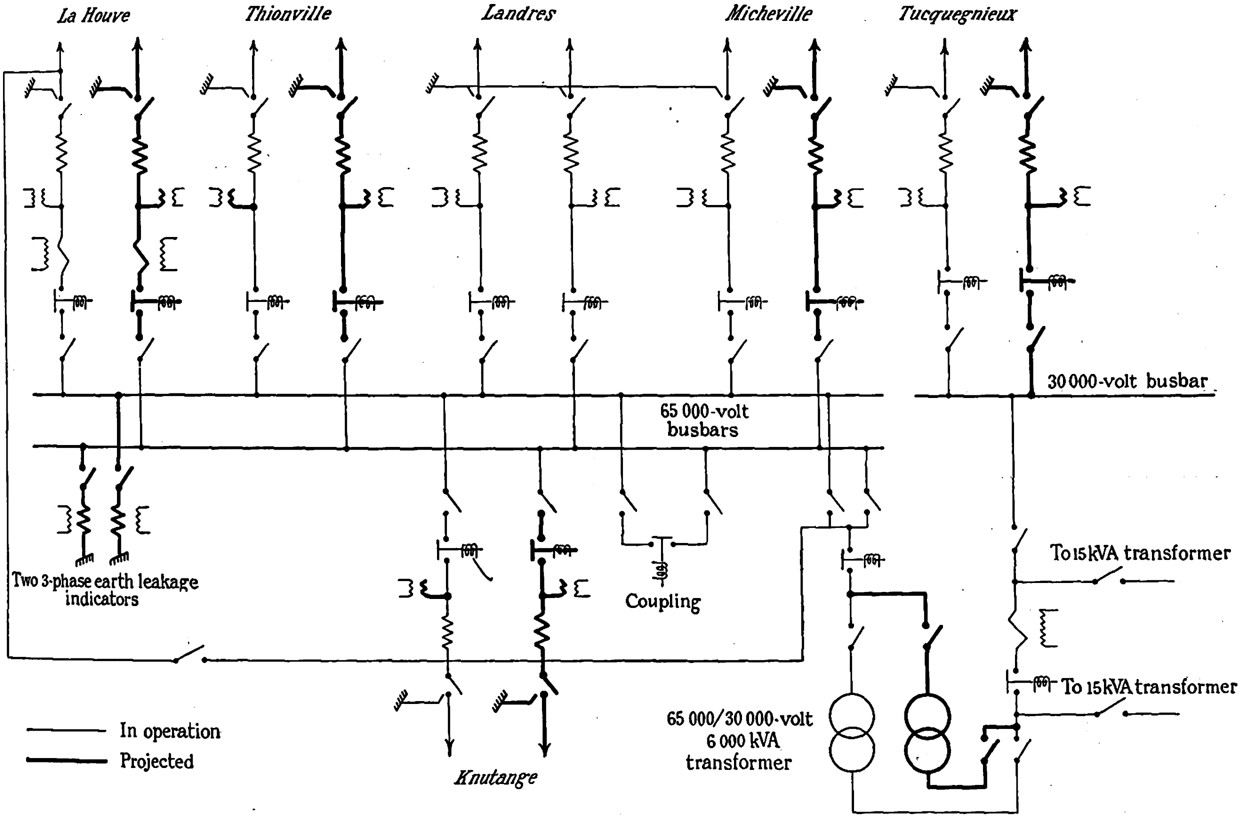

FIG. 7.—Diagram of connections of Fontoy outdoor substation.

The machines are as follows:—

5 four-cylinder gas engines	22 000 kW
20 two-cylinder gas engines	50 000 kW
15 turbo-alternators	45 000 kW
6 convertor groups connecting up works which run on direct current	9 200 kW

(The total power of these d.c. works is approximately 30 000 kW.)

The total power connected to the network is therefore supplied by 40 miscellaneous units, in the following proportions: gas engines 56 per cent, steam turbines 36 per cent, and convertors 8 per cent. If we include the generating units in the stations supplying the convertors the proportion of steam turbines drops to 32 per cent.

The gas engines are invariably of the 4-stroke type at 94 r.p.m. (with a few exceptions at 107 r.p.m.). The type of machine varies from one station to another. Efforts are being made to generalize scavenging, which up to the present is not employed except on a few of the units and which, amongst other advantages, increases the power of the engine.

Ignition is of the contact-breaker type from a separate source. The governor acts, according to the make of gas engine, either on the composition of the mixture or on the amount of inlet and, in certain cases, upon the time of ignition.

DEVELOPMENT OF THE COMPANY'S INSTALLATIONS.

In the first period of its development (1920–1923) the company concentrated its attention more particularly on the interconnection between the mines in order to facilitate pumping-out. To this end they constructed substations and local lines at 30 000 volts.

In 1924–1927, after having adopted the general plan of the network, 65 000-volt lines were constructed between Auboué–Landres and Fontoy–Thionville, and in 1925 the Fontoy substation on which the first test for paralleling between the Auboué and Thionville stations was carried out. In the following year Fontoy was connected to Micheville and Landres by 65 000-volt lines.

In the beginning of 1928 the majority of the larger works of the company were connected together, and the third period (1928–1929) began. This consisted of duplicating the lines, which were still provisionally of the 3-wire type, and completing the ring, more particularly by two new lines between Landres and Saulnes and Auboué and Thionville. In 1929 a new and greatly extended programme was established, including the installation in the 8 principal metallurgical centres of high-pressure turbo-alternators, which will be dealt with later.

When this programme is completed a sum of more than 45 million francs will have been spent by the company on the lines and for the substations, without taking into consideration the installations that have been carried out in the members' own premises (which amount to 63 million francs for new units only), a total of nearly 100 million paper francs (the gold value of which varied during the course of the work) having been invested in the scheme.

Below are given details of the more important installations which were designed in accordance with the principles mentioned above (see also Figs. 6 and 8).

65 000-*Volt Lines* (140 km).—These lines are on steel lattice poles, and are of the 6-wire type with rigid pin-type insulators having 4 petticoats.

	70 000-V type	80 000-V type	5-element suspension type (per element)
	kV	kV	kV
Puncture voltage ..	275	290	115
Dry flash-over voltage	165	185	240
Wet flash-over voltage*	115	136	162

* Resistivity of water assumed to be 4 000 ohms.

The average figures per km of line are as follows:—

Insulators: 40.

Copper (six 50-mm^2 wires): 2·7 tons.

Steel: 12 tons.

Cement (approximately 125 tons of foundations): 15 tons.

Inclusive cost: 80 000 francs (approx.).

30 000-*Volt Lines* (80 km).—These are also on steel lattice-work 6-wire poles with rigid pin-type insulators having 3 petticoats.

Puncture voltage: 115 000 volts.

Dry flash-over voltage: 110 000 volts.

Wet flash-over voltage: 45 000 volts.

Landres–Saulnes 65 000-*Volt Line* (25 km).—This line is of the 2-circuit type on steel lattice-work poles with 5-element suspension-type insulators.

Puncture voltage: 115 000 volts per element.

Dry flash-over voltage: 85 000 volts per element.

Wet flash-over voltage: 45 000 volts per element.

65 000/30 000-*Volt Substation at Fontoy.*—This station comprises five outgoing 2-circuit feeders; two of these are entirely equipped and three are as yet only equipped with the necessary gear for three wires and one outgoing 30 000-volt feeder equipped for three wires but with provision for six.

One 65 000/30 000-volt 6 000-kVA transformer interconnects these two networks.

The State Substation at Landres.—This substation places at the disposal of the company, in exchange for a subsidy supplied by the latter, three outgoing 6-wire feeders, two of which are fully equipped, and four 30 000-volt 3-wire outgoing feeders. In addition, the company has permission to use several lines which belong to the State network at the outgoing side of the Landres substation, including three outgoing 3-wire feeders which are equipped for 120 000 volts but are at present used at 65·000 volts, and which eventually may be used at a voltage of 150 000.

The installations are completed by 10 works substations, five of which are already equipped for 10 000 kVA and three more which are provided with 6 000-kVA transformers, in general at 65 000/5 500 volts, and are connected to the switching stations between the high-tension feeders. The most typical substation is that at Rombas. This contains a 10 000-kVA transformer, with provision for two more.

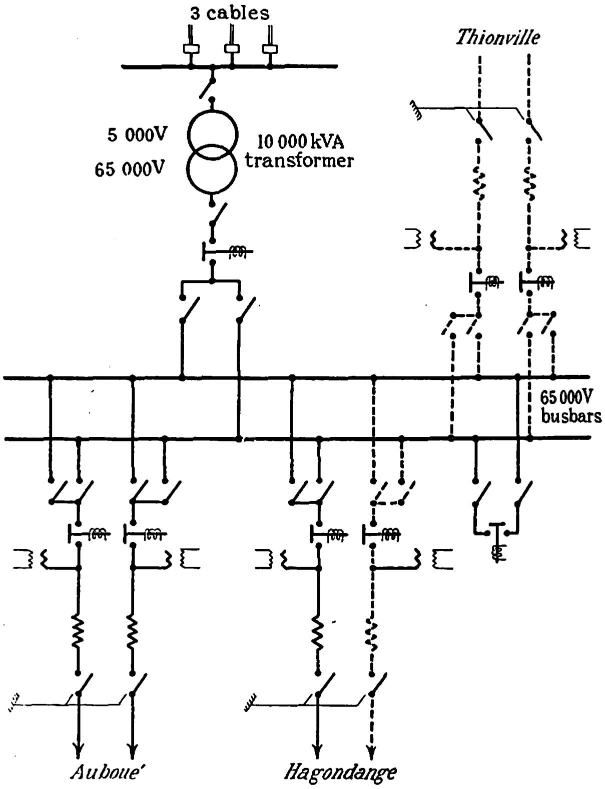

FIG. 8.—Diagram of connections of Rombas substation.

The telephone network of the load dispatcher is entirely distinct from the power network and is installed on the French State poles; it is equipped with selective calling apparatus supplied by the Western Union Telegraph Co.

Part (2). OPERATION OF THE NETWORK; PARALLEL RUNNING AND UTILITY OF THE NEW STEAM UNITS.

The first industrial test in connection with the parallel running of metallurgical central stations was carried out on the 25th March, 1925 (between Auboué and Thionville). These two were blast-furnace stations and were approximately 50 km apart; they were interconnected (provisionally at 30 000 volts) by a 3-conductor line (each conductor being of 50-mm^2 cross-section) and by two 6 000-kVA 30 000/6 000-volt transformers which fed a network supplying power to the mines. In August 1925 the 60 000-volt network of the Houve mines, fed by a 40 000-kW power station 70 km away from the above-mentioned power stations, was connected to the other network, the voltage of which had been increased to 65 000. The Micheville works were connected to the network in January, 1926. The Micheville station is a typical example of a complete steelworks with blast furnaces and rolling-mills, and contains a power station of 18 000 kW capacity.

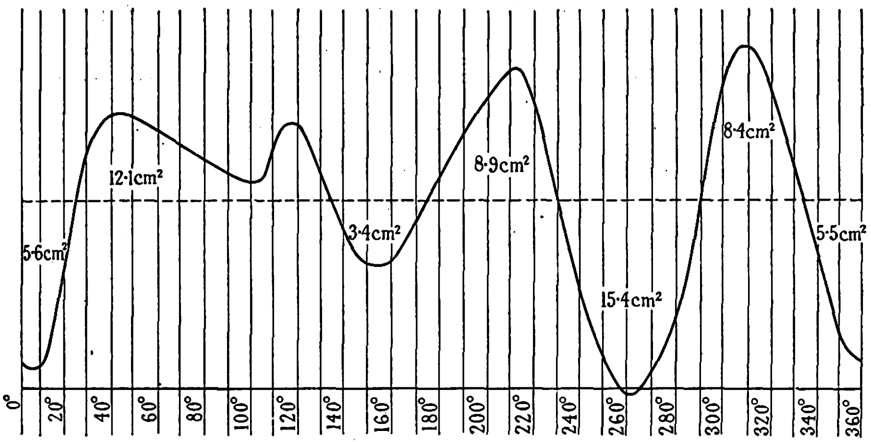

FIG. 9.—Torque curve of a 4-cylinder 4-stroke gas engine with 90° cranks.
1 cm = 30·02 kg.

Finally, since 1926, the Lorraine metallurgical group has been connected up to the distribution network of the Lorraine Electrical Co., fed by a steam power station of 50 000 kW at about 140 km from Landres. It already runs in parallel with a group of Swiss hydro-electric power stations. In the ordinary course of events the operation of these stations is eminently satisfactory * (see Fig. 2, which shows the frequency and voltage between the hours of 5.30 and 11 a.m.). For two reasons, however, a temporary service is adopted. The variation of the amount of power available on the metallurgical group's network, and the lack of elasticity of the gas engine, force the steam stations of the adjacent distributing companies to take up automatically the role of peak-load or buffer stations, for which they are not prepared. Again, if the load dispatcher of the company runs up a set without sufficient precaution after the breakers have tripped out, it is quite possible that the safety valves on the boilers in the steam stations may start to blow off. The remedy consists in the generalization of steam stations in the metallurgical stations by giving, if possible, to these new units a degree of sensibility of regulation which is closer than that of the units in the neighbouring companies' networks. Perhaps it will be necessary to consider a systematic modification of the degree of sensibility of the latter, the devices being so designed that they come into operation automatically as soon as parallel running with the metallurgical network commences. However, this remedy, which is very effective in connection with short peaks, requires elasticity in the production of the metallurgical stations. On account of the impossibility of storing the available gases this cannot be accomplished in the way that it should be done, i.e. ensuring a supply which is perfectly constant according to a predetermined time-table.

The difficulty is a commercial and not a technical one, and is eased somewhat by equipping the boilers of a certain number of the metallurgical stations with a means of using pulverized fuel.

The second difficulty is caused by peaks of short duration but of a periodic character, giving rise to a certain amount of hunting, which in turn affects the lighting and on rare occasions may make the defective generator fall out of step. This would not occur if all the units were in a perfect state of maintenance and if they were automatically tripped out as soon as their running became irregular. It is hoped to achieve this result by means of a reverse-power relay, and already parallel running has had the advantage of directing the attention of the station superintendents to these irregularities, which attentive local supervision cannot allow to pass. An examination of this phenomenon of hunting is not without interest and one of the authors' colleagues, Mr. Fournier, has analysed it experimentally in a very thorough manner.

His research may be summarized as follows: We know that a rotary electric generator possesses a certain period of oscillation which is a function of constant factors for a given machine (the moment of inertia of the rotating parts, the number of poles and the normal torque) and of a variable factor which depends both upon the machine and upon the network (the ratio of the impedance of the lines connecting the unit to the network to the internal impedance of the machine). The inherent period therefore depends to some extent upon the network. In our case it can cause a variation of the order of ± 25 per cent. If a rhythmic disturbance of a periodical character occurs, the frequency of which is of the same order as the inherent frequency of oscillation of the alternator, this machine will oscillate about

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* In particular the normal variations of load have never given rise to any difficulty in maintaining the normal voltage at the points where the supply is used, nor has it been necessary to install any synchronous condensers or induction regulators.

the position which corresponds to its running in synchronism with the network,* and hunting can occur which may at times produce reverse power and may cause the machine to fall out of step.

Now the complete cycle of operations of a 2- or 4-stroke gas engine running at 94 r.p.m. recommences every two revolutions, that is to say, 47 times per minute. These characteristic irregularities correspond to the following frequencies (see Figs. 9 and 10):—

188 per minute (cycle of work done by gas in the cylinders).
94 per minute (angularity of connecting rod).
47 per minute (pre-ignition, misfiring, unbalancing in a cylinder).

The inherent frequency of oscillation of a turbo-alternator unit being of the order of from 90 to 140 per minute, there is but little danger of resonance, for the irregularities at frequencies of 94 and 188 are generally of small amplitude. In the case of flywheel-type alternators driven by gas engines the normal inherent frequency is of the order of 70 to 75 per minute and occasionally 60, and for certain conditions of connections of the network there is risk of this frequency approaching the figure of 47, which is the frequency of the most violent irregularites in running (pre-ignition in a cylinder).

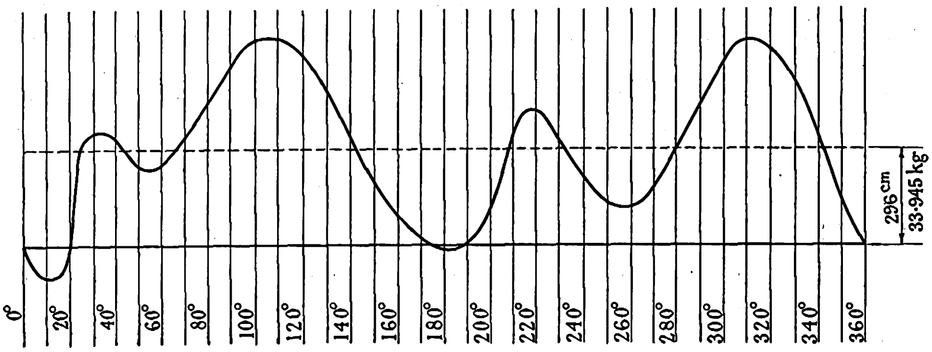

FIG. 10.—Torque curve of a 2-cylinder 4-stroke gas engine.

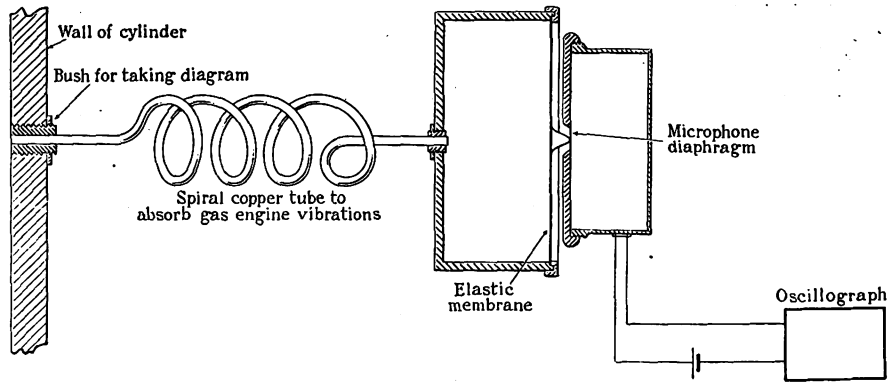

FIG. 11.—Piezo-microphonic device for recording the pressure in gas-engine cylinders.

Oscillographic records have confirmed these conclusions. When stations are run singly, hunting is not of much importance and relatively little attention is paid to the voltage or the frequency. The inertia of the flywheels takes its part in the regulation of the system and gives rise to what is sometimes considered as an improvement, that is to say the adoption of a very small coefficient of cyclic irregularity by using a considerable moment of inertia. (In practice the machines with the highest moment of inertia are precisely the type which give rise to the most dangerous hunting. This is very easy to explain on account of the preponderating importance that they assume in times of disturbance, owing to the exchanges of kinetic and electrical energy in the network.) Therefore for parallel running it is an advantage that all the units should have a reasonable moment of inertia, and that the moment of inertia should not vary very greatly. On the other hand, damping windings, by reducing the angular displacement during the hunting, amplify the oscillation of the alternator wattmeter.

It can also be shown that the greater sensitiveness of the turbo-alternators causes them to take part in these rhythmic exchanges of energy and that their distance apart does not protect them, but on the contrary can, on account of the impedance of the interconnecting line, produce conditions favourable to hunting. The remedy consists in developing the power of the turbo-alternator sets installed in the individual stations. This installed power represents practically 60 per cent of the total output. These theoretical considerations become quite clear in the light of the tests carried out by the authors' colleague, Mr. Fournier,* by means of an oscillograph connected to the alternator of a gas-engine unit and also by means of a device recording with another oscillograph the instantaneous pressure in one of the cylinders of the same gas engine, employing a microphone connected in such a way as to make it sensitive to variations in pressure (Fig. 11)*.

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* These oscillations are quite visible by the stroboscopic method when several flywheel-type alternators are close together.

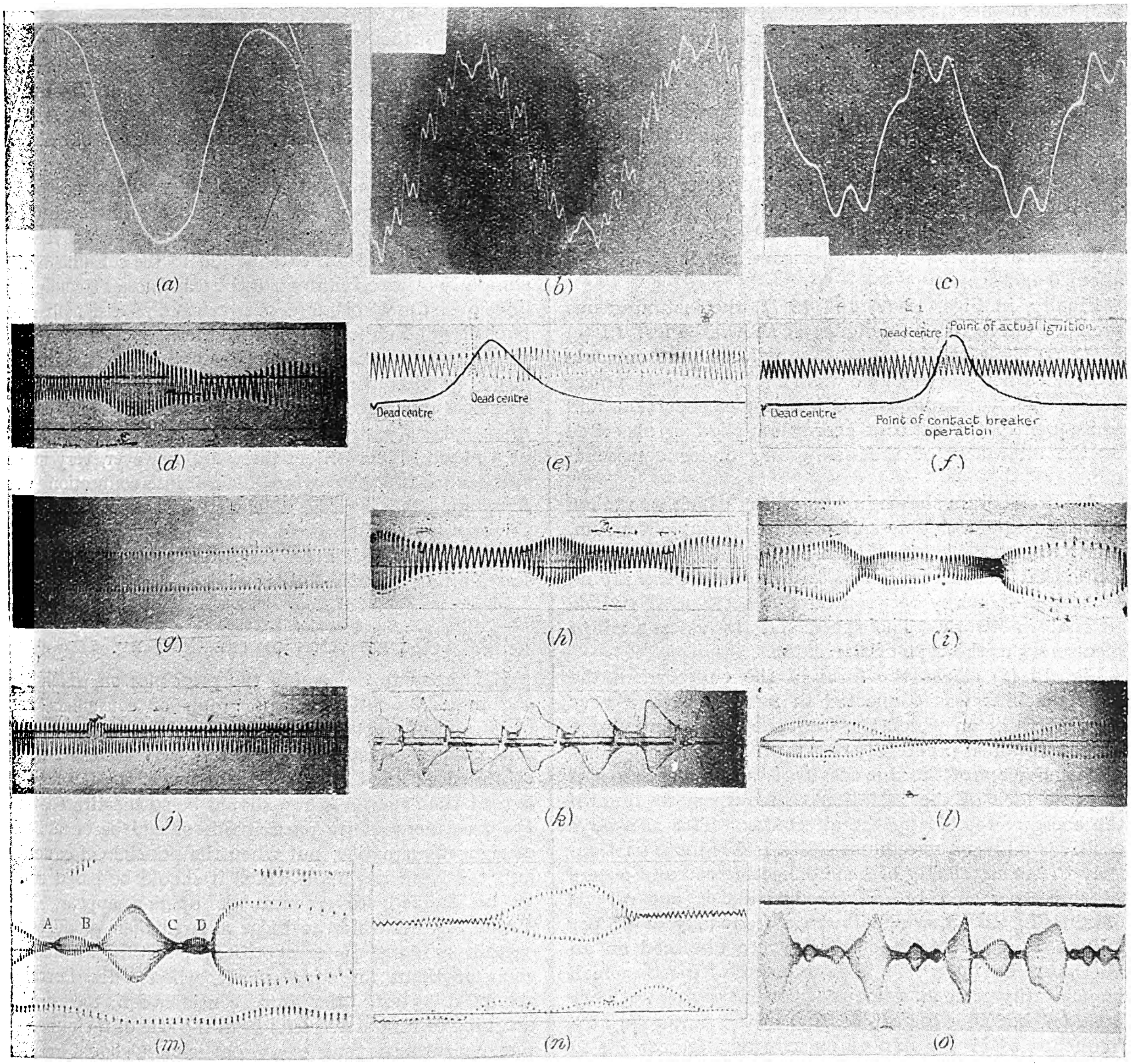

FIG. 12.—Oscillograms in connection with a gas-engine driven alternator running in parallel with the general network.

(a) Voltage curve of network.
(b) Tooth harmonic curve (gas-engine group) (artificially magnified).
(c) Tooth harmonics (turbo set) (artificially magnified).
(d) Ignition record.
(e) and (f) Instantaneous pressure curve in one of the cylinders.
(g) In-phase current of alternator feeding an independent local network.
(h) In-phase current of alternator feeding a large network (normal conditions).
(i) Pulsation at a frequency of 47 (per minute).
(j) In-phase current of alternator having high moment of inertia (normal operation).
(k) In-phase current, but influenced by a pulsation at a frequency of 47 (per minute) set up by another machine.
(l) In-phase current of a set running under normal conditions on a network, producing hunting. The energy supplied cancels itself out almost periodically.
(m) Reversal of power. At AB and CD the machine runs as a synchronous motor.
(n) In-phase current supplied by a station connected to the network, without periodic reversal of power.
(o) In-phase current supplied by a station connected to the network, with periodic reversal of power.

These results are shown in Fig. 12.

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* These tests would have been quite complete if Mr. Fournier had been able to record simultaneously the speed or the angular acceleration of the rotor. Nevertheless this research has contributed very largely to our knowledge of what happens in gas-engine groups during disturbances and has also indicated a practical remedy.

* The variations of pressure inside a gas engine cause the membrane to oscillate. The oscillations are transmitted by means of a small boss on the microphone disc, and consequently a microphonic current proportional to the pressure in the cylinder is recorded on the oscillograph. The oscillogram obtained thus shows to a given scale the variation of pressure inside the cylinder.

Figs. 12 (*a*, *b* and *c*) are instantaneous voltage diagrams, the first two being taken on the company's networks, and the third on a circuit fed by turbo-alternators only. (*a*) is the fundamental. In Figs. 12 (*b*) and 12 (*c*) the tooth harmonics have been artificially magnified. They are somewhat numerous but are less accentuated than in networks fed by turbo-alternators only. Fig. 12 (*d*) shows how the ignition points were recorded by means of a third oscillograph excited at the precise instant of ignition. It is seen that this causes a kick in the oscillogram. During these tests it was found that the time necessary for a contact breaker to operate after it is connected to the supply is equal to two cycles (0·04 sec.) and that two cycles later the spark takes place. Ignition takes place with surprising precision and is effected in about 0·002 sec.

Finally, in Figs. 12 (*e*) and 12 (*f*) the instantaneous pressure curve of the cylinder is shown. Figs. 12 (*g*) to 12 (*i*) show the instantaneous value of the currents recorded when the machine was running at unity power factor. They therefore give the in-phase current and consequently the ratio of energy supplied or absorbed by the alternator of the gas group under consideration.

The oscillogram shown in Fig. 12 (*g*), which was taken on a 2-cylinder double-action engine (simple tandem, 94 r.p.m., 50 cycles, feeding a separate local network), shows that the current is constant, because there are no exchanges of energy between the flywheel and the whole alternator network. The speed and the voltage adapt themselves to the type of alternator.

Fig. 12 (*h*) shows the form of the curve when the same machine was connected in parallel with a very large network on which the frequency and the voltage were maintained practically constant.

The envelope of the sine curves of the in-phase current gives an idea of the variation with respect to time of the energy supplied by the alternator. This is always positive and has a maximum which is due more particularly to the angularity of the connecting rod and occurs 94 times per minute. If the ignition is cut off we obtain Fig. 12 (*i*), which shows a frequency of 47 per minute. Figs. 12 (*j*) and 12 (*k*) were obtained on an alternator having a very high moment of inertia which momentarily gives an amount of power varying but very little (*j*), but showing a pulsation in the power (*k*) at a frequency of 47 per minute as soon as the network to which it is connected has impressed upon it a periodical variation at the frequency of 47 per minute due to another machine. This phenomenon is accentuated in Fig. 12 (*l*) by the exchanges of kinetic and electric energy, although the machine is quite normal. In this case the power supplied by the unit is cancelled out nearly periodically. In Fig. 12 (*m*) a reversal of power can be seen. During intervals of time such as BC, the alternator gives a certain output; on the other hand it receives a certain amount of energy from the network during the intervals AB and CD and at such times acts as a synchronous motor. Finally, Figs. 12 (*n*) and 12 (*o*) were taken by connecting the oscillograph to the interconnecting line between the metallurgical stations of the network and show that the in-phase current gives maxima and minima 47 times per minute. Fig. 12 (*n*) shows no reversal of power, but Fig. 12 (*o*) shows a periodical variation.

The curves in Fig. 12 which show this phenomenon correspond to hunting at the frequency of 47 per minute mentioned above.

In the authors' opinion the difficulties encountered are not sufficiently serious to cause the advantages of parallel running in general to be lost sight of. By increasing the total interconnected power to its maximum, the relative importance of these disturbances is diminished and the peaks are reduced. Finally, this plan will reduce to a minimum the losses of gas which may occur in works or parts of works which are interconnected. But in the present state of the art, and with a view to giving the maximum satisfaction to the consumers, the company takes advantage of the existence of 6-conductor lines over the whole of its network and provisionally runs two distinct circuits. The first of these interconnects pure blast-furnace works and runs in parallel with the large neighbouring supply companies. The second connects the steelworks to its network and consequently is subject to variations in voltage and frequency of a much higher order; these are, however, very much smaller than they were before interconnection was adopted. The overall efficiency of the installation is thereby greatly improved and the production of finished metal is increased under conditions which would themselves almost justify the enterprise.

OPERATION OF THE COMPANY.

It is easy to determine the principles on which the commercial relations of a group of consumers and producers of electrical energy should be based, but it is much more difficult to lay down the relations and to establish a fixed plan. For instance, it is generally agreed that such a group should be so constituted that the treatment of its participants should be on a basis of rigorous equality, but when the principle of equality and the elements upon which it should be based come to be defined, divergences of opinion appear. The Union des Centrales de Liége allowed their producers a certain amount of competition, but they assured to each of them an equal profit, whereas the Lorraine group did not take into consideration the profits accruing to its participants from the sale of their energy, but guaranteed that every participant should receive equality of treatment as regards quantity and price.

The Union des Centrales de Liége functions as a co-operative society, whereas the Lorraine metallurgical group functions as a clearing house. The Union des Centrales de Liége supplies through its network industries of very diverse natures; some of these are producers and others consumers. The service rendered by the Union by taking energy from the former and delivering it to the latter has therefore a very particular characteristic; the operations of buying and selling are confined to the co-operative partners and thus lose all commercial appearance. The Lorraine metallurgical group, however, supplies through its networks, almost exclusively, metallurgical concerns which are producers of energy. In this case it is not purely a question of mutual exchanges between the participants, or, if there are such exchanges, they are a secondary consideration and do not constitute the *raison d'être* of the group.

The network of the Société is, as has been indicated, a network of producers, and the agreement binding these had to be established in such a manner that it would not interfere with the commercial activities of the company; on the contrary it had to give the maximum of elasticity. The formula is a simple one. The starting point is the estimate that is made in each of the works of the amount of power available. By "power available" is meant the power that each individual station can produce with the gas at its disposal, allowance being made for a certain reasonable amount of reserve and subtracting therefrom the amount of works power that it consumes. This figure is fixed every year by a commission of experts whose decisions are final; in this way a quota is arrived at for each works, and remains in force throughout the year, to determine what proportion of the total energy required the station must deliver.

The Société has, of course, the exclusive right to sell the current produced in the works of its individual stations; it draws up agreements with consumers and remains free to negotiate with other supply companies such agreements as it may think fit and proper. In fact, the company acts in the same way as any producer would act; the energy sold is distributed among the various adherents in such a way that at the end of the year the distribution is proportional to the quota. This distribution is made for every category of supply, for which the charges are not necessarily the same; it therefore follows that, in particular, the supplies handled by the company in its own network are sold direct to its customers and are not supplied under the conditions that have to apply when energy has to be transported over several hundred kilometres. The company informs the works of the price adopted in every case and therefore fixes the tariffs which are paid to the works.

In practice, however, the operation is not quite so simple. It is clear that the role of sales clearing house for electrical energy played by the Société has assumed a very great importance, for it is from this that all natural developments should commence, but it has not been forgotten that the adherents are chiefly metallurgists and that the sale of electrical energy is of interest to them, although only of secondary interest. The network should first and foremost supply its industries and ensure that the works of its adherents receive the electrical energy that they require. At the commencement the function of the Société was simply to act as a buffer to increase the stability and the continuity of the central stations and, more particularly, ensure the feeding of iron mines. It still possesses this function, and the commercial formulæ which correspond to it have been designed with this end in view.

The supply of energy to an iron mine belonging to one of the adherent works is done by a system of toll; the mine has a certain maximum demand and consumes monthly a certain number of kWh. The Société simply requests the station to supply it with the same number of kWh, to which are added the transmission losses at the same instantaneous demand, which is deducted from the amount of power available for the determination of the quota; the accounts are adjusted from month to month and the company receives for this service a fixed payment per kWh.

The formula for this payment is not applied exclusively to mines, that is to say, to the firms served by the network. It is also applied to all the other consumers in the supply area of the Société, and agreements have been made between the company and neighbouring supply companies. Thus central stations situated near blast furnaces can, to-day, ensure the production of electrical energy necessary for certain works situated 100 km and even further away. The transmission of energy between the blast furnace and the works is ensured by the lines belonging to the Société as far as the State substation at Landres and from there by main transmission lines and, if necessary, by other distribution lines until it arrives at the point of utilization.

A system of tariffs to cover exchanges of energy between stations was more difficult to establish, as also was a formula which would express the service given in this way to gas-driven central stations.

Of what does the exchange or buffer service to a station consist? When a certain number of metallurgical works are connected in parallel to a network, the maximum power utilized, or, in other words, the peak on the whole system, is less than the sum of the individual peaks of each works, which, generally speaking, occur at different times and therefore are not superposed; as the total power is distributed among all the central stations, each will have to cope with a production peak which is less than the peak it would have had to supply to its own metallurgical works if it had been running isolated. A central station connected to the network can thus reduce the number of running machines by taking from the network the peak energy; on the other hand it delivers to the network the energy which the same station can supply during its hours of low local load. It is evident that the amounts of energy consumed by the works at the instant of peak load and the amounts of energy supplied by the works at the instant of minimum load are altogether different. The supply to the works, therefore, does not have its counterpart in the kWh delivered to the network, which for the latter has an almost negligible value.

The formula adopted by the Société makes but little difference to the tariffs applied to these two classes of load, but it taxes the half-hourly power taken from the network, i.e. the number of kilowatts utilized by the works for its buffer services.

This empirical tariff system, which has only the merit of simplicity, is applicable only to works which have not a continuous amount of available power to contribute to a network. For this type of station no buffer is, in fact, required, or, rather, there are no exchanges of energy with the network, since their stations have always more energy available than is required by the works.

As the role of producer tends to become general amongst the participating stations of the Société, all of which can dispose of large quantities of surplus gas, the buffer formula will have a steadily decreasing application.

THE ROLE OF THE LOAD DISPATCHER.

In order to ensure the best conditions of parallel running of a number of central stations and to obtain the best results from interconnection, each of the central stations must be constructed, not only with its own overall efficiency in view, but also with a view to the stability and efficiency of the whole of which it is only a part; hence the necessity of establishing between the central stations a control which will at every instant be informed by each of the stations of all the factors which are likely to influence the operation of the network, and which will transmit in the same manner to each of the interconnected stations the information resulting from the examination of all the details.

The dispatcher should know at every instant:—

(1) The amount of power supplied to the network by each of the stations.

(2) The power consumed.

(3) The amount of reserve power.

The Société's load dispatcher must at every instant possess the necessary data for him to determine as closely as possible these three elements. To this end, each works compiles and sends to the dispatcher a weekly list of machines available for parallel running on the network and also a list showing its daily consumption. The power available is deduced from these figures. It goes without saying that every incident at a works which may modify either its means of production or the importance of its consumption is immediately reported to the dispatcher.

The dispatcher is situated in the centre of the network at Briey, and has power to control the running of the machines if necessary; in particular he can have any machine stopped which causes any disturbance in the network, and he can also order another machine to be connected to a network, provided one is available. The dispatcher arranges the running of the machines and, in particular, the supply of wattless current. In his office there is no apparatus for measuring energy, but only certain hand-operated panels which show him the state of affairs at every part of the network and the condition of the machines in the various stations; in addition he is connected by telephone to all the switching stations and to all the central stations, and he periodically receives information as to the running of the network.

As and when the importance of the central stations and the loads of the networks increase, the role of the dispatcher will become more and more complicated. His task is, in fact, to ensure continuity of service. All metallurgical networks are liable to a further cause of disturbance in addition to those which exist in all other networks. The central stations are fed by blast-furnace gas and any disturbances in this supply of gas have an effect on the network. At the present moment this difficulty is but little felt because only a portion of the blast-furnace gas is used and any accident to a blast furnace leaves a sufficient quantity of gas to feed the station. This state of affairs will be changed when the new stations are put into service and they have been installed to utilize the total amount of gas available. When this occurs the dispatcher will have to be informed by every works, not only as to the state of the machines, but also as to their output of gas, and he will have to take all precautions to ensure that at any instant the reserve machine and the reserve of fuel necessary for the continuity of service are available.

In order to ensure this, the company has under consideration the inauguration in the works of a special organization in connection with each service interested, and will thus be informed minute by minute of all the variations in the feed gas and in the production of current in the stations; this organization will be in continuous communication with the Société's load dispatcher, who, in this way, will possess all the necessary information to enable him to follow the production of energy. As soon as a works utilizes the whole of its gas, the associated station finds itself in exactly the same position as a hydro-electric station without reserve water; the production of energy of the gas station depends, in fact, on the output of gas at any instant. A stoppage of a blast furnace in a metallurgical works connected to the network must be avoided in order to prevent disturbances in the feeding of energy to the network. It is the task of the dispatcher to guard against all such incidents and obviously he cannot do this unless he is kept informed of the details of the running of each station.

NEW POWER STATIONS OF THE SOCIÉTÉ ÉLECTRIQUE DE LA SIDÉRURGIE LORRAINE.

The central stations which have been connected to the network since 1923 existed a long time before this date and had been designed to cope with the internal needs of the works; the output of these machines had been calculated by taking into account the basis of energy consumption corresponding to the needs and not to the possibilities of production which were given by blast-furnace gas. In consequence of this, in nearly all the works belonging to the company there was a surplus of gas which was not utilized, the whole of which constituted for the company a source of energy capable of supplying about 50 000 kW. In order to exploit this it was necessary to install in every works the necessary means of production. The question was whether gas engines or steam turbines should be installed.

The battle between the champions of the gas engine and of the steam turbine has altered in character several times during the last 20 years, and every time with a marked preference in favour of the gas engine with the turbine as an auxiliary. The defenders of the gas engine admitted that this type of machine lacked a certain amount of elasticity and was not suitable to deal with such an irregular amount of consumption as that required by a rolling-mill. They therefore added to their gas engine a turbine partially fed by the steam produced by boilers placed on the exhaust; they had thus the double advantage of regularizing the running of the gas engine by means of the turbine, which was done in such a way as to absorb the peaks and to increase the thermal efficiency of the installation from 23 to 26 per cent (for engines without scavenging). On the other hand, a steam turbine fed by high-pressure boilers has an efficiency of 21·6 per cent.

Translated into cubic metres of blast-furnace gas, these figures give the following consumptions:—

Gas engines with regenerative boilers—3·8 cubic metres of gas per kWh at the terminals.

Steam turbines with high-pressure boilers—4·6 cubic metres of gas per kWh at the terminals.

In other words, 100 cubic metres of blast-furnace gas will give, with gas engines, 26 kWh and with turbines 21·7 kWh. Therefore the gas engine shows an efficiency in kWh which is 20 per cent better than that of the turbine. In spite of this advantage, which is to a very great extent compensated by the high cost of manufacture and operation, the solution based upon the use of turbines has been adopted for the technical reasons given above, in order to reduce the proportion of gas engines running in parallel on the network.

At the present time the power produced by gas engines represents 56 per cent of the total power installed in interconnected stations; the importance of the turbines which are running is too small to enable a practically constant frequency to be maintained. The new installations will reduce the above figure to 40 per cent and will give the turbines a preponderating effect without which the network would be liable to cause disturbances in neighbouring networks.

The steam turbine has a further advantage. Instead of depending very closely upon the blast furnace as does an internal-combustion engine, and reflecting every disturbance which occurs in the production or consumption of gas, the turbine has associated with it a boiler. The effect of variations in the calorific value or pressure of the gas is therefore less direct and can be entirely compensated by the intervention of coke-furnace gas or by pulverized fuel, which can be put into service in boilers specially designed for gas without any very great increase in cost.

The stability of running of the turbine as compared with gas engines, which are subject to rather frequent stoppages, is a final argument for the adoption of the steam turbine when it becomes a question of metallurgical works delivering current to a network on which continuity of service is the most important factor. The authors' remarks on this subject do not, of course, indicate a definite solution to the problem of the production of metallurgical energy and do not condemn the gas engine, which, under certain conditions, and more particularly in connection with isolated works, may be preferable to the turbine on account of its higher efficiency. Turbine central stations are, at the present moment, being installed in seven works belonging to the group. Their total power will be 64 000 kW distributed over seven turbo-alternator units, five being of 10 000 kW and two of 7 000 kW. Each station will comprise one group only, but provision has been made for installing eventually a second unit which most probably will be of a more powerful type.

The steam characteristics are a pressure of 35 kg/cm^2 (497 lb./sq. in.) and a superheat of 425 deg. C. The feed-water is brought up to a temperature of 130° C. by being passed through reheaters fed by steam bled from the turbine. The air necessary for combustion is reheated to 180° C. by means of Ljungström heaters placed at the back of the economizers. In works which have coke furnaces at their disposal, burners are provided for employing blast-furnace gas or coke-furnace gas, it being possible to use these two gases either together or separately. Automatic regulators placed in each boiler will maintain a constant pressure of steam and will not call upon the coke-furnace gas until the whole of the blast-furnace gas has been utilized. This device has a very great advantage in that the automatic intervention of coke-furnace gas in order to maintain the load on the station will allow a better utilization of blast-furnace gas to be made.

To the best of the authors' knowledge it is the first time that 10 000-kW units have been installed in France in metallurgical works. The tendency up to the present has been to make the combined power of the units equal to a small fraction of the total power of the works. Moreover, gas engines could not be built for outputs of more than from 2 000 to 4 000 kW. Now that in works in Lorraine 10 000-kW units are being installed which correspond on an average to half of the productive capacity of the station, certain stations will have only one unit running in order to ensure their service, and this would appear to be the practice of the future, viz. to install in the works steam-generator units of a capacity such that the whole of the output of blast-furnace gas can be utilized at any moment, and to allow these boilers to feed a high-power turbo-alternator set designed with a heavy overload capacity. Such an installation is quite capable of producing, under the best conditions of continuity, the current required in the works, on condition that sufficient reserves can be maintained. The works which produce their current with a single machine should have means of stopping periodically and at the same time allowing their gas to be utilized on other sets. This difficulty is not prohibitive. Without entering into prolonged economic considerations, however, it may be said that a 10 000-kW group costs less to install than a 2 500-kW gas engine. Stand-by reserves, i.e. units which can be ready at any instant to take their share of the load in the event of a sudden stoppage of the main group, are somewhat difficult to ensure. If five works are equipped in the same manner with a single unit the network will continue to operate as if it were served by only one station equipped with five similar units. Therefore, in order to take precautions against a sudden stoppage of one of the stations and at the same time to maintain the production, it is necessary that at every instant the remaining four units should have a sufficient overload capacity, which in this case would be 25 per cent. This condition, however, is not sufficient, and in most cases the overload can only be obtained by using fuel which is independent of the works, and this fuel can only be pulverized fuel.

This is the system that has been under consideration for the operation of the new steam stations of the company. Each of the five units of 10 000 kW is designed for an economical load of 8 000 kW and for a continuous overload of 12 000 kW in four of the stations. The supplementary load of 4 000 kW can be obtained exclusively with pulverized fuel. The stoppage of one of the turbines can therefore be entirely compensated by forcing the others with, if necessary, the utilization of pulverized fuel until the station in which the stoppage has occurred has taken steps to put its reserve units into service.

CONCLUSION.

The Société Électrique de la Sidérurgie Lorraine has solved the problem put to it and has been able to overcome the difficulties inherent to this programme, not only from the technical but also from the commercial point of view.

Exchanges of energy have developed regularly and since 1928 have exceeded the figure which was predetermined at the outset as being necessary in order to make a sufficient return on the capital invested.

The number of kWh transmitted by the network of the company from the commencement is as follows:—

1923	7 931 074
1924	22 413 015
1925	36 555 028
1926	65 703 130
1927	89 732 038
1928	112 403 727

These figures include the toll energy and the buffer energy; for example, the figures for 1928 can be divided as follows:—

Normal supply	72 052 663 kWh
Toll supply	36 003 009 kWh
Compensation supply between works	4 348 055 kWh

For 1929 the total production will reach 130 million kWh, and in 1931 will exceed 200 million kWh.

From the present time the amount of energy taken into account, which has been almost entirely produced by waste gas, represents annual receipts of the order of 20 million francs.

The company is of opinion, however, that it has not yet done all that is possible; new stations which will be in service during 1930 will considerably increase the amount of energy available and will permit the company to increase its radius of action. When that occurs new markets will have to be found, more particularly for utilizing the energy available at night. The new units will help to improve the operation of the existing stations and of the network in such a manner as to ensure that the amount of current produced by the metallurgical works will be as regular and give the same continuity of service as the current supplied by the thermal or hydro-electric stations which feed the distribution networks.

This result will certainly be attained and even exceeded: a hydro-electric station operated by running water is incapable of providing its own reserve and, should the flow of the river become insufficient, it is obliged to turn to another source. On the other hand, a metallurgical station, if it is equipped with boilers and steam turbines, is sufficient in itself and can cope with variations in the output of blast-furnace gas by utilizing coke-furnace gas or coal. For this reason it possesses, without immobilizing large amounts of capital, surplus energy which can be used at any time when necessary.

In order to ensure new outlets for the increased production of energy the company has already interconnected two large distribution networks in Alsace and Lorraine and in the Vosges, and has participated in the creation of two new companies which are constructing high-tension lines to join up with the Parisian region and the north of France via the Ardennes.

DISCUSSION AT THE JOINT MEETING OF THE INSTITUTION AND THE BRITISH SECTION OF THE SOCIÉTÉ DES INGÉNIEURS CIVILS DE FRANCE, 12TH DECEMBER, 1929.

Mr. N. G. Hackney: I should like to express, as President of the British Section of the Société des Ingénieurs Civils de France, the great pleasure and gratification we feel at the presentation of this paper before the leading society of experts in this country in the subject with which it deals. This is the second or third paper dealing with electrical matters which has been read at a joint meeting of the Société and the Institution, and I hope that we shall have further ones in the future, just as we hope to have papers on other branches of engineering read before institutions dealing with those other aspects of the subject.

Mr. I. Scott Mackenzie: I have read the paper with very great interest, because at the Devonshire Works of the Staveley Coal and Iron Co., near Chesterfield, we have been running for about five years three large (5 000-kW) gas-driven alternators similar to those mentioned by the authors. The late chairman of the Company, Mr. Charles Markham, saw engines of this type operating in Belgium at Liége and Seraing, and formed the opinion that it would be a good thing to install them at Staveley with a view to making the best possible use of the blast-furnace gas which, owing to its low calorific value (about 100 B.Th.U.), could not be sold like coke-oven gas, and had to be used, more or less inefficiently, for firing Babcock and Wilcox boilers. Our electrical system at Staveley now consists of a large station at Devonshire Works, containing three 5 000-kW gas engines and 10 000 kW of steam turbine plant, which feeds into a ring connecting up our other works and collieries, some of which have mixed-pressure turbine generating plant of their own. It was thought at first that it would be difficult to run low-speed gas engines at about 90 r.p.m. in synchronism with turbines, but in actual practice we have not found this to be the case, particularly since our system has been connected up with that of the Derbyshire and Nottinghamshire Electric Power Co., which has a very large power station at Spondon, near Derby. I am fully in agreement with the authors that in order that gas engines may run satisfactorily on a system, turbine plant, which heavily preponderates, must operate in synchronism with them; I would go even further and suggest that the relative proportions should be:— turbines 70 per cent and gas engines 30 per cent. Whilst admitting the high thermal efficiency of gas engines, particularly when the steam which can be raised by utilizing the exhaust gases from the engines is taken into account, I am of opinion that they are more expensive to buy than a complete turbine plant of similar capacity, although the gas-engine makers submit that this is not the case. The capital cost of our gas engines at Staveley, including the very elaborate gas-cleaning plant which had to be installed, was approximately £22 per kW, as compared with the complete cost of a modern station such as Padiham, Lancashire, which was, I understand, between £13 and £14 per kW. The gas engines themselves have not given us much trouble, but we have had a great many breakdowns in connection with the exhaust pipes and the boilers, which are fired by means of the exhaust gases. I should be very grateful if the authors would say what their experience has been in this connection, and whether they can suggest any means of overcoming the difficulties which we have experienced. One more drawback which we have found to gas engines is that they cannot be started up and shut down like turbines, mainly because of the aforementioned difficulty with exhaust pipes. As a result of our experience, we find the best plan is to start up a gas engine and run it on full load as long as possible, which, on the average, is about 12 weeks. The longest run we have ever had is 15 weeks, but a 12 weeks' run may be taken as a fair average, and at the end of that time an engine has to be shut down for cleaning. Although we have three 5 000-kW gas-driven alternators installed, we have hitherto never run more than two at a time, keeping one in reserve, and this, of course, has tended to increase our generating costs, because, although only two engines were running, the cost figures had to include the depreciation of three engines. Now, however, that we are connected up with the power company's system we shall be able to run all our gas engines at all possible times. The authors do not refer to the question of

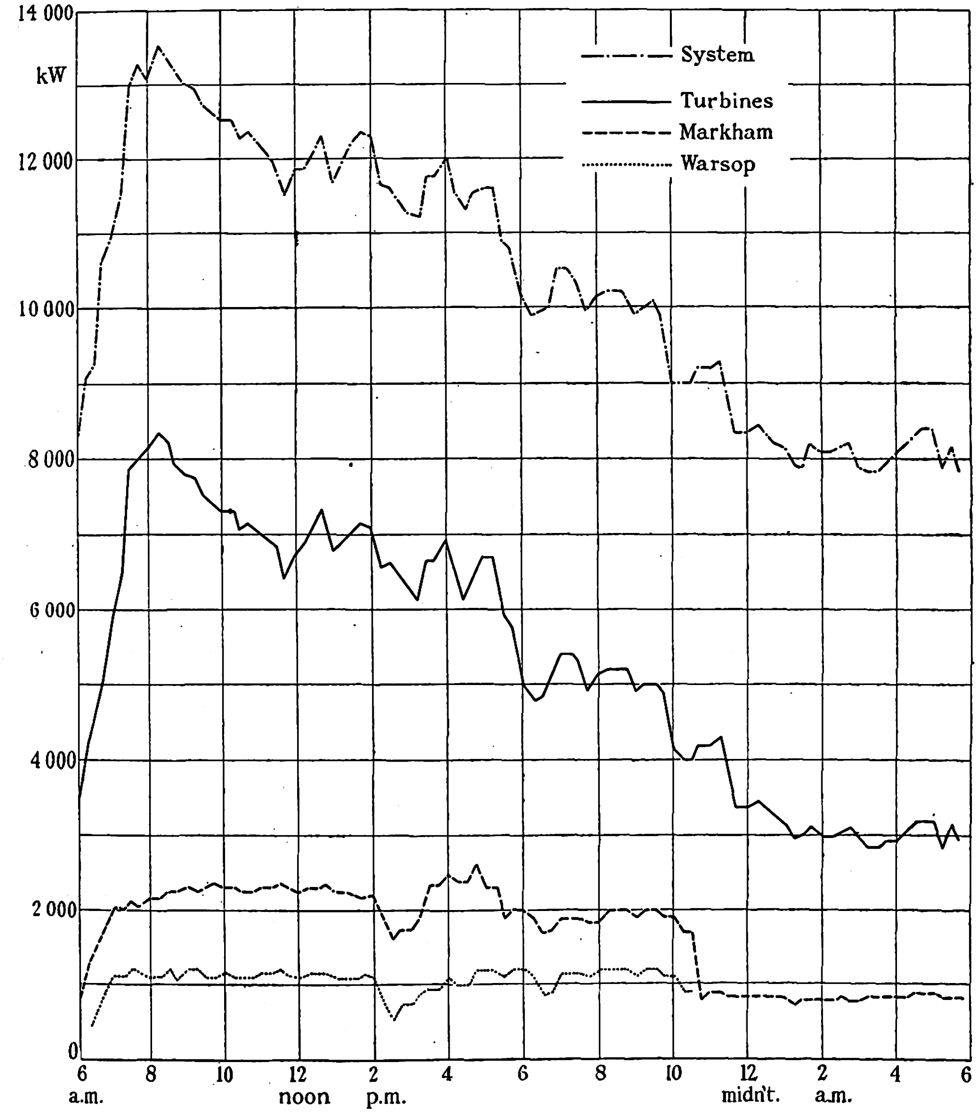

FIG. A.—Load curves for the 6th December, 1929.

costs, and I feel that it may interest the members to learn the figures of costs obtained at Staveley. In the appended costs is included an allowance for the value of gas consumed by the gas engines and turbines, at the rate of 1 lb. of coal for every kWh generated by the gas engines and 2½ lb. of coal for every kWh generated by the turbines. It may be thought that 1 lb. of coal for the gas engines and 2½ lb. of coal for the turbines are high figures, but our turbine plant is not particularly up-to-date, and I had to make the best terms I could with the engineers who run our blast furnaces. Taking an average for the last 6 months, our "all-in" cost of generating electricity, including coal and other fuel, oil, waste, water, stores, wages, repairs and maintenance, depreciation, establishment and management charges, and all auxiliaries (including gas cleaning, which is an important item in connection with gas engines), came to 0·25d. per kWh at the busbars of the station for the gas engines and 0·35d. per kWh for the turbines. In a way, it is not quite fair to compare these two figures because, as will be seen from the load curves shown in Fig. A, we run the gas engines at full load the whole time, and take up any peaks or other variations by means of the turbines. The voltage and frequency charts (Fig. B) show that we are able to maintain quite steady voltage and frequency. Before our system was connected to that of the undertaking to which I have already referred, the cyclical variations of the gas engines produced fluctuations of voltage which were rather troublesome, but since we have been running in synchronism with the other system these troubles have disappeared almost entirely. It may be of interest if I mention that we generate at two different frequencies at Staveley, i.e. 30 and 50 cycles per sec., our total output being about 90 million kWh per annum. Our original plant, which was installed over 20 years ago, was all at 30 cycles, but recently, owing to our giving a supply to various outside consumers, including the Derbyshire undertaking, we have had to install frequency-changers. Two of our 5 000-kW gas engines generate at 30 cycles and one at 50 cycles, and the two systems are connected up through two large 2 500-kW reversible frequency-changers, which can run at either 30/50 cycles or 50/30 cycles or, in some cases, merely "float" between the two systems. We have experienced no trouble whatever with running the electrical part of the plant, particularly, as I have already mentioned, since we have been connected up with the large network and generating station of the Derbyshire and Nottinghamshire Electric Power Co. The authors' remarks in connection with the oscillograph records shown in Fig. 12 are particularly interesting, and I am fully in agreement with the authors that, for the parallel running of gas engines and alternators, it is an advantage that all units should have a reasonable moment of inertia, and that this should not vary very greatly. In practice, there can be no doubt that machines with the highest moment of inertia are precisely the type which give rise to the most dangerous hunting, on account of the preponderating importance that they assume in times of disturbance owing to the exchanges of kinetic and electrical energy in the network. The piezo-microphonic device for recording the pressure in gas-engine cylinders, shown in Fig. 11, is very ingenious.

Mr. Roger T. Smith: The problem of the use of waste heat from blast furnaces for the production of electric power, either for domestic use in steelworks or for sale outside to a network, is shown in this paper to be one of extraordinary difficulty. Owing to the great cost of starting a blast furnace, the cycle of operations of a large group of blast furnaces is, as the authors have pointed out, relatively constant. The daily and the annual production of gas are fairly well known, and the more furnaces there are the better it is for the system. The paper clearly explains the variation in the quantity of gas per shift and per day, but the peaks in the load and those in the supply of gas do not coincide. I should like to ask the authors how far they have succeeded in making the shifts fit in with the variation of load. It is not quite clear from the paper whether the variation of the shifts is an accomplished fact. The interconnection of the electrical distribution side is a great help in smoothing-out peaks in the load, but the result of some years of working shows that the gas engine, with no overload capacity, must not preponderate over the steam turbine as a source of power. One of the most interesting points in connection with this system, on which the paper does not say very much, is the question of safety. How far is it possible to submit to breakdowns, and how frequently do they occur? There is the intrinsic liability to failure due to overhead lines, of which we at present in this country know very little, but with which in a few years' time we may become much more familiar. In Lorraine, matters are not helped by the use of single lines, with provision for duplicating, nor by pin insulators on a 65 000-volt line. The network is further handicapped by the fact that so far it has not been possible to install either a balanced selective system of protection or the impedance system of protection which are being studied. I believe it is a fact that in Mr. Mackenzie's system at the Staveley ironworks there is no protection of the lines, but only protection of the generators. Then also, from the point of view of safety, there is the switching of substations. Fig. 8 shows the high type of double-busbar substation, with alternate feeders connected to the double-busbar and there are arrangements for changing the feeder from one bar to the other through rotating links. If a feeder switch breaks down there is, however, no bypass link to connect the feeder temporarily to the bars while the switch is being repaired. I should like to know whether trouble has been caused by the failure of switches after short-circuit, owing to the impossibility of connecting the feeder to the bars while the switch is being repaired. The Rombas substation is fairly typical of such a modern substation as would be used on our own grid system, with the exception I have mentioned; but in Fig. 7, representing the Fontoy substation, alternate feeders are connected to alternate busbars with no arrangement for changing a feeder from one bar to the other. Both transformers are connected through one switch to either busbar, and it is not possible to have one transformer on one bar and one on the other. Again, the potential transformers

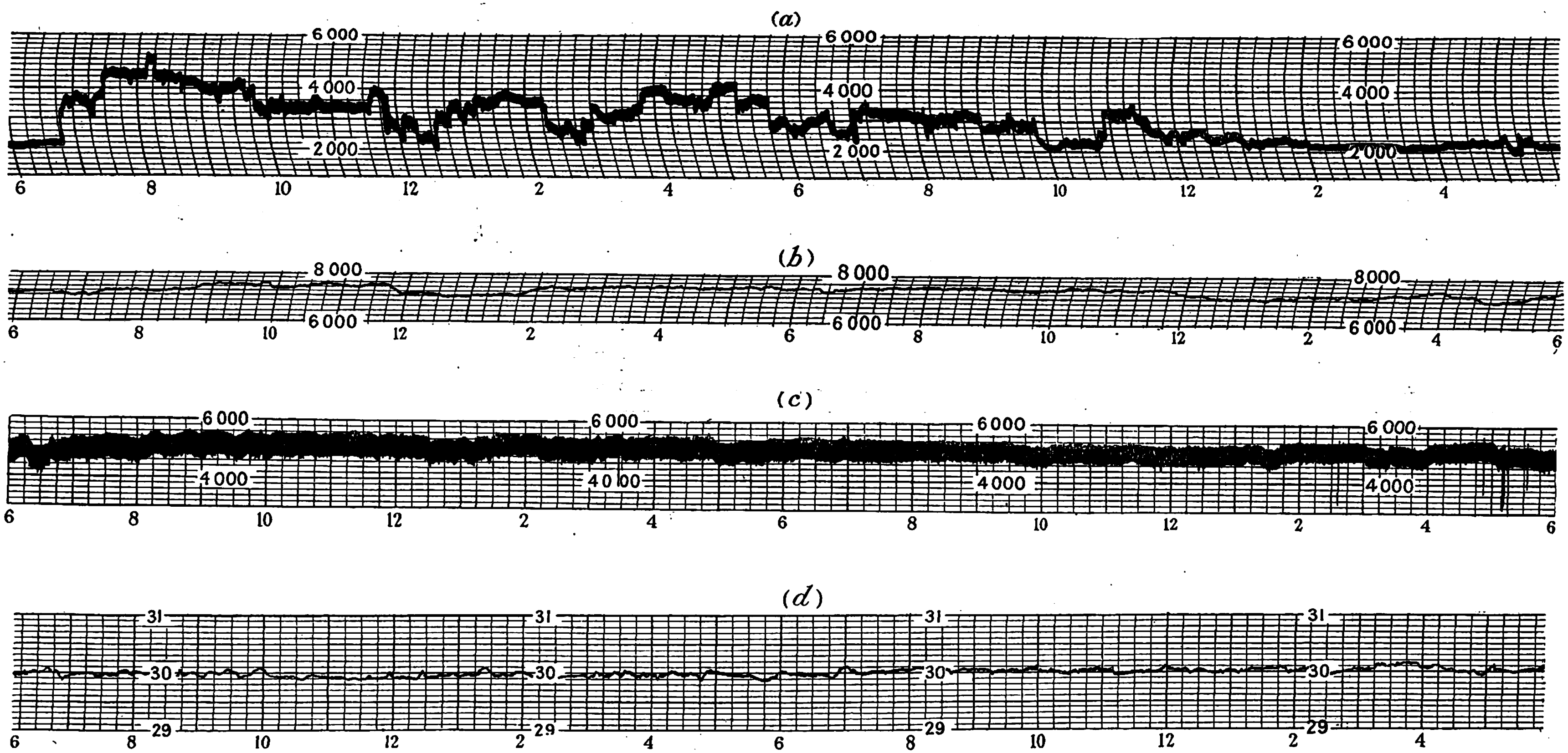

FIG. B.—Voltage and frequency charts for the 6th December, 1929.

(a) Output of 5 000-kW turbo-alternator.
(b) Voltage.
(c) Output of gas-engine-driven alternator No. 3.
(d) Frequency.

are connected on the high-voltage side, whereas in the British grid system we connect them on the low-voltage side and compensate for the loss of voltage in the main transformer. I should be glad to hear whether there has been trouble, at least at substations, from these comparatively small voltage-transformers being connected on the high-voltage side with no protective system and a not very elastic switching system. Breakdowns, when they occur, must be fairly complete. One dislikes to speak of breakdowns, but it is important for other engineers to hear of them, and I hope that the authors in their reply will speak about the sort of breakdowns that do occur and about their frequency. Mr. Mackenzie gave the arranged price which his electrical department was charged for the blast-furnace gas. I should like to know whether the Lorraine Société have a uniform agreed figure for all kinds of blast-furnace gas used in the gas engines, and, if so, what it is in terms of kilograms of coal per kWh.

Major T. Rich: This paper is very interesting, for it brings out a second case where the amount of power generated does not depend exactly on the amount which is required but on that which is available. It is rather like the water power in the Pyrenees, where different power stations use the water. In this case, the gas available from time to time is used. Water power has the advantage that it can be stored where the configuration of the land permits, but blast-furnace gas has such a low calorific value that it is very difficult to store it. In the Pyrenees a large proportion of the power is used for electrochemical work, and here in the east of France the bulk of the power is used for steelworks, the balance being sold outside. There is a remarkable spirit of co-operation all over France. In the rural districts half-a-dozen farmers will buy a threshing machine and form a small company to run it. They work together and arrange their dates in an extraordinary way. In the same way in the Pyrenees, in this steelworks area and elsewhere, we find the same spirit of practical co-operation, without interference from Government or outside organizations. It is a great advantage to the nation as a whole. Other points which the paper brings out are the questions of the cost of power and thermal efficiency. In this country we very often go too far in the way of thermal efficiency and believe that the saving of a fraction of a pound of coal in steam generation or heat utilization is the main object. We find here that a lower thermal efficiency is more useful from one point of view and, as is frequently the case in power stations, unless the load curve is very good one can easily get too high a thermal efficiency and have to pay very heavily for it in capital outlay. A point in connection with the utilization of steelworks power in general networks is that where, as in France, the national trade policy does not make for violent fluctuations in the steel market, it is more easy to make arrangements in advance over a long period to enable such surplus power to be used. If there are great variations and a possibility of the closing of large numbers of blast furnaces, as we find in this country, it may not be worth while to spend large sums on capital outlay. It appears from the paper that, having started with 65 000-volt pin insulators and continued with 85 000-volt pin insulators, they are now adopting suspension insulators for the 65 000-volt mains. With regard to overload capacity, it must be very interesting to use gas-fired boilers and arrange for the possibility of pulverized-fuel firing. There are some cases in this country where oil fuel is used to supplement stoker firing. This shows the extraordinary elasticity of the modern thermal arrangements of the steam-turbine plant. Have the authors ever considered the question of steam storage? We hear a good deal from time to time about marvellous steam-storage apparatus which will revolutionize power-station operation; if steam storage ever does all that is promised it will be possible to utilize the surplus gas until outside demand or the peak load comes on, and then to make use of it where it can be of the greatest value.

Messrs. L. A. E. Sékutowicz and **A. Evain** (*in reply*): The information given by Mr. Scott Mackenzie is interesting and shows that alternators driven by gas engines are quite capable of feeding a public supply network and of maintaining an almost constant output when operating in parallel with suitably regulated steam turbines. The difficulty experienced in Lorraine arises from the predominance of rolling-mill motors, the stopping, starting and running of which produce frequent variations in demand of much greater extent than those shown by Mr. Scott Mackenzie's load curve (Fig. A). We notice that the characteristics of the Staveley day-load curve are particularly advantageous from the point of view of economical running. We are in agreement with Mr. Mackenzie as to the desirability of having a preponderance of steam turbines, also as regards their lower first cost and the necessity for having a large reserve in the case of gas engines. The cost of operation quoted by Mr. Mackenzie for gas engines seems to us to be low and, as he states, steam turbines are at a disadvantage in the comparison because they alone provide the peak supplies and their efficiency has been taken at far too low a value. With modern installations we reckon to obtain, in the case of gas engines and regenerative boilers, a consumption of 3 500 calories per kWh (equivalent to 0·5 kg of coal at 7 000 calories per kg) and, with high-pressure steam turbines [30 kg per cm^2 (483 lb. per sq. in.), the steam being superheated to 400°C.] a consumption of 4 400 calories per kWh (equivalent to 0·63 kg of standard coal). Such coal costs in France about 160 francs per ton, so that the above consumptions are equivalent to a cost of 8 and 10 centimes per kWh respectively. Taking into account essential stand-by plant, the cost of maintenance and renewals and the capital charges amount to a smaller total in the case of turbines, for a similar period of use. The capital expenditure for turbines is, in fact, only about one-half, and the importance to be attributed to the equipment for purifying the gas which must, on the other hand, be provided is far from compensating for the difference involved by an outlay larger by 45 per cent. Attendance and maintenance are also less costly in the case of turbines.

Mr. Roger Smith, to whom we are indebted for reading the paper at the meeting, has drawn attention to several important points which we may not have made quite clear. Fig. 5, which refers not to an average day but to one selected at random, shows that it was not possible to provide for any rearrangement of working between 6 a.m. and 2 p.m. From 2 p.m. to 10 p.m. resumptions of work are always spaced out, and the ratio of the minimum to the maximum (about 0·7) is notably higher than it would have been if the concession that one of the most important steelworks should be shut down for one shift during the day and should work one shift during the night had not been obtained.

With regard to reliability, the system is satisfactory in practice and never gives any cause for serious complaint. The metallurgical works had already separated their internal equipment into several circuits before they were linked up for parallel working. One of these circuits, the safety circuit, grouped together the essential works plants and several steam-driven generators. Interruptions, when they occur, only interfere with the output for the duration of the fault itself. These interruptions are not frequent. In 1929 there were only 9 breakdowns on the 65 000-volt grid, and only one accident due to a meter transformer. On the other hand, there were some interruptions of the works plant as the result of overloads, which were remedied by finer setting of the relays. In the same year only 9 insulation faults occurred with 4 000 insulators, accompanied in 7 cases by damage to the cable. The arrangements briefly described in the paper constitute the basis of the protective system. Because they have so far been satisfactory in practice the installation of balanced selective protective apparatus has been postponed, but the possibility that such equipment may be necessary is kept in view. Since the inconvenience to external consumers due to surges and sudden variations of load has been greater than that arising from damaged lines the double network has provisionally been used for isolating the steelworks. Future events will show whether the rarity of line faults, the efficacy of the impedance relays and the earthing of the neutral justify the retention of this provisional solution, or whether, on the other hand, progress in the maintenance of gas engines and a greater use of turbines will bring about a return to a network using 6-conductor lines working in parallel; such a scheme would allow of better use being made of the copper in the lines. It would be inaccurate to say that there is no risk of breakdowns with overhead lines. Voltage-rises—the causes and attendant circumstances of which we are investigating (particularly with the aid of a "klydonograph")—produce, in fact, distortion and fracture of the insulators. Suspension insulators, which we are trying on the latest line, are no more effective than rigid insulators in combating this trouble. If the line insulation was strengthened too much the transformers would suffer. As regards the planning of the substations, simplicity has been the first consideration; this was all the more essential since at the outset it was not definitely settled what connections would ultimately be necessary. Only once has a circuit breaker exploded. The voltage transformers have not given any trouble. We have continued, however, to test apparatus of this kind on high voltages in view of the risks involved and of the installation of selective relays which might have been rendered necessary. As Mr. Roger Smith observes, the design of the stations (such as the one at Fontoy) constructed at the outset has not the flexibility desirable to-day. Simple apparatus of that kind was adopted primarily for reasons of economy. It was estimated that the financial return on the system would be completely assured when the output reached 100 million kWh. This forecast has been entirely confirmed by the facts and, while retaining its essentially co-operative character, the Société is able to pay a dividend of 6 per cent. It intends to continue to complete and gradually to perfect its equipment, and this has already been achieved in the new stations. Attention is especially concentrated upon the adoption of modern methods of telecommunication for supplying the load dispatcher with all the information that may prove useful to him.

Major Rich has drawn attention to a very important aspect of the problem—the difficulty of accumulating sufficient energy to make the supply equal to the demand. It should be observed that even if steam storage were unable, under the prevailing conditions of space and cost, to cope with the needs of a group such as our own, and if the blast-furnace gas were of such poor quality as not to make storage worth while, nevertheless coke-oven gas is of sufficient value to allow of the use of gasometers of reasonable cost and volume. It is possible in some measure to achieve the end in view by temporarily substituting one gas for the other in suitable services and by storing gas of high calorific value. Installation of electric furnaces and grouping of chemical industries round the coke-works will, no doubt, provide further facilities for this. Major Rich has also drawn attention to the risk of an enforced stoppage in the metallurgical processes of production. The risk of insufficient output also exists with hydro-electric power during periods of insufficient rainfall. It may be that, in the case of the metallurgical works, the energy demands (especially for mines and industrial processes) will diminish simultaneously with the output. The installation of pulverized-fuel boilers and interconnection with collieries may serve, in addition, as effectual solutions of the problem.

WATER PENETRATION EFFECTS IN LEAD-SHEATHED POWER CABLES.*

By E. A. BEAVIS, B.Sc., Associate Member.

(*Paper first received* 21*st March, and in final form* 12*th November*, 1929.)

SUMMARY.

The immersion in water of lead-covered cables, with a view to the detection of faults in the lead sheathing, is discussed. Tests of the time taken to show up these defects in power cables at different water pressures are given for various cable samples. The conclusions drawn are that, except possibly in the case of low-voltage cables, no such defects will be discovered during factory routine, and that for high-voltage cables, at least, water immersion should be definitely discontinued.

INTRODUCTION.

In the normal course of cable manufacture it is customary to immerse drums of lead-cased cable in water for at least 24 hours previous to the carrying out of any electrical tests. This has been the recognized routine on all cables for many years, and is incorporated in the British Standard Specification.

The reasons for "tanking" cable in the lead-cased stage are twofold; first, to enable electrical tests to be taken at a uniform temperature, and secondly, to test the soundness of the lead sheathing. In the large tank that is necessary to cope with a batch of cable drums, the water temperature varies very little over the course of months, and the time of immersion enables the cable to take up the steady uniform temperature which is so essential for the accuracy of the electrical tests. Should the water penetrate any pin-holes or other defects in the lead sheathing and thus enter the insulating material, the electrical tests will be expected to locate it.

In regard to power cables, however, with an impregnated-paper insulating material, it is extremely improbable that any such defects in the sheathing will be discovered by the subsequent testing, except perhaps in the case of the lowest-tension cables. With the advent of super-tension cables it became fairly obvious that no water could possibly penetrate sufficiently into the thickness of insulating material concerned within the given time, to be subsequently discovered by any electrical tests; and so in many cases for cables of 22 kV and above the question of "tanking" has been entirely waived.

It must be conceded that if the water immersion test is incapable of showing up any defects in the sheathing, it is not only useless but constitutes a positive danger, since any water penetrating the insulating material must be sealed therein permanently by the further manufacturing processes of compounding, armouring and serving the lead-cased cable. It is quite probable, too, that such an occurrence will not manifest itself until long after the cable is laid and in operation, but that it will inevitably create trouble is certain, whereas with cable that has not been subjected to the water test the chances of any such defect in the lead showing up at a later date are remote, and consequently the possibilities of experiencing trouble are appreciably lessened.

EXPERIMENTAL INVESTIGATION.

In order to obtain some definite data on this subject of water penetration, it was decided to carry out experiments on various cable samples of different thicknesses of insulating material, the lead sheath in each case having a central puncture in the form of a small hole exposing the outer layer of the insulation. Routine a.c. voltage tests and d.c. insulation tests were to be carried out periodically in the ordinary way until breakdown occurred, in order to ascertain the time required to show up the fault under the practical specified conditions. However, a few preliminary attempts showed at once that the investigation was likely to prove an extremely protracted and tedious business if carried out under the normal conditions, and in these circumstances the continued application of periodic voltage tests might complicate matters by weakening the insulating material. Arrangements were therefore made to place the samples

TABLE 1.

Results of Tests on 0·15 *sq. in.* 33-*kV, Single-core Cable* (*thickness of insulating material,* 0·35 *in.*).

Date (Immersed in tank)	Insulation test		Voltage test at 50 cycles per sec.		
	1 min.	5 mins.	Voltage	Time	Temp.
	MΩ	MΩ	kV	mins.	F.
24/11/26	170 000	264 800	40	15	54°
2/12/26	126 000	153 000	40	15	52°
20/12/26	100 800	134 000	40	15	50°
13/1/27	82 800	105 000	40	15	50°
28/1/27	106 000	96 400	40	15	50°
4/2/27	122 000	110 000	40	15	50°
8/2/27	214 000	237 800	40	15	50°
11/2/27	97 740	134 400	40	15	50°
17/2/27	49 160	53 800	40	15	50°
18/2/27			(Broke down)	10	50°
Total time of immersion, 87 days			Sum total time of tests, 8 hrs. 55 mins.		

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* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (excepting those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

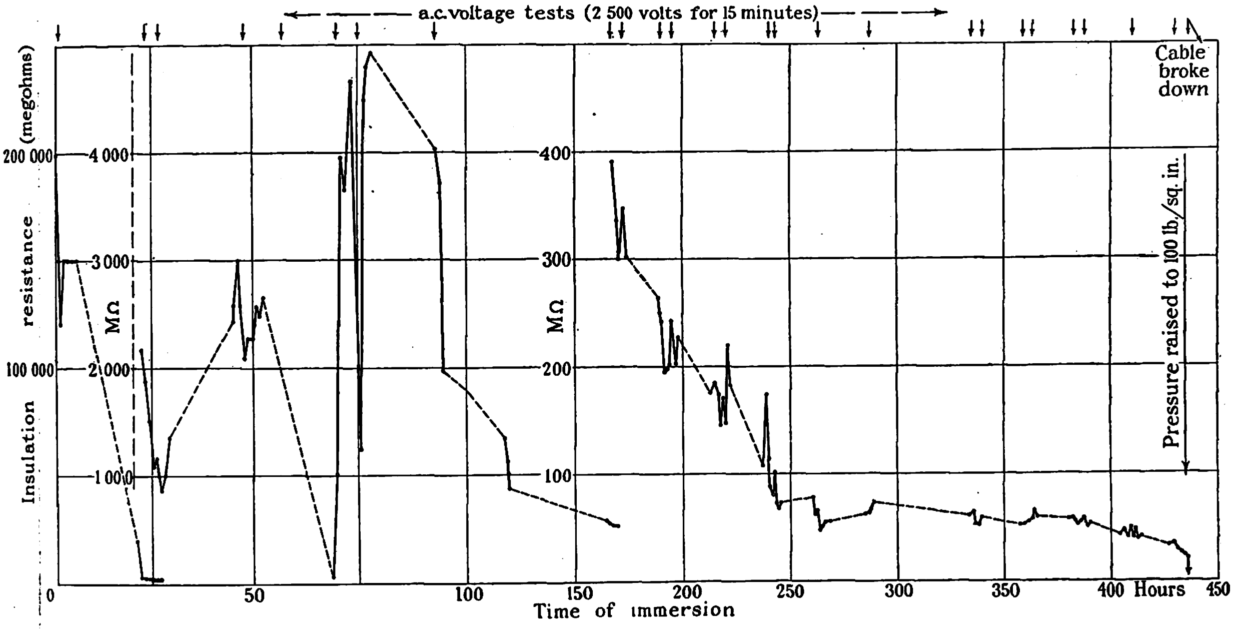

FIG. 1.—D.C. insulation resistance tests on cable sample No. 6 at 50 lb./sq. in. pressure.

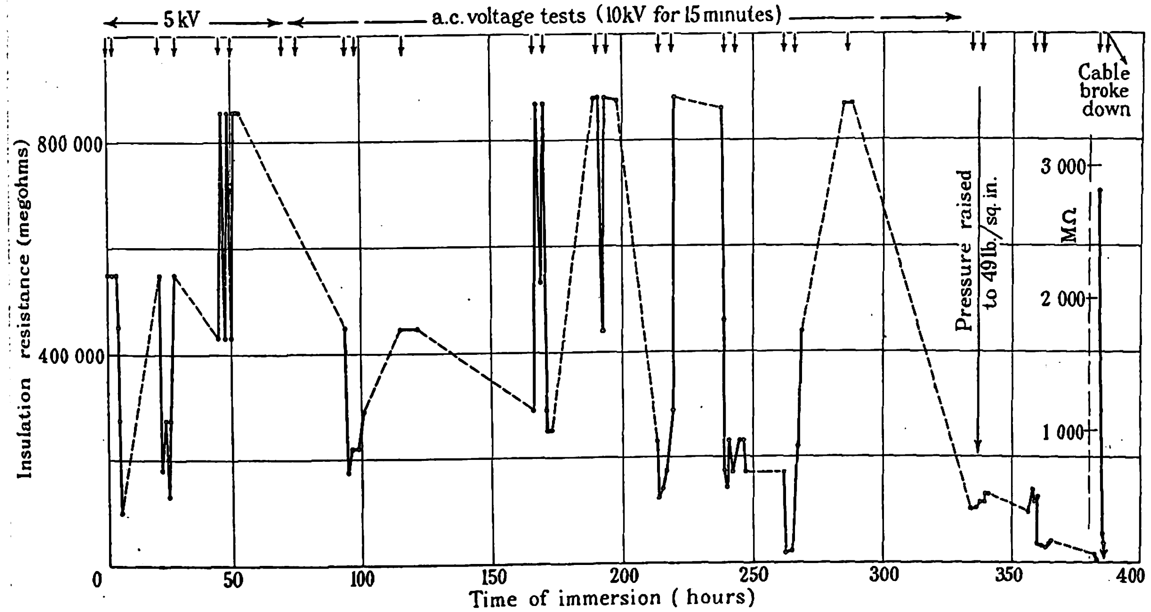

FIG. 2.—D.C. insulation resistance tests on cable sample No. 9 at zero pressure.

in a hydrostatic tube to enable various pressures to be applied and so shorten the time required for breakdown. The samples were about 6 ft. long, one end being sealed with a lead cap filled with compound, and the other end trimmed for testing. The testing end was brought out through the gland of the tube, and a watertight joint was made by means of a lead plug wiped on the cable sheath and covered with a layer of gutta-percha. The results tabulated in this paper have been obtained from a general analysis of the test figures on two different types of cable samples, and the illustrations indicate the trend of the values both for breakdown and for particular comparative insulation tests. In a few of the initial tests the water was drained off nightly and at week-ends, so that the test values may be somewhat modified by this procedure; in the case of all the others, however, the pressure was maintained continuously until the completion of the test. Owing to the general nature of the experiments the results cannot be expected to attain a high order of accuracy, but they indicate plainly the nature of the conclusions to be drawn from the investigation. One of the preliminary attempts

TABLE 2.

Water Penetration of Cables under Hydrostatic Pressure.

Length of Samples, 6 ft. Large Pin-hole Fault created in Centre of each Sample.

Type of cable	Sample number	Pressure	Insulation resistance tests [1-minute readings with direct current]				Voltage tests (15 minutes at 50 ~)				Remarks
			Initial test	First test showing defective insulation	Total time to give defective result	Actual time under pressure	Testing voltage	Number of tests	Total time to breakdown	Actual time under pressure	
		lb./sq. in.	MΩ	MΩ			volts		hrs. mins.	hrs. mins.	
0·1 sq. in. single low-tension thickness of insulating material 0·08 in. (16 papers)	1	200	76 100	0·87	Less than	1 minute	2 500	2	3 25	3 25	—
					hrs. mins.	hrs. mins.					
	2	150	56 200	1·04	1 35	1 35	2 500	5	21 13	4 16	Pressure removed at night
	3	100	22 900	4 250	21 55	5 25	2 500	25	335 49	80 49	Pressure removed at night and week-ends
	4	100	54 550	2 240	25 0	8 10	2 500	7	144 5	33 20	Pressure removed at night and week-ends
	5	75	38 300	53·3	1 4	1 4	2 500	6	—	73 24*	Pressure continuous
	6	50	199 500	19 950	21 42	21 42	2 500	18	—	435 34*	Pressure continuous
		100	—	—	—	—	—	—	436 14	0 40	Raised to 100 lb./sq. in.
0·01 sq. in. single (2 200-volt) thickness of insulating material 0·12 in. (24 papers)	7	97	594 000	198 000	1 12	1 12	5 000	1	2 40	2 40	Pressure continuous
	8	73	592 000	423	1 50	1 50	5 000	2	22 35	22 35	Pressure continuous
	9	0	550 000	117 000†	—	337 50	5 000 10 000	10 12	—	337 50*	Pressure continuous
		49	—	33 600	21 0	21 0	10 000	5	385 40	47 50	Pressure raised to 49 lb./sq. in.
	10	30	872 000	300 000†	—	288 30	10 000	19	—	288 30*	Raised to 40 lb./sq. in.
		40	—	305 000†	—	143 0	10 000	8	—	143 0*	Raised to 70 lb./sq. in.
		70	—	75 800	1 8	1 8	10 000	1	432 38	1 8	—
	11	62	598 000	245	1 45	1 45	10 000	2	18 26	18 26	—

* No voltage breakdown. † Insulation test prior to increase of pressure.

mentioned above, in which a sample of single-core 33-kV cable had been used, was completed in the course of time. This sample, which was about 20 ft. long, had a piece of lead 3 inches in length cut out of the centre, and was then bent into U shape and placed in an open tank of water, the two ends being left exposed. Routine voltage tests, combined with prolonged insulation tests with direct current from a battery of 300 cells, were carried out daily. The final breakdown occurred after a period of almost three months. Some of the test results obtained are given in Table 1.

The breakdown took place at the defective place and it was found that the water had penetrated the outer papers for at least 2 ft. on either side of the fault. The daily insulation tests show that after about 3 weeks the electrification becomes unsteady and a great deal of

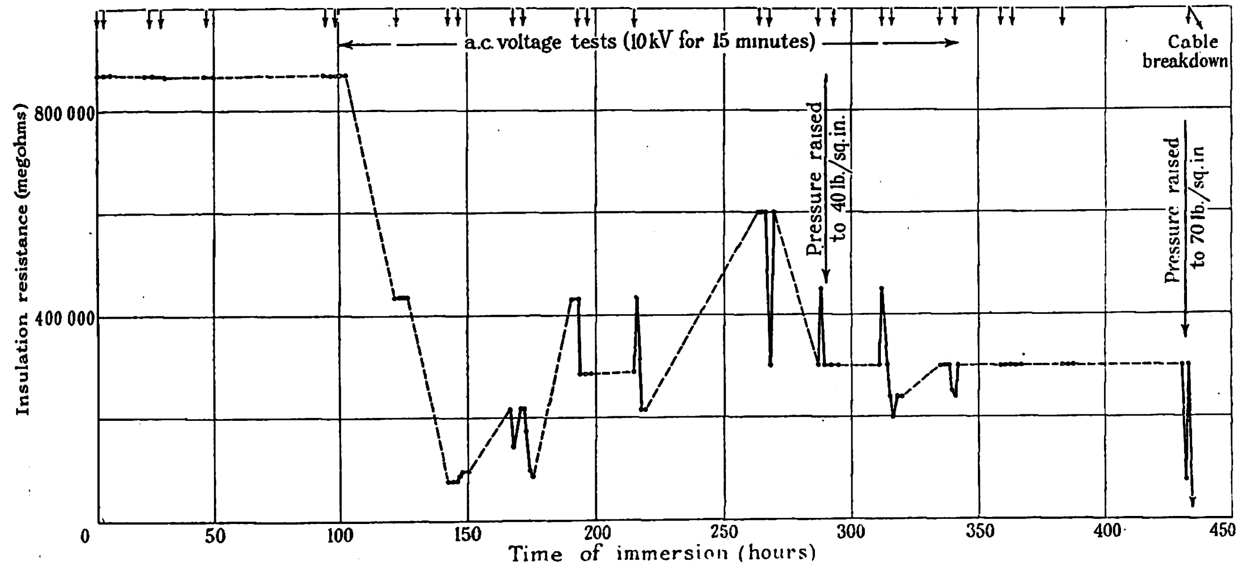

FIG. 3.—D.C. insulation resistance tests on cable sample No. 10 at 30 lb./sq. in. pressure.

TABLE 3.

General Analysis of Cable Breakdown by Water Penetration. Time Test of Defective Insulation under various Pressures.

Sample number	Pressure	D.C. insulation resistance tests: Time for insulation to attain values of 2 000 MΩ, hrs.	mins.	200 MΩ, hrs.	mins.	Value at break-down*	Voltage tests: Time of breakdown by 50-cycle alternating current, hrs.	mins.
	lb./sq. in.					MΩ		
1	200	—		—		0·34	3	25
2	150	—		< 1	35	1·04	4	16
3	100	5	30	38	12	0·27	80	49
4	100	8	10	20	7	0·35	33	20
5	75	—		< 1	4	3·23	> 73	24†
6	50	23	27	192	2	—	>435	34†
	100	—		—		22·7		40
7	97	—		< 2	20	99·2	2	40
8	73	< 1	50	< 2	15	1·29	22	35
9	0	—		—		—	—	
	49	45	20	47	30	139	47	50
10	30	—		—		—	>431	30†
	40	—		—		—	>143	0†
	70	> 1	8	—		75 800	1	8
11	62	< 1	45	> 18	25	427	18	26

* Last insulation test previous to breakdown by voltage. † No voltage breakdown.

variation takes place day by day. One cannot place too much reliance on these tests, however, owing to the small deflection obtained, and also owing to the possibility of insulation weakness caused by the voltage tests.

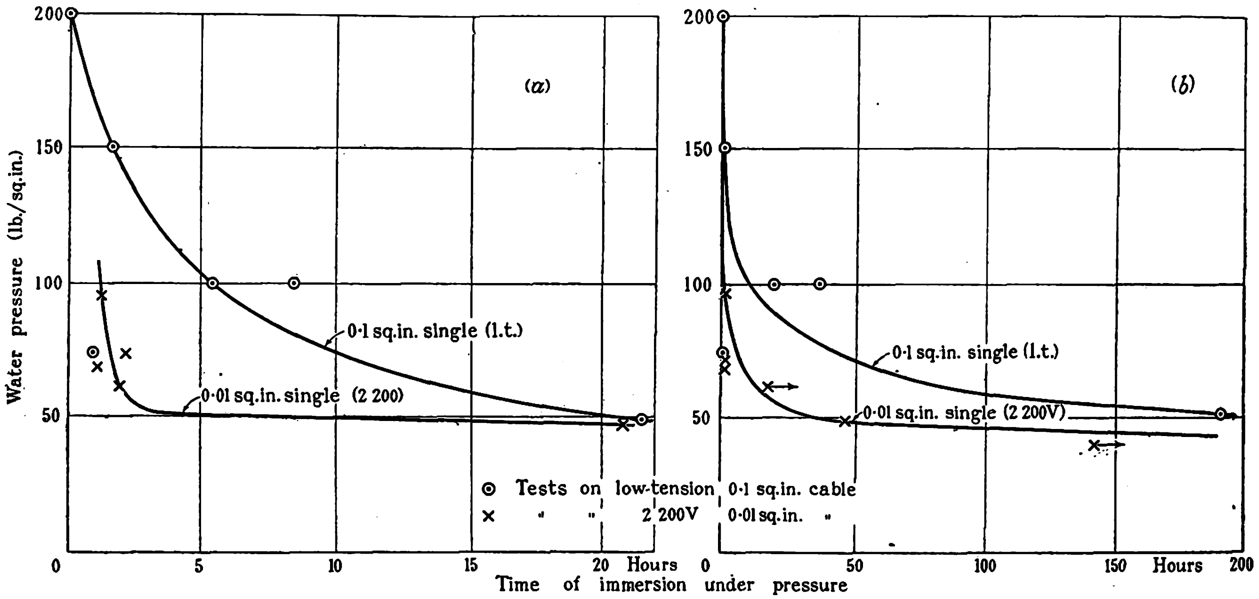

FIG. 4.—Results of defective insulation and pressure.

(a) Curves showing time of the first dielectric test, indicating defective insulation.
(b) Curves showing time taken for insulation resistance to fall to 200 megohms.

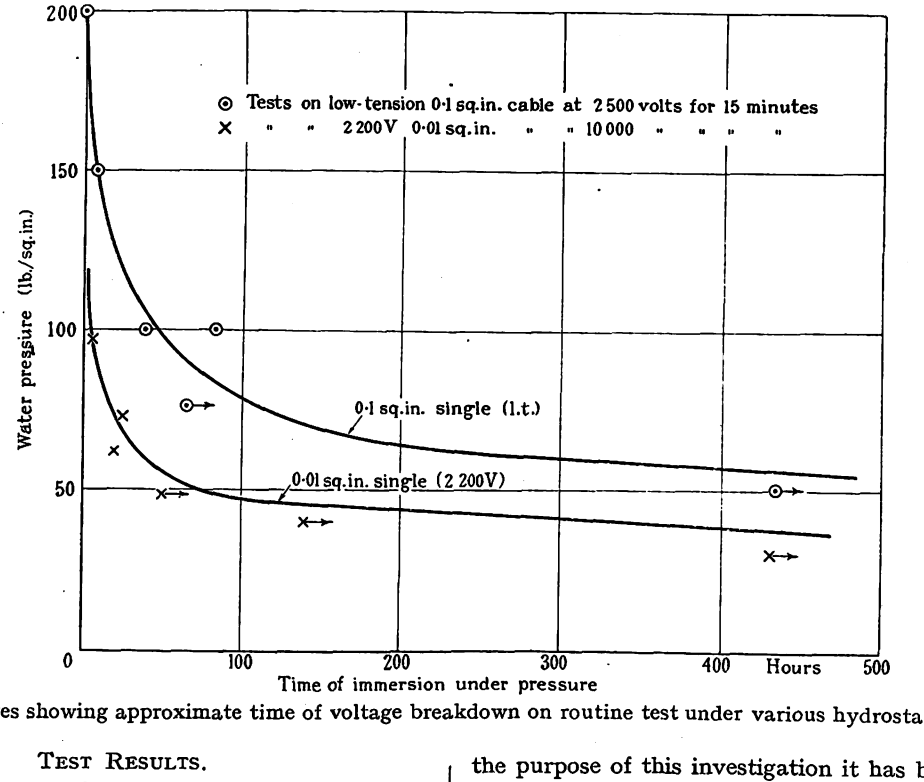

FIG. 5.—Curves showing approximate time of voltage breakdown on routine test under various hydrostatic pressures.

TEST RESULTS.

The insulation tests for three samples are given in Figs. 1, 2 and 3, the thick lines on these curves corresponding to the actual periods of test. It is probable that a small part of the variation obtained may be due to slight daily changes of temperature, but it will be seen that there is a tendency for the values to fall initially with time after a certain period, and then to become unsteady with, however, a falling characteristic. For the purpose of this investigation it has been considered that the insulating material becomes defective on showing signs of progressive deterioration, and the first of the tests, indicating appreciably lower values of insulation resistance that continue to decline, denotes the start of faulty insulation. The time taken to show up defective insulation in this way by the battery test is indicated in Table 2, together with the actual values of insulation resistance at this stage. The time taken for complete breakdown of the cable by the a.c. 50-cycle voltage periodic test is also noted, and in each case the total time during which each sample was under actual water pressure is given. Approximate comparison between samples tested at different pressures has been attempted, by noting from the insulation-test curves the time required by each to attain to stated values for dielectric resistance, namely 2 000 megohms and 200 megohms respectively. In these cases the true periods of time for the samples under actual hydrostatic pressure only have been considered, and are given in Table 3. The period for voltage breakdown of the samples is also included for direct reference. Curves are plotted from these results. Fig. 4 shows the pressure/time characteristic for defective insulation in connection with the battery tests, and Fig. 5 the same characteristic with respect to the cable breakdown by voltage test. The curves are of the exponential type and indicate a pressure varying inversely as some function of the time.

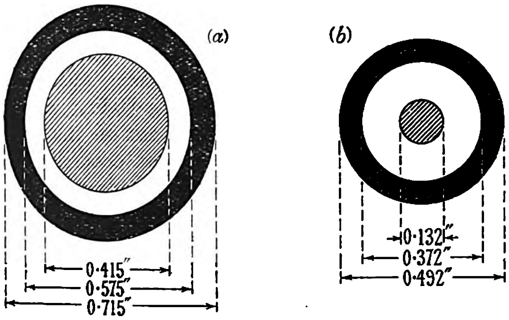

Fig. 6.—Cable sections.

Dielectric volume per inch:—
(a) 0·1 sq. in. low-tension cable.—$\pi(0\cdot2875^2 - 0\cdot2075^2) = 0\cdot1243$ cub. in.
(b) 0·01 sq. in. 2 200-V cable.—$\pi(0\cdot186^2 - 0\cdot066^2) = 0\cdot0951$ cub. in.

Although in these results the indication of water penetration with respect to thickness of insulating material alone is somewhat misleading, since the samples of the higher-voltage cable have in most cases given the lower values, it is naturally to be expected that the thicker insulation will in general take longer to show up any defects, as witness the tests on the 33-kV sample. The insulation values of the greater thickness of insulating material are necessarily of a higher order, and the defect is much more difficult to detect with any certainty, particularly in the early stages. It is unfortunate in this instance that the cables are so dissimilar in conductor section, but owing to restrictions connected with the gland and hydrostatic tube it was impossible to make use of high-voltage cables of a useful comparative size. It is quite probable, however, that, since the water does not penetrate directly through the insulation in a radial direction —in any case at low pressures—but enters via the gaps between the paper tapes, the actual volume of the insulating material partially governs its rate of progress. This is only surmise, but it is interesting to note that in Fig. 6, which shows the cable sections of the two types, the thicker insulating material has the lower volume.

CONCLUSIONS.

In the case of a thin insulating material such as that used in low-tension cables, the insulation resistance is soon affected by the penetration of moisture. With increasing numbers of insulating papers constituting a greater thickness of insulating material the effect is not so marked, and the time required to show up any defect in the lead sheathing becomes seriously prolonged under normal working conditions. This may occur to such an extent as to make it extremely unlikely for routine tests to detect the fault, and unless breakdown takes place on over-voltage test the defect must remain undiscovered in the factory.

With the thicknesses of insulating material necessary for high-voltage cables it naturally follows that the immersion test is useless from the point of view of testing the soundness of the sheathing. In order, therefore, to avoid the unnecessary risk encountered by this procedure it is advisable to discontinue the test for any but the lowest-voltage cables. In view of the fact that until recent times high-voltage cables have been immersed in water in the lead-cased stage (and in many cases specifications still call for this requirement) it seems reasonable to suppose that some of the faults that develop long after the cables have been in operation may be attributable to this cause.

GENERAL REMARKS.

As already pointed out, the tanking of cable drums also enables electrical tests to be carried out at a uniform temperature, and the question naturally arises as to how the elimination of the tanking process generally will affect these conditions. Before venturing any suggestion with regard to this point, it is as well to look into the matter of the routine tests carried out on all drums of cable in the lead-cased state. The normal specification requires an a.c. voltage test for 15 minutes at about 2½ times working voltage at supply frequency, followed by d.c. battery tests for capacity, insulation resistance and conductor resistance. The results of these latter tests have usually to conform to certain limited requirements, varying with the size of conductor and type of cable, particularly so with the capacity and copper resistance which also thereby act as a check on the actual drum length under test. The a.c. voltage and d.c. insulation tests—the latter consisting of 1 minute's electrification, which may be further prolonged if necessary—endeavour to determine the presence of weak spots in the insulating material that might be occasioned by faulty manufacture, imperfect drying and impregnation, etc. The insulation resistance is mainly a question of the composition of impregnating compound, and with the varying constituents favoured by the different cable makers for low- and high-tension cables it is quite possible to obtain values for cable insulation that vary from a few megohms to some thousands of megohms per mile. Nowadays it is not usual, therefore, to set any general limits to this characteristic, but not many years ago high values for insulation were regarded with some suspicion. It is doubtful whether the d.c. tests of insulation resistance are of any real use save as an indication of uniformity of production, except possibly in the case of low-tension cables. The electrical tests taken after lead sheathing are repeated in the armoured stage, in which case the cable drums are usually standing in the testing area of the cable shop. During the process of compounding, armouring and serving, the cable undergoes various temperature changes and may require a matter of 12 hours or more to attain the shop temperature. Experience in connection with comparison of tests of the lead-covered cable in tank and in the finished condition, combined with a careful record of shop temperatures, show that the cable insulating material has a big time-lag with regard to changes in external temperature. As comparatively rapid variations may take place in the ambient air-temperature of the shop during the course of day and night, the thermometer affords only a very approximate idea of the true cable temperature at any particular period, on account of the slowness of the change taking place within the insulating material. There is some difficulty, therefore, in determining the correct temperature of drums of cable in the open shop, but in actual practice experience has shown the allowance to be made generally for insulating material lag, and in consequence it is possible to obtain satisfactory tests on armoured cable that can be reasonably accurately checked with those of the lead-cased stage. The cable insulation-resistance varies indirectly with temperature, and on account of its higher temperature coefficient it is most susceptible to local variations of temperature. The d.c. capacity test includes a certain amount of absorption effect, which, however, has only a very slight effect on the results within the normal range of shop temperatures. The conductor resistance test is the most reliable guide to the cable temperature and is the one usually accepted in practice. It is quite possible, however, for this value to be appreciably incorrect in cases where the insulating material has undergone drastic temperature changes, such as would be occasioned by special heating tests like those undertaken on super-tension cables—either by current loading or in a heated oven—unless the full time necessary for the insulation to attain a steady state is allowed in every case. For routine work, however, the conductor resistance can be looked upon as the chief characteristic with respect to cable temperature; that being so, it is this test which needs mainly to be considered in relation to the altered conditions involved by eliminating the tanking arrangements. It is hardly necessary to take into account the other battery tests, as in reality these decline in importance as the voltage for which the cable is designed increases, and it is not proposed that the water immersion should be abolished for the lower-tension cables. With regard, therefore, to those cables which it is deemed inadvisable to submit to tanking for the reasons put forward in this paper (let us say those of 6 600 volts and over), they will require to be tested at shop temperature. After lead casing, therefore, the cable will take at least about 30 hours to attain the surrounding temperature before any satisfactory tests can be obtained.

The time suggested here is only an average figure, as the rate of cooling is dependent upon factors concerned with the length and size of cable and the drum dimensions; and the actual period that need elapse before testing will again depend upon the type and accuracy required of the results. Voltage tests are not affected by temperature conditions, but it is rare that any battery tests are in any case reliable under less than 24 hours from the time of sheathing. An appreciable time is required for the cable drum to steady down over the last few degrees drop in temperature, and as variations of the conditions in the vicinity will probably have taken place over this period it is doubtful whether the true cable temperature can be known to within a degree or so. For the resistance of the copper conductor, which increases 0·22 per cent per degree F. rise, the question of a degree or two is relatively unimportant, as it is barely within the accuracy of the measuring apparatus, quite apart from the matter of the permissible stranding allowance of the conductor. Although the variations in shop temperature, excluding any local effects that take place with the advent of the different seasons, are much greater than those occurring in the water tank, experience has shown that it is quite possible to carry out the work of testing in the open shop, with satisfactory results that meet the toleration required in general practice. There is therefore no adequate reason for the tanking of cable drums to be considered essential, and, as already suggested, for high-tension cables it should be definitely avoided. It is always possible, of course, where any doubt arises regarding test-results, to revert to the old order, or if necessary to effect a compromise in special cases and arrange for a certain percentage of drums to be tanked, thus lessening to some extent the risk due to possible defects in the lead sheathing. The matter is one that concerns the cable maker chiefly, as he is generally liable under maintenance guarantee for any faults of this description; and it may not be so vital to the interests of the customer or his consulting engineer, who are satisfied if the cable meets the required specification in the factory. Nevertheless, faults that develop under service conditions are disconcerting to all parties, and anything which is capable of removing some of the danger of such occurrences, and which can with advantage be carried out in the factory, should be given every consideration.

The author's thanks are due to Messrs. Siemens Bros. and Co., Ltd., for permission to publish the results of this investigation, which was carried out in the testing departments of their Woolwich works.

THE PRESSURES ON THE DIAPHRAGM OF A CONDENSER TRANSMITTER IN A SIMPLE SOUND FIELD.*

By W. WEST, B.A., Associate Member.

(*Paper received 7th August*, 1929.)

SUMMARY.

It has been observed that the free air pressures of a sound wave may be increased at the diaphragm of a microphone in a ratio greater than 2 : 1 at certain frequencies, when there is concavity in the face of the microphone. A method of calculating the magnitude of this increase is applied to a condenser transmitter of the Wente type, and close agreement is found with experimental results. The calculations involve certain simplifying approximations the validity of which is discussed.

SECTION (1).

The condenser transmitter has been in use for many years in the perfected form, the design of which is due to Wente,† but although it is frequently required for the purpose of measuring sound pressures in free air its performance is usually measured in terms of a uniformly distributed pressure actuating the diaphragm. This type of instrument satisfies, to a greater extent than any other now in existence, the essential requirements to be met in a large class of acoustical measurement, as typified, for example, in the testing of loudspeakers for frequency characteristics. In order that accurate measurements of sound pressures (or intensities) may be made, it is necessary for the calibration of the transmitter to be obtained in terms similar to those required in its use. The difference that exists between the performance of a transmitter of this type when measured in terms of actual pressures on the diaphragm, and in terms of pressures in free air, has been discussed by Mr. A. J. Aldridge of the Post Office Research Section, with reference to characteristic curves obtained for a particular instrument.‡

In the present paper it is proposed to show that the characteristic for free air pressures may be deduced, with fair accuracy, from a calibration of actual pressures —when certain simplifying assumptions are made. There are two important corrections to be made; one of these is due to the augmentation of the sound pressures at the face of the transmitter as a consequence of the obstruction presented to the sound waves, and the other is required to take into account the fact that the pressure at the face of the transmitter is not necessarily the same as that on the diaphragm, which is recessed. Of these corrections the former has recently received attention,§ but the latter has to a large extent been ignored or overlooked; it is therefore the subject chiefly to be dealt with.

SECTION (2).

The calculations necessary to take into account the effect of the recess in front of the diaphragm are based on the conception of acoustical impedances and of reflection factors at the ends of a tube in which sound is sustained. The method has been applied to the measurement of acoustical impedances.† Consider a short tube the ends A and B of which are terminated by acoustical impedances having reflection factors (for velocities or pressures) of g_A and g_B respectively. The length l between the ends may either be taken as the distance between surfaces at which reflection takes place without change of phase (as at a rigid surface), or it may refer to the distance between the actual terminations of the tube. In the former case the factor g is simply a numerical ratio which may have any value between ± 1; in the latter case it is understood to be the product of such a ratio and a term ϵ^{-2ika}, where $i = \sqrt{(-1)}$; $k = 2\pi$ divided by the wavelength, and a is the "end correction" of the tube (dimension length). Adopting the second notation, assume that sound is maintained by the motion at end A of an absorbing piston the velocity of which is $V\epsilon^{i\omega t}$. The air velocity at A is the sum of the velocities at A of all the waves passing up and down the tube, namely,

$$v_A = V\epsilon^{i\omega t} - Vg_B\epsilon^{i(\omega t - 2kl)} + Vg_Ag_B\epsilon^{i(\omega t - 2kl)} - Vg_Ag_B^2\epsilon^{i(\omega t - 4kl)} + \ldots \text{ to infinity}$$

$$v_A = \frac{V\epsilon^{i\omega t}(1 - g_B\epsilon^{-2ikl})}{(1 - g_Ag_B\epsilon^{-2ikl})} \quad . \quad . \quad . \quad . \quad (1)$$

The pressure at end A is similarly given by

$$p_A = \rho cV\epsilon^{i\omega t} + \rho cVg_B\epsilon^{i(\omega t-2kl)} + \rho cVg_Ag_B\epsilon^{i(\omega t-2kl)} + \rho cVg_Ag_B^2\epsilon^{i(\omega t-4kl)} + \ldots$$

$$p_A = \frac{\rho cV\epsilon^{i\omega t}(1 + g_B\epsilon^{-2ikl})}{(1 - g_Ag_B\epsilon^{-2ikl})} \quad . \quad . \quad . \quad (2)$$

where ρ = density of air and c = velocity of propagation of sound in air. The pressure at end B is

$$p_B = \rho cV\epsilon^{i(\omega t-kl)} + \rho cVg_B\epsilon^{i(\omega t-kl)} + \rho cVg_Ag_B\epsilon^{i(\omega t-3kl)} + \ldots$$

$$p_B = \frac{\rho cV\epsilon^{i(\omega t-kl)}(1 + g_B)}{(1 - g_Ag_B\epsilon^{-2ikl})} \quad . \quad . \quad . \quad (3)$$

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (excepting those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] See Reference (1). [‡] *Ibid.*, (2). [§] *Ibid.*, (3) and (4).

[†] See Reference (5).

The impedance per unit area at end A of the tube is

$$Z_1 = \frac{p_A}{v_A} = \frac{\rho c(1 + g_B\epsilon^{-2ikl})}{(1 - g_B\epsilon^{-2ikl})} \quad . \quad . \quad . \quad (4)$$

and the pressure ratio

$$\frac{p_A}{p_B} = \frac{1 + g_B\epsilon^{-2ikl}}{(1 + g_B)\epsilon^{-ikl}} \quad . \quad . \quad . \quad . \quad (5)$$

Equation (4) may be put into the form

$$Z_1 = \rho c\left[\frac{(1 - g_B^2) - i\,.\,2g_B \sin 2\,kl}{1 + g_B^2 - 2g_B \cos 2kl}\right] \quad . \quad (6)$$

If reflection from end B takes place as from a substantially rigid surface, $g_B = 1$ and

$$Z_1 = -\,i\rho c \cot kl \quad . \quad . \quad . \quad . \quad (6a)$$

while

$$p_A/p_B = \cos kl \quad . \quad . \quad . \quad . \quad (5a)$$

Now suppose that end A is open and provided with an infinite flange, then the total impedance per unit area at A is $Z = Z_1 + Z_0$, where Z_0 is the impedance per unit area due to the reaction of the air outside the tube. (The electrical analogue is therefore a simple circuit comprising two impedances in series.) If the total sound pressure applied at end A is p, then it follows that the ratio

$$\frac{p}{p_A} = \frac{Z}{Z_1} = 1 + \frac{Z_0}{Z_1}$$

and

$$\frac{p}{p_B} = \frac{p}{p_A}\cdot\frac{p_A}{p_B} = \left(1 + \frac{Z_0}{Z_1}\right)\cos kl \quad . \quad . \quad (7)$$

The impedance Z_1 is given in equation (6*a*), and Z_0 is known to consist of a resistance component R per unit area due to radiation of sound, and a reactance component $im\omega$, where m is the added mass per unit area due to the presence of the external air. Hence

$$\frac{p}{p_B} = \cos kl - \frac{m\omega}{\rho c}\sin kl + \frac{Ri}{\rho c}\sin kl \quad . \quad (7a)$$

The average values of R and m for a circular piston of radius r have been evaluated.*

Thus

$$\frac{R}{\rho c} = 1 - \frac{J_1(2kr)}{kr} \quad . \quad . \quad . \quad . \quad (8)$$

and

$$\frac{m}{\rho r} = \frac{K_1(2kr)}{2(kr)^3} = \frac{\mathbf{H}_1(2kr)}{(kr)^2} \quad . \quad . \quad . \quad (9)$$

(Tables for the functions $J_1(x)$ and $\mathbf{H}_1(x)$ are available. Both are to be found in "The Theory of Bessel Functions," by G. N. Watson.)

SECTION (3).

Reference will now be made to measurements of the frequency characteristics of a condenser transmitter (No. 47) of the 370W type. The results of similar measurements on another instrument (No. 111) of the same type have already been published,† but they refer to the calibration of the instrument with its protecting cover in position. This cover consists of a metal cap fitting over the face of the transmitter, with a recessed wire-gauze shield covering the diaphragm. The presence of the cover somewhat increases the depth of the recess and reduces the diameter.

As the result of a recent investigation (see Reference 4) a special source of sound has been designed to enable measurements to be made at higher frequencies. This source of sound operates on the same principle as a Bell type of telephone receiver, but its diaphragm, being clamped on a diameter of 1·9 cm, has a fundamental natural frequency of about 3 600 cycles per sec. The external diameter of the instrument is limited to 4 cm. The adjustment of a small acoustical resonator in front of the diaphragm enables measurements to be made over a frequency range of 2 500 to 5 000 cycles per sec. The apparatus and methods of carrying out the measurements do not otherwise differ from those previously described.*

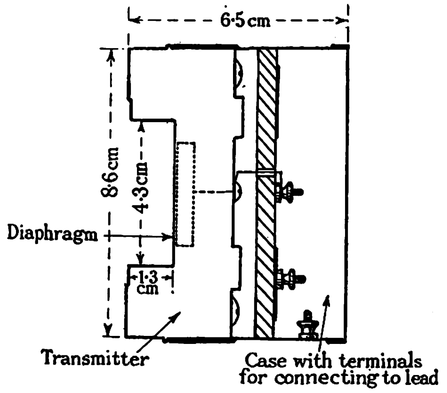

FIG. 1.—Outline of cross-section of condenser transmitter.

On the back of the condenser transmitter was mounted a short cylindrical case to provide mountings for terminating the lead to the amplifier and to act as a screen. No description of the instrument beyond that of its external geometrical shape and dimensions is necessary for the present purpose. These are sketched in Fig. 1, which shows an outline of the cross-section including the case at the back. The general form is that of a short cylinder having a cylindrical cavity in the front face.

Frequency characteristics of this instrument, obtained by means of the Rayleigh disc, are shown in curves (1) and (2) of Fig. 2, curve (1) being obtained in terms of sound pressures in free air and curve (2) in terms of actual pressures on the diaphragm. Curve (3) shows the maker's calibration (by thermophone) for the *type* and is introduced in justification of the form of extension of curve (2) beyond 3 300 cycles per sec., which was the highest frequency at which readings were taken for this condition of test. Obviously, the difference between curves (1) and (2) cannot be accounted for solely by the effect of the obstruction of the instrument to the sound waves.

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* See Reference (6), par. 302.

† *Ibid.*, (2).

* See Reference (4). The transmitter was so located in the testing cabinet (Fig. 5 of this reference) that, while it faced the source of sound, secondary or reflected waves from its surface would be incident more or less at right angles to the plane of the Rayleigh disc, and would therefore not affect a measurement of the primary wave.

SECTION (4).

The corrections, mentioned in Section (1) as being necessary to correlate the two curves, may be applied if certain simplifying assumptions are made, discussion of which will be deferred to Section (5). Firstly, if the existence of the cavity in the face of the transmitter is ignored, there will be at this face an increase in pressure due to obstruction of the sound field; it will be assumed that the pressure will be increased in the same ratio as would occur at the point nearest to the source of sound on a solid spherical obstacle, 10 cm in diameter. This correction factor, or ratio of actual to free air pressure, can be calculated, and it is plotted against frequency in curve (1) of Fig. 3. In making the calculations the value of c, the velocity of propagation of sound, was taken as 34 000 cm per sec. Points on the curve at frequencies above 2 500 cycles per sec. ($k \times$ radius of sphere > 2) were obtained from the table published by Ballantine (see Reference 3), the remainder chiefly from calculations supplied by Rayleigh (see Reference 6, chap. 17).

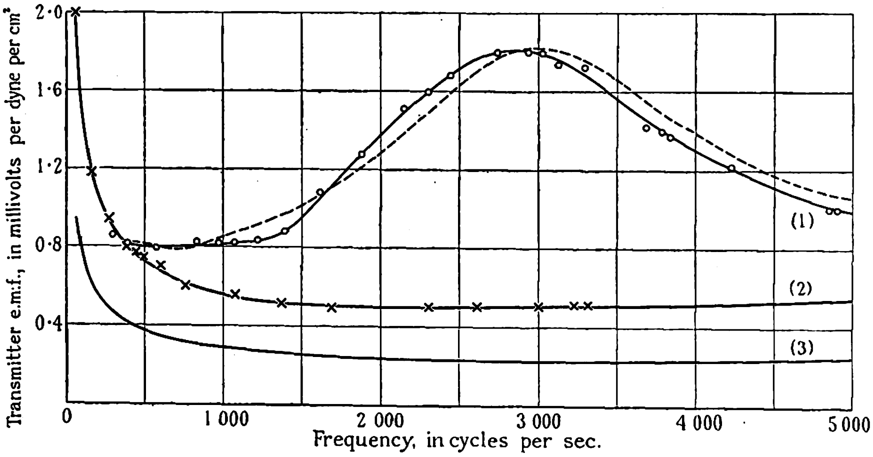

FIG. 2.—Frequency characteristics of condenser transmitters.

Curve (1).—In terms of free air pressures.
Curve (2).—In terms of pressures on the diaphragm.
Curve (3).—Maker's curve for the type (by thermophone).
Dotted curve.—Calculated curve for free air pressures (based on Curve 2).

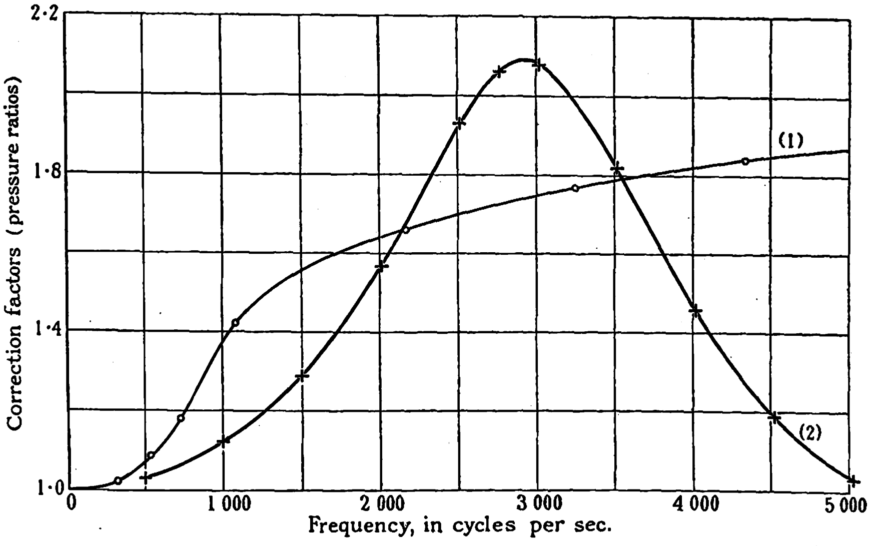

FIG. 3.—Correction factors for reducing pressures on the diaphragm into terms of free air pressures.

Curve (1).—Calculated ratio of actual to free air pressures on a sphere of 10 cm diam.
Curve (2).—Calculated ratio of pressures on diaphragm to pressures at aperture of condenser transmitter.

Secondly, the ratio of the pressure p at the face of the transmitter to the pressure p_B on the diaphragm may be calculated from equation (7a), with the assumptions that the motion of the diaphragm is insignificant and that the external acoustical impedance at the aperture of the cavity is equivalent to that on (one side of) a piston enclosed by an infinite baffle. In order to simplify the calculation put $R' = R/(\rho c)$ and $m' = m/(\rho r)$, these values being obtained from equations (8) and (9). Then equation (7*a*) may be rewritten

$$\frac{p}{p_B} = \left[\cos kl - m'kr \sin kl\right] + i\left[R' \sin kl\right] = X + iY$$

and the numerical value of $p_B/p = \left[X^2 + Y^2\right]^{-\frac{1}{2}}$, where $X = \cos kl - m'kr \sin kl$ and $Y = R' \sin kl$.

Details of the calculations are given in the table, and the values of the correcting factor p_B/p are plotted against frequency in curve (2) of Fig. 3.

TABLE.

($l = 1{\cdot}3$ cm, $r = 2{\cdot}15$ cm)

Frequency	kr	kl	$\cos kl$	$\sin kl$	m'	R'	X	Y	p_B/p
500	0·2	0·12	0·993	0·120	0·840	0·020	0·973	—	1·03
1 005	0·4	0·24	0·971	0·238	0·807	0·078	0·894	—	1·12
1 505	0·6	0·36	0·936	0·352	0·770	0·170	0·773	0·060	1·29
2 010	0·8	0·48	0·887	0·462	0·714	0·288	0·623	0·133	1·57
2 515	1·0	0·60	0·825	0·565	0·647	0·423	0·460	0·239	1·93
2 765	1·1	0·66	0·790	0·613	0·610	0·495	0·379	0·304	2·06
3 015	1·2	0·72	0·752	0·659	0·571	0·567	0·301	0·374	2·08
3 520	1·4	0·84	0·667	0·745	0·493	0·708	0·153	0·528	1·82
4 020	1·6	0·96	0·573	0·819	0·414	0·837	0·031	0·685	1·46
4 525	1·8	1·08	0·471	0·882	0·338	0·947	−0·065	0·835	1·19
5 025	2·0	1·20	0·362	0·932	0·267	1·030	−0·136	0·960	1·03

The application of both of the correction factors to the calibration of the transmitter in terms of actual pressures [curve (2) of Fig. 2] results in the broken curve shown in the same figure. No ordinate on this curve differs from the corresponding ordinate on curve (1) by as much as 10 per cent.

SECTION (5).

It was first assumed that the effect of the transmitter as an obstacle in the sound field created pressures at the surface equivalent to those on a sphere 10 cm in diameter. Since such an effect has been calculated only for a spherical shape, the assumption of an " equivalent sphere " is essential. Although it is not to be expected that the true effect will take the exact form shown in curve (1) of Fig. 3, it is very probable that the differences at all points will be small, at least in the case of a short cylindrical obstacle, provided that a suitable diameter is chosen for the equivalent sphere. There is also some confirmatory experimental evidence of this (see Reference 4). In estimating the diameter of the equivalent sphere the presence of the recess may be ignored since it is given separate consideration, i.e. the cavity may be considered to be filled with solid to the front face of the transmitter. As a result of previous experience, the author has estimated that for pressures at the centre of a flat face of a short cylinder (the length of which is, say, less than the radius) the circumscribing sphere forms a useful approximation. For the transmitter the circumscribing sphere has a diameter of 10·8 cm, but the length is greater than the radius. Ballantine (see Reference 3) proposes an estimate based on equal volumes of sphere and obstacle, when the obstacle " occupies a volume of reasonable (say cubical) shape " (presumably when extreme dimensions taken through the centre do not differ too greatly). On this basis the diameter of the equivalent sphere would be 9 cm, but as this hardly exceeds the actual diameter (when taken over the slightly projecting ridge) no account would be taken of the comparatively more gradual streamline presented by the sphere, and this value would probably underestimate the effect. For these reasons the intermediate value of 10 cm was chosen for the diameter of the equivalent sphere, though either of the other values mentioned could be used without greatly affecting the result.

Secondly, the motion of the diaphragm is neglected in the assumption that $g_B = 1$, i.e. that the mechanical impedance of the diaphragm is very great as compared with the characteristic impedance of a tube (ρc per unit area). In this type of instrument the diaphragm is stretched and the fundamental natural frequency exceeds 10 000 cycles per sec. The chief constraint to motion is imposed by the air cushion at the back, for which some impedance values are quoted by Crandall.* These were calculated for an early form of condenser transmitter probably of similar dimensions and construction, and will serve to indicate the degree of approximation that has been made. For example, at 3 000 cycles per sec. the mean resistance per unit area is about 5 000 and the mean stiffness per unit area about 3×10^8 [reactance $= 3 \times 10^8 \div (2\pi \times 3\,000) = 16\,000$]. This takes no account of the stiffness of the diaphragm *per se*, or of its mass, but it will serve to assume an impedance of, say, $5\,000 - i\,10\,000$. This impedance per unit area may be related to g_B by putting $l = 0$ in equation (4), and it will be convenient to separate g_B into the form $g_B = g\epsilon^{-2ik\alpha}$, where g is simply a numerical ratio. Hence

$$\frac{\rho c(1 + g\epsilon^{-2ik\alpha})}{(1 - g\epsilon^{-2ik\alpha})} = 5\,000 - i\,10\,000$$

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* See Reference (7), art. 11, Fig. 5.

Equating real and imaginary parts,

$$\frac{\rho c(1 - g^2)}{1 + g^2 - 2g \cos 2ka} = 5\,000$$

and
$$\frac{\rho c \,.\, 2g \sin 2ka}{1 + g^2 - 2g \cos 2ka} = 10\,000$$

Since ka is very small, $\sin 2ka = 2ka$
and $\cos 2ka = 1 - \frac{1}{2}(2ka)^2$, with sufficient accuracy.

The solution of these equations gives $g = 0{\cdot}997$ and $2ka = 0{\cdot}006$, or $a = 0{\cdot}005$ cm. The sign of a is positive and the correction therefore tends to increase the length of the tube.

It may also be concluded that the performance of the transmitter cannot be appreciably affected, at the frequencies considered, by changes of the impedance imposed by the external air. Such an effect has been observed (see Reference 4) in the case of a very light diaphragm, but it applies chiefly to the position of the fundamental natural frequency, which is well beyond the frequency range dealt with and is, moreover, less liable to alteration for the greater density of the diaphragm.

The only other approximation of any consequence was that the impedance, looking outwards from the aperture of the transmitter, was assumed to be equal to the average impedance over the surface of a piston, of the same area, surrounded by an infinite baffle. This assumption is somewhat bold, but a consideration of such information as is available indicates that it is more reasonable than would appear at first sight. Consider first the resistance component, retaining for the time being the fiction of piston motion at the aperture. It is known that at very low frequencies the value of R' with a small baffle is one-half of that given by equation (8), applicable to an infinite baffle. It probably increases towards this value in much the same way as curve (1) of Fig. 2 approaches the value 2 as the frequency is raised. It can be seen from the table on page 444 that the term Y, involving this component, has little or no influence below, say, 2 000 cycles per sec., and above this frequency errors in the value of R' are probably less than 20 per cent (as deduced from curve 1 of Fig. 2). All dissipative forces other than that due to radiation have been neglected as being comparatively very small, but in so far as such do exist they will tend to reduce this error.

At low frequencies at any rate, the mass component m' is also overestimated, though not to so great an extent as the resistance component, since it plays no part in radiating sound and, being more influenced by local conditions, it probably does not require so large a baffle for the practical equivalent of one that is infinitely extended. Thus at very low frequencies the addition of an infinite baffle on the end of a tube, initially without any baffle at all, is known to increase the value of m' only in the ratio $0{\cdot}82$ to $0{\cdot}6$, or about $1{\cdot}37$ to 1. Since the presence of the flange forming the face of the transmitter may be expected to exert an influence even at low frequencies, it seems probable that the admitted overestimate of m' at low frequencies is rapidly reduced as the frequency is raised into the range where the correction factor becomes important. At the higher frequencies the conditions are less certain, but the term X, involving the mass, has little influence on the correction factor from about 3 500 to 5 000 cycles per sec.

In discussing the assumption of piston motion at the aperture * it may be recalled that at very low frequencies it involves an error in the "end correction," i.e. in m', in the ratio of $0{\cdot}85$ to $0{\cdot}82$ when applied to an open-ended tube with an infinite flange. This appears to be a comparatively small effect, but an element of uncertainty is introduced when the irregular distribution of impedance over the surface of the piston is considered. It is this irregularity which chiefly causes the actual motion at an aperture to depart from that of a true piston, and in assuming the impedance per unit area to be equal to the average value of that on a piston no account is taken of the form of the distribution. This is important if (the length of the tube being short) an irregular distribution of pressure is created on the diaphragm, since the effects of pressures at the centre are stronger than of those nearer the edge. Under the actual conditions, however, it is probable that variations of impedance appear as variations of velocity at different parts of the aperture rather than as variations of pressure. Warren † has drawn attention to the differences in impedance at the centre and at the edge of a circular piston. He shows that the impedance at the centre is greater than that at the edge, and observed increases in amplitude or velocity towards the edge of an aperture may thus be accounted for.

SECTION (6).

The close agreement reached between the calculated and the experimental curves has the double value of inspiring confidence in the methods of calculating the corrections, and of providing an additional check on the accuracy of the Rayleigh disc methods of calibration, there being (as far as the author is aware) no direct alternative method at present available for effecting a calibration in terms of free air pressures.

In a more recent form of Wente condenser transmitter the recess has been reduced to $0{\cdot}85$ cm in depth, the radius remaining the same. That the effect of the recess is still appreciable is shown by a calculation at 3 500 cycles per sec., at which frequency the correction factor for the recess has a value of $1{\cdot}63$, which is probably nearly the maximum value attained.

The calibration and use of a transmitter in terms of free air pressures require that sound shall emanate from a single source; this necessitates the absence of reflecting surfaces, that is the carrying out of experiments in open air, or the acoustical equivalent. The latter alternative is available by covering all the solid surfaces in a testing cabinet with a sufficient quantity of a material suitable for accepting and absorbing sound.

The value to acoustical engineering practice of the conception of acoustical impedances is generally recognized; it would be increased by a more definite knowledge of the actual magnitudes of the impedances in some

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* At the lowest frequency calculated (500 cycles per sec.) the assumption of piston motion results in a value ($0{\cdot}84$) of m' in excess of that calculated by Rayleigh for an open-ended tube with an infinite flange, namely $0{\cdot}82$, but at this frequency the correction is, in any case, very small.

† See Reference (8).

common cases (e.g. of apertures surrounded by finite flanges) where direct calculation has failed. Experimental methods are available which would serve to furnish data of this kind.

The measurements which have been recorded were carried out at the Post Office Engineering Research Station and are published by permission of the Engineer-in-Chief of the Post Office.

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ALTERNATING-CURRENT TESTS ON HIGH-SPEED TELEGRAPH CABLES.*

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(*Paper received* 7*th June*, 1929.)

Summary.

This paper is concerned with the alternating-current characteristics of loaded telegraph cables and their relation to transmission capacity. The general principles of transmission are reviewed, and by the use of periodic theory the performance which may be expected from a cable of given a.c. characteristics is estimated.

Methods of testing are described by which complete data of the a.c. constants may be obtained during the process of manufacture. The effects of frequency, current, temperature and pressure are investigated, and the results of tests on the core for a long high-speed cable are discussed and used to estimate the performance of the cable when laid.

Apparatus and alternative methods for testing the laid cable are detailed and a method of deducing the primary constants from attenuation and propagation-time tests is developed; values determined are compared with results of factory tests. Deductions regarding the value and regularity of the inductance loading are made from impedance tests.

Departure and arrival curves for loaded cables are constructed from theory and compared with records obtained by test.

Finally, the assumed criteria for satisfactory working, expressed in terms of attenuation, are verified by transmission tests.

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List of Symbols.

B = flux density.
C = capacity to earth, per unit length of cable.
d = diameter of loading wire.
E = voltage applied to cable.
G = leakance to earth, per unit length of cable.
H = effective magnetizing force.
h_1 = voltage head-end loss.
h_2 = current head-end loss.
I_r = current at receiving end.
I_s = current at sending end.
I = current in cable.
L = inductance, per unit length of cable.
l = length of cable.
f = frequency of impressed voltage = $\omega/(2\pi)$.
$P = \sqrt{\{(R + j\omega L)\ (G + j\omega C)\}}$ = "propagation constant" = $\alpha + j\beta$.
α = attenuation constant.
β = wavelength constant.
R = resistance of unit length of the cable.
R_{ad} = added resistance, comprising:—
R_{ae} = resistance due to after-effect.
R_h = resistance due to hysteresis.
R_{cc} = resistance due to eddy-current.
r = mean radius of loading spiral (cm).
S = speed, in letters per minute.
V = voltage-drop in cable.
V_r = voltage at receiving end.
V_s = voltage at sending end.
$Z_0 = \sqrt{\{(R + j\omega L)/(G + j\omega C)\}}$ = "characteristic impedance."
Z_r = receiving impedance of cable.
Z_e = effective impedance of cable.
μ = permeability of loading material.
ρ = resistivity of loading material.
σ = impurity coefficient.

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* Thesis approved for the degree of Doctor of Philosophy in the University of London.

The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (excepting those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

(1) INTRODUCTION.

The electrical testing of submarine telegraph cables has, up to within a few years of the present time, been confined to direct-current measurements of resistance, capacity and insulation. Accurate data of the resistance of the conductor and its capacity to earth enabled the speed capabilities of the cable to be determined, and was essential for the localization of faults; while observation of the insulation of conductor to earth indicated the quality of the dielectric and ensured that leakage should be kept within a limit which would have no adverse effect on the speed of working.

The art of "loading," or adding inductance to telegraph cables, was advocated by Oliver Heaviside as long ago as 1885, but did not become a practical proposition until 1924, when the first long-distance loaded cable was manufactured.* The resultant greatly increased speed of working was obviously no longer determined by d.c. resistance and capacity alone; the cable could no longer be considered as a medium for the diffusion of impulses of direct current, for its electrical condition in operation approximated more nearly to that of a line carrying alternating current. Consequently, while the old d.c. tests were still required for reasons other than speed estimates, they had to give place in importance to a.c. measurements, upon the results of which the performance of the cable could be accurately predicted.

It is proposed in this paper to describe the development and application of means of testing which have accompanied recent progress from the unloaded low-speed cable, capable of transmitting a few hundred letters per minute, to the loaded high-speed cable working at speeds up to 2 000 letters. The tests necessary to ensure a complete knowledge of the electrical properties of the new type of cable, both during manufacture and after laying, will be described, and test data will be examined for such consistent behaviour as may be generalized for future use as the basis of cable design.

(2) REVIEW OF GENERAL PRINCIPLES.

(*a*) *Telegraphic Equation.*—In Fig. 1, A represents the conductor and B the insulator of a cable of length l. The conductor has resistance R and inductance L per unit length, and its leakance and capacity to earth are G and C respectively. For any small section of length δx, at distance x from the source of an applied voltage E, the constants are $R\delta x$, $L\delta x$, $G\delta x$ and $C\delta x$. Let the current-change in the section be $-\delta I$ and the voltage-change $-\delta V$. Considering the decreasing voltage,

$$-\delta V = R\delta x I + L\delta x(dI/dt)$$

where d/dt is the time differentiator and the current-change is small enough to be neglected. Or, when δx becomes dx,

$$-dV/dx = RI + L(dI/dt) \quad . \quad . \quad . \quad (1)$$

Similarly, considering the decreasing current,

$$-\delta I = G\delta x V + C\delta x(dV/dt)$$

and $$-dI/dx = GV + C\,(dV/dt) \quad . \quad . \quad . \quad (2)$$

Transient Condition (*Unloaded Cable*).—For an unloaded low-speed cable, L and G are negligibly small, and in this case

$$-dV/dx = RI \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and $$-dI/dx = C(dV/dt) \quad . \quad . \quad . \quad . \quad (4)$$

Hence, by differentiation,

$$d^2V/dx^2 = RC(dV/dt) \quad . \quad . \quad . \quad . \quad (5)$$

and $$d^2I/dx^2 = RC(dI/dt) \quad . \quad . \quad . \quad . \quad (6)$$

From equation (5) or (6) is derived an expression* for the current I_r at the receiving end of the cable:

$$I_r = \frac{E}{Rl}\left[1 + 2\sum_{m=1}^{m=\infty} \epsilon^{-\frac{m^2\pi^2 t}{RCl^2}} \cos m\pi\right] \quad . \quad . \quad (7)$$

whence it is apparent that the rate of increase of current at the receiving end of the (unloaded) cable is controlled by the product of its total resistance and total capacity. This led to the practical rule, known as the "Kelvin *KR* law," that speed of signalling could be estimated by dividing a constant by the factor RCl^2.

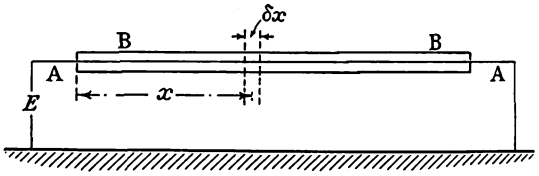

FIG. 1.

Periodic condition.—If the sending voltage is sinusoidal, of the form $E\epsilon^{j\omega t}$, the time differentiator d/dt is replaced by $j\omega$, and equations (1) and (2) become

$$-dV/dx = (R + j\omega L)I. \quad . \quad . \quad . \quad (8)$$

and $$-dI/dx = (G + j\omega C)V \quad . \quad . \quad . \quad (9)$$

whence $$d^2V/dx^2 = (R + j\omega L)(G + j\omega C)V \quad . \quad . \quad (10)$$

and $$d^2I/dx^2 = (R + j\omega L)(G + j\omega C)I \quad . \quad . \quad (11)$$

By the solution of equation (10) or (11) the telegraphic equation for periodic conditions is obtained.†

It is expressed by

$$\left.\begin{aligned} V &= V_s \cosh Px - Z_0 I_s \sinh Px \\ I &= I_s \cosh Px - V_s/Z_0 \sinh Px \end{aligned}\right\} \quad . \quad . \quad (12)$$

where $$P = \surd\left\{(R + j\omega L)\,(G + j\omega C)\right\} \quad . \quad . \quad (13)$$

$$Z_0 = \surd\left\{(R + j\omega L)/(G + j\omega C)\right\} \quad . \quad . \quad (14)$$

where V_s and I_s = voltage and current at sending end, and V and I = voltage and current at distance x from sending end.

The quantity P is known as the "propagation constant," of which the real part is the attenuation constant α and the imaginary part the wavelength constant β; so that

$$P = \alpha + j\beta \quad . \quad . \quad . \quad . \quad . \quad (13a)$$

Z_0 is termed the "characteristic impedance" of the cable.

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* O. E. BUCKLEY: *Journal of the American I.E.E.* 1925 vol. 44, p. 821.

* Sir W. THOMSON: "Papers," vol. 2, p. 62 (1884). For complete treatment, see H. W. MALCOLM: "The Theory of the Submarine Telegraph and Telephone Cable," ch. 8 (London, 1917).

† H. W. MALCOLM: *loc. cit.*, ch. 4.

From equation (12) above,

$$V = (V_s - Z_0 I_s)(\epsilon^{Px}/2) + (V_s + Z_0 I_s)(\epsilon^{-Px}/2)$$

and

$$I = \{I_s - (V_s/Z_0)\}(\epsilon^{Px}/2) + \{I_s + (V_s/Z_0)\}(\epsilon^{-Px}/2)$$

When the cable is of infinite length, V and I decrease as x increases, and since V_s, I_s and Z_0 are independent of x, the coefficients of ϵ^{Px} (an increasing function of x) in the above equations must be zero. Hence,

$$V_s = Z_0 I_s \quad . \quad . \quad . \quad . \quad . \quad (12a)$$

and

$$V/V_s = I/I_s = \epsilon^{-Px} \quad . \quad . \quad . \quad (12b)$$

(*b*) *Applicability of Periodic Condition to Speed Estimates.*—Telegraphic signals consist of aperiodic positive, negative and zero impulses, an average of nearly four of which make up a letter. If positive and negative impulses alternated, the fundamental frequency f of the train (two successive impulses in which would make one cycle) would be related to the speed in letters per minute, S, by the equation

$$f = 4S/(60 \times 2) = S/30 \quad . \quad . \quad . \quad (15)$$

Now larger received signals result from aperiodic than from periodic impulses, owing to transient currents, present in the former case and absent, after the first few cycles, in the latter. Thus, in signalling, a letter such as J (— + + +) arrives at greater magnitude than the letter C (+ — + —) sent at the same speed—in fact the chief object of the curbing, or shaping, apparatus at the ends of the cable is to reduce the size of all signals to that of the periodic or quasiperiodic ones, e.g. C, K (+ — +) and R (— + —).

Hence it may be stated that a cable which will transmit a frequency f in sufficient strength (i.e. which will have a sufficiently low attenuation at f cycles per sec.) will permit of a working speed of $30f$ letters per minute.

This applies to all cables, loaded or unloaded, fast or slow, and an approximation to the allowable attenuation may be obtained from the application of the Kelvin KR law to the speeds of unloaded cables. The average value of the Kelvin constant with modern apparatus is 800—i.e. for satisfactory signalling,

$$S = 30f = 800/RCl^2 \quad . \quad . \quad . \quad . \quad (16)$$

Now the attenuation constant of an unloaded cable for alternating current is approximately $\alpha = \sqrt{(\frac{1}{2}\omega RC)}$, leakance and inductance being neglected, and, if αl is the attenuation,

$$\alpha l = \sqrt{(\tfrac{1}{2}\omega RCl^2)} = \sqrt{\{\tfrac{1}{2}\omega \times (800/30f)\}} = 9 \cdot 1 \quad (17)$$

We have now to consider the influence on this approximation, derived from standard practice on unloaded cables, of certain factors peculiar to cables of the loaded type.

(*c*) *Distortion, Interference, and the Practical Standard of Satisfactory Transmission.*—The loaded cable has advantages over the unloaded in that it transmits with less distortion and suffers less from interference.

The attenuation constant of the loaded cable, from equation (13) above, reduces to

$$\alpha = \tfrac{1}{2}R\sqrt{(C/L)} + \tfrac{1}{2}G\sqrt{(L/C)} \quad . \quad . \quad (18)$$

on the valid assumption that ωL and ωC are large in comparison with R and G respectively. Part of the factor R (the d.c. resistance of the conductor) is not dependent, and part (the iron losses, etc.) is dependent on frequency; but in a properly designed loaded cable the dependent part is kept relatively small and, again, the second term of the attenuation, $\frac{1}{2}G\sqrt{(L/C)}$, is small compared with the first, $\frac{1}{2}R\sqrt{(C/L)}$.

The variation of attenuation with frequency, at the frequency for which the cable is designed, is thus less than that of an unloaded cable, for which $\alpha = \sqrt{(\frac{1}{2}\omega RC)}$. This means that distortion is less, and that uniformity in size of signals is obtained with less curbing.

With regard to interference, high-speed loaded cables have up to the present been designed for simplex working only. They are not, therefore, subject to the limitation in speed due, on unloaded cables, to difficulties in maintaining an adequate duplex balance.

Further extraneous interference has been greatly reduced by the introduction of the balanced sea earth.* The usual local receiving earth is replaced by a length of line B (Fig. 2) of the same characteristics as the cable A, terminated by a resistance R. The sea earth extends into water of depth about 100 fathoms, where disturbances, mostly occurring in shallow water, are slight. As the characteristic impedance of the cable does not vary appreciably with frequency within the working range, and is nearly a pure resistance, it can readily be reproduced, with sufficient accuracy, by the resistance R. Thus any disturbance originating at a point C meets with impedances on line and earth equal in the direction of the receiving end, and practically equal in the other (seaward) direction for the critical frequency band. Thus the disturbances to which the receiving apparatus is most sensitive are made ineffective, as they arrive by the two paths in equal strength and opposite directions.

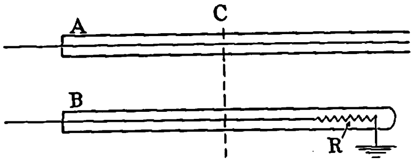

FIG. 2.

From the above considerations of distortion and interference, an increase may be expected in the permissible attenuation figure of 9·1 arrived at in equation (17).

As the result of experience on the first long loaded cable it was stated † that attenuations of 9 for relay working, and 10 for recorder working, were allowable, while for the Pacific Cable Board's continuously-loaded Bamfield (Vancouver)–Fanning Island II (1926) cable the following guarantee was given: "The completed cable when laid and throughout the guarantee period shall be capable of transmitting at the rate of 600 letters per minute simplex; the speed shall be calculated on the basis of a received current of 10 R.M.S. microamperes with receiving apparatus of impedance equal to the characteristic impedance of the cable when sending reversals with 60 volts (d.c.) at the dot frequency, counting 4 centre-holes per letter." This corresponded to an attenuation of approximately 9·3. This figure may be taken as a safe standard for satisfactory recorder working under average conditions, as will be seen in Section (6).

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* J. J. GILBERT: *Bell System Technical Journal*, 1926 vol. 5, p. 404.
† O. E. BUCKLEY: *loc. cit.*

(3) Tests on Cable during Manufacture.

(*a*) *General.*—It is not intended to discuss electrical tests on the raw materials forming cable cores, but mention may be made of an inductance test which is carried out on the loaded conductor, immediately after the annealing, and before the insulating process.* In this test a short part of the moving conductor which has just left the annealing furnace makes sliding contact with two fixed brushes. This part forms one arm of a bridge in which it is approximately balanced by a standard inductance. A Sumpner dynamometer is used as a detector, and deflections due to unbalance in the bridge, consequent on changes in the inductance of the moving conductor along its length, give, on a suitably calibrated scale, a continuous indication of inductance. The bridge is normally supplied with alternating current at a frequency of 50 cycles per sec., and the constants of the conductor are such that the resistance forms only a small part of the total impedance.

The cores of all cables are subjected to tests of d.c. resistance, capacity and insulation by well-known methods, and the effects of pressure and temperature on these constants are determined. In the case of loaded cables, in addition to the usual d.c. tests, each length of core is tested for a.c. resistance and inductance, and selected lengths are tested for leakance and capacity. Determinations are also made of the variation of the primary constants with frequency, current, temperature and pressure.

The importance of these a.c. tests at the present early stage of development of the loaded cable is considerable, as complete data must be available as a basis for the design of future cables and for progressive improvement in materials and factory processes.

For resistance and inductance tests the core, in lengths of about 2 nautical miles, must be wound on drums bifilarly in order to reduce the geometric inductance of the core (as distinct from the inductance added by the loading) to a small and calculable amount—in most cases 0·7 mH per nautical mile. The standard test frequency is that determined by the methods given in Section (2) (*b*); the standard test current is 1 mA (R.M.S.), this being the smallest current at which tests can conveniently be made.

With the bifilar winding used the external magnetic field of the coil is very small, but exact tests have shown that the eddy-current component of the effective resistance is measurably increased if the drum is made of ordinary commercial iron. The increase was found to be of the order of $5 \times f^2 \times 10^{-6}$ ohms for a coil of normal length, this being, in most cases, quite negligible.

It is impracticable to test complete coils for leakance and capacity, for the reasons given in Section (3) (*d*), and the best procedure is to take representative specimens of length about 70 ft. This length gives bridge settings of convenient magnitude and allows of the use of standard air condensers with an equal ratio bridge. The standard test frequency, for convenience in dealing with a large number of specimens, is 1 000 cycles per sec., produced from a thermionic oscillator; the e.m.f. between conductor and earth being 40 to 50 volts. In practice, samples are always immersed in salt water for leakance and capacity tests, as it has been found that if fresh water is used the resistance between earth-plate and core is sufficient to produce an apparent increase in leakance of 5 or 10 per cent.

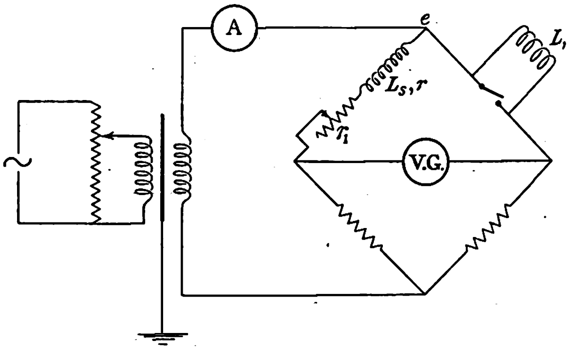

Fig.

(*b*) *Inductance and Effective Resistance.*—Two convenient methods are available for resistance and inductance measurements: (i) the Maxwell* bridge with standard self-inductance, and (ii) the Heaviside-Campbell † bridge with standard mutual inductance. The arrangement of these bridges as used is given in Figs. 3 and 4, the equations for balance being

(i) Maxwell bridge, $L = L_s$, $R = r + r_1$

(ii) Heaviside-Campbell bridge, $L = 2M$, $R = r_1$

with equal ratios in each case.

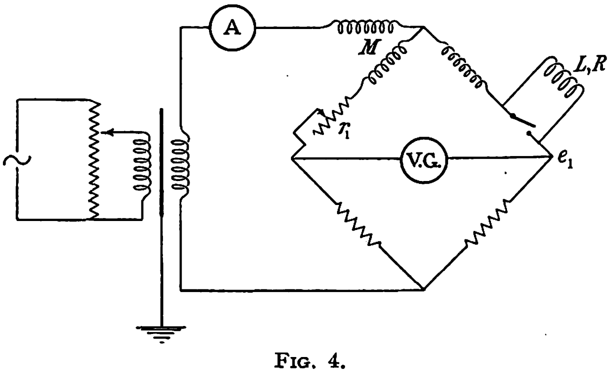

Fig. 4.

The advantages of using equal ratios whenever possible, in order to minimize and check errors due to earth capacities and residuals, is evident. In practice it is advisable to extend the range of the standards, if necessary, rather than to resort to an unequal ratio bridge. Under such conditions, and with the low frequencies used, earth capacity errors are not serious, and may for all practical cases be eliminated by earthing either terminal of the test coil, these being the points having greatest earth capacity. In Fig. 3 the point e is chosen as this connects to earth, in addition, one side of the standard. In Fig. 4 the earth is at e_1, as the alternative point would, if earthed, give the effect of increased impurity in the mutual inductance standard.

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* British Patent No. 256680.

* J. C. Maxwell: "A Treatise on Electricity and Magnetism" (1873), 3rd edition, vol. 2, p. 398.

† O. Heaviside: *Philosophical Magazine*, 1887, vol. 23, p. 173; also A. Campbell: *Proceedings of the Physical Society of London*, 1908, vol. 21, p. 69.

Alternating current is supplied to the bridge through a screened transformer, and is measured by a thermal milliammeter A consisting of vacuum thermo-junction and d.c. microammeter. It is regulated by a potentiometer or a series resistance (the former being generally more convenient) placed on the primary, or alternator, side of the transformer. It has been found that with the regulator on the secondary, or bridge, side, balance is more susceptible to capacity errors when testing with very small currents, i.e. when the part of the potentiometer resistance tapped to bridge is small or, with the series regulator, when the resistance is large.

In both bridges a 4-pole change-over switch enables a d.c. source and detector to be substituted for the a.c. supply and vibration galvanometer, so that d.c. and a.c. resistances can be readily compared under the same conditions of test.

Further details with regard to the construction and working of the bridges are as follows:—

Maxwell Bridge.—An accurate standard of self-inductance is required, and for high sensitivity the bridge should have a resistance not greatly in excess of that of the lengths of core to be tested. Such a standard was specially designed and constructed for the purpose. It consists of two tapped coils, one of 100 mH by tens, and the other of 500 mH by hundreds. The resistance of the first coil is 4 ohms, and that of the second 20 ohms. It was anticipated that, by the use of stranded wire, the effective resistance of any section of the coils at a frequency of 200 cycles per sec. would not differ from the d.c. resistance by more than 0·2 per cent, and calibration by means of Hay's bridge,[*] using a standard condenser of known power factor, and comparison with standardized coils, have shown the difference to be within this specification.

The required sections are connected in circuit by means of a plug commutator, which also completely isolates sections not in use, thereby minimizing earth capacity. The coils are not astatic, but are placed at right angles to each other in a common case and have negligible mutual inductance. In practice it has been found that, if the standard is so placed that it is not nearer than 2 ft. to any large mass of metal or any other part of the bridge, no measurable errors are caused by eddy currents or interference produced by the external field.

A specially constructed variable self-inductor of range 10 mH is used in series with these fixed subdivided coils, the combination forming a continuously variable standard from about 1 mH to 600 mH.

Heaviside-Campbell Bridge.—The variable mutual inductance standards available permit of measurements of self-inductance up to 220 mH on an equal ratio bridge. When the test inductance is beyond this value the "known" arm of the bridge is loaded by a fixed standard of self-inductance, the effective resistance of which is exactly balanced out, for convenience in working, by a non-inductive resistance in the "unknown" arm.

In order to determine the effect of impurity in the mutual inductance[*] on effective resistance measurements, a series of standardized coils was tested on the equal ratio Heaviside bridge at a range of frequencies up to 200 cycles per sec. The impurity coefficient, σ, is given by $R_t - R_a = 2\sigma$, where R_t is the true, and R_a the apparent, effective resistance of the coil. The results of these impurity tests are given in Fig. 5. The coefficient was found to vary substantially as the square of the frequency up to 200 cycles per sec. In most practical cases the correction is negligible.

Of the two bridges, the Maxwell bridge has been found somewhat easier to work, as accuracy of setting is slightly greater than with the other. In both cases, however, it is possible to detect unbalances of 0·02 per cent in inductance, and 0·25 per cent in effective resistance, between 20 and 100 cycles per sec. with 1 mA testing current on coils of average length.

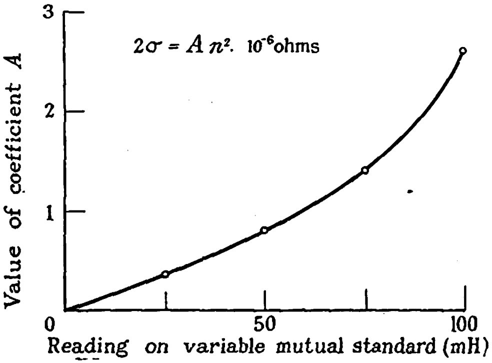

FIG. 5.

(*c*) *Leakance and Capacity.*—For leakance and capacity testing, the Wien series resistance bridge[†] with Wagner earth connection,[‡] and the Wien parallel resistance bridge[†] with direct earthing, are suitable. The series resistance arrangement has been extensively used in the past for testing short lengths of cable.[§] The arrangement is shown in Fig. 6, and with equal ratios the balance equations are

$$C = C_s/(1 + \omega^2 C_s^2 R^2)$$

$$G = 1/r = (\omega^2 C_s^2 R)/(1 + \omega^2 C_s^2 R^2)$$

In all practical cases $\omega^2 C_s^2 R^2$ is negligible compared with unity, so that $C = C_s$ and $G = \omega^2 C_s^2 R$.

For this test it is necessary that the tank of water containing the specimens of cable should be insulated from earth, although the insulation need not be of a very high order. The bridge components are electrostatically screened, the screens being connected as shown to the points at earth potential. The possible points of connection of the screens of R and C_s are shown in Fig. 7, and are all theoretically imperfect.

In case (*a*), as used, the screen of C_s is not at exactly the same potential as either set of condenser plates, and a small fraction of the effective capacity (as calibrated with moving plates connected to screen) is not in series with the resistance.

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[*] C. E. HAY: *Professional Papers of the Institution of Post Office Electrical Engineers*, No. 53, Nov. 1912.

[*] S. BUTTERWORTH: *Proceedings of the Physical Society of London*, 1921, vol. 33, p. 312.

[†] MAX WIEN: *Annalen der Physik*, 1891, vol. 44, p. 697.

[‡] K. W. WAGNER: *Elektrotechnische Zeitschrift*, 1911, vol. 32, p. 1001.

[§] A. ROSEN: *Proceedings of the Physical Society of London*, 1923, vol. 35, p. 235

The errors introduced thereby, however, are calculable for a given setting of R and are negligible in practice.

The other cases are inadmissible, as in (*b*) there is a capacity to earth within the arm for which the Wagner earth does not correct, in (*c*) both screens are not at earth potential, and in (*d*) the capacity between the resistance R and its screen is added to that of C_s.

The series resistance bridge has been found to give accurate results at 1 000 cycles per sec. for specimens of average capacity (0·003 μF), but it suffers from the following disadvantages: (i) the containing tank must be insulated if the Wagner earth is used, (ii) the time taken in calculating results from bridge readings is appreciable when testing is carried out on a commercial scale, and (iii) the series resistance corresponding to a given power factor varies inversely as the frequency, and for low frequencies (e.g. 50 cycles per sec.) is impracticably large. For general convenience the author has found it preferable to use a parallel resistance arrangement, adapted as a substitution method, as shown in Fig. 8.*

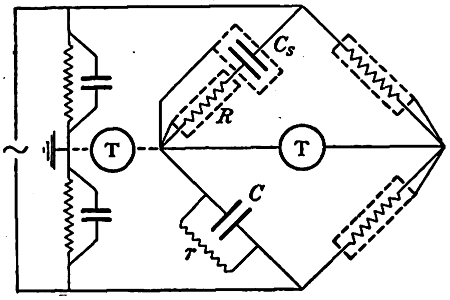

FIG. 6.

The initial balance of this bridge is taken with standard air condensers C_s and mica condenser C_1 (of capacities slightly higher than that of the test specimen) and resistances R, R_1, of 100 000 ohms each. The test core is then put in parallel with C_s and R, and these standards are adjusted to values C_s' and R' for balance.

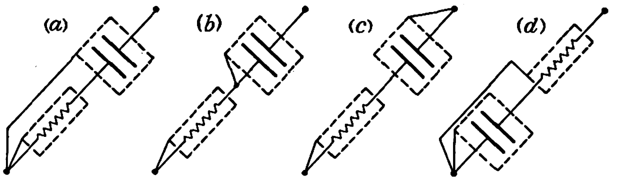

FIG. 7.

Then, $(1/R) + j\omega C_s = (1/R') + j\omega C_s' + (1/r) + j\omega C$

Hence $C = C_s - C_s'$

$$G = 1/r = (1/R) - (1/R') = (R' - R)/RR'$$

The auxiliary condenser C_s and resistance r_s are introduced to enable zero balance to be obtained with C_s set at a convenient value and with R = 100 000 ohms.

In practice the adjustment to R is made on the last few hundred ohms, so that RR' may usually be taken as 10^{10}, and calculations are thus simplified. It is evident that an accurate setting of R is necessary, but with a supply voltage of 40 or 50 volts it is possible to set the resistance to one or two ohms and obtain the leakance of the average sample to within 1 per cent at 1 000 cycles per sec. For low frequencies, a step-down transformer between bridge and detector (in this case a vibration galvanometer) enables the sensitivity to be kept up so that results within a few per cent are obtainable.

Owing to the high impedance of the bridge it is essential that the insulation of leads from the source of supply should be high and constant. Given this condition, and reliable high resistances, the bridge is very convenient to work, and the fact that the method of procedure is direct substitution, with a direct earth, avoids errors which would otherwise be introduced by residuals and earth capacities.

The accuracy of the bridge is checked from time to time by comparison with the series resistance bridge and by tests on an air condenser and standard 2-megohm leak.

Power Factor of Standard Condensers.—In most routine tests this may be neglected, but in some cases, where it is not small compared with that of the specimen measured, it may be approximately determined on the parallel resistance bridge as follows:—The bridge is balanced with a variable condenser, part of capacity C_s (Fig. 8), set at its maximum reading. A second variable air condenser, set at a low reading, is then connected in parallel with it, and the bridge rebalanced by reducing the capacity of the first condenser and by adjusting R. The power factor of the second condenser is thus obtained, the assumption being made that the power factor of the first varies with the reading, i.e. that the leakance is the same for all settings. This instrument is then available as a standard for determining the power factor of others in a similar manner.

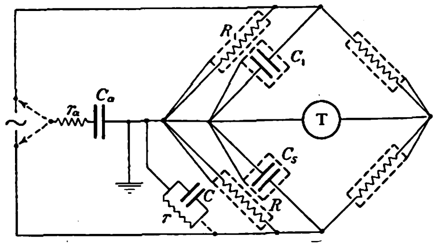

FIG. 8.

Condition of Specimens for Leakance Determination.—It is important that specimens of core should be soaked in water for some days previous to testing, although a good approximation may be obtained after the first few hours if the average behaviour of the material with time of immersion is known. Leakance of gutta-percha and allied gums has been found to increase during the first three or four days of immersion, this being due to the absorption of a small quantity of water. After about the sixth day this action ceases, and a very slow improvement with time sets in. The measured leakance, however, is greatly influenced by the condition of the few inches of core immediately above the surface of the water, and it is essential that this core surface be quite dry. If it

* F. W. GROVER: *Scientific Papers of the Bu eau of Standards*, 1907, No. 64, p. 393.

is damp, the leakance measured is increased more than in direct proportion to the small extra surface thus in partial contact with the water, and errors of as much as 10 per cent may result. This effect is independent of the surface insulation between the exposed copper ends and the surface of the water or the film of moisture on the core near the surface. It is explained by the following considerations.

The condition of the end is as indicated in Fig. 9, and the equivalent circuit diagram in Fig. 9A. Here G and C represent the leakance and capacity of the core in water, δG and δC the small additional leakance and capacity introduced by the extra damp length. It is assumed that the film will have a somewhat high resistance, the mean value of which is represented by R, to the surface of the water.

Let ΔG and ΔC be the apparent additional leakance and capacity introduced by the film of moisture, i.e. the admittance of branch a′b′.

Then $\quad 1/(\Delta G + j\omega\Delta C) = R + 1/(\delta G + j\omega\delta C)$

whence $\quad \Delta G + j\omega\Delta C = \dfrac{\delta G + j\omega\delta C}{1 + R(\delta G + j\omega\delta C)}$

and, by separation of real and imaginary parts,

$$\Delta G = \frac{\delta G + R(\delta G^2 + w^2\delta C^2)}{1 + 2R\delta G + R^2(\delta G^2 + \omega^2\delta C^2)}$$

and $\quad \Delta C = \delta C/\left\{1 + 2R\delta G + R^2(\delta G^2 + \omega^2\delta C^2)\right\}$

From the above it will be seen that, as R is decreased from ∞ to zero, ΔC is increased from 0 to δC; while ΔG is increased from zero to a value greatly in excess of δG, to which it descends as R approaches zero. For example, if, at 1 000 cycles per sec., $R = 2$ megohms, $\delta C = 30\ \mu\mu$F, $\delta G = 0{\cdot}001\ \mu$mho, ΔG becomes approximately $0{\cdot}07\ \mu$mho, an amount usually appreciable compared with the leakance of the whole specimen.

In consequence of the fact that wax is not "wetted" by water, the ends of all specimens are coated with paraffin, so that there is no unwaxed surface at the water line. By this means the damp-surface error just described may be avoided.

(*d*) *Corrections arising from Length of Test Coils.*—The methods previously described measure the closed- and open-circuit impedances of the core, and these impedances may be taken as equal to $R + j\omega L$ and $G + j\omega C$, respectively, if the length is sufficiently short. In any cable having distributed constants R/l, L/l, G/l and C/l per unit length, however, we have, for the closed-circuit impedance,

$$Z_c = Z_0 \tanh Pl, \quad \text{where} \quad Z_0 = \sqrt{\left(\frac{R + j\omega L}{G + j\omega C}\right)}$$

and $\quad Pl = \sqrt{\left\{(R + j\omega L)(G + j\omega C)\right\}}$

The expansion of tanh Pl gives

$$\begin{aligned} Z_c &= \sqrt{\left(\frac{R + j\omega L}{G + j\omega C}\right)}\left\{Pl - \tfrac{1}{3}(Pl)^3 + \tfrac{2}{15}(Pl)^5 - \ldots\right\} \\ &= \frac{(R + j\omega L)^{\frac{1}{2}}}{(G + j\omega C)^{\frac{1}{2}}}\left\{(R + j\omega L)^{\frac{1}{2}}(G + j\omega C)^{\frac{1}{2}} - \tfrac{1}{3}(R + j\omega L)^{\frac{3}{2}}(G + j\omega C)^{\frac{3}{2}} + \ldots\right\} \\ &= (R + j\omega L)\left\{1 - \tfrac{1}{3}(R + j\omega L)\ (G + j\omega C) + \tfrac{2}{15}(R + j\omega L)^2(G + j\omega C)^2 - \ldots\right\} \\ &= (R + j\omega L) + \left\{\tfrac{2}{3}RLC\omega^2 + \tfrac{1}{3}GL^2\omega^2 + \tfrac{2}{5}RL^2C^2\omega^4 \ldots + j\omega(\tfrac{1}{3}L^2C\omega^2 - \tfrac{1}{3}R^2C + \tfrac{2}{15}L^3C^2\omega^4 \ldots)\right\} \end{aligned}$$

That is to say, the measured value of R must be reduced by

$$\tfrac{2}{3}RLC\omega^2 + \tfrac{1}{3}GL^2\omega^2 + \tfrac{2}{5}RL^2C^2\omega^4 \ldots$$

and that of L by

$$\tfrac{1}{3}L^2C\omega^2 - \tfrac{1}{3}R^2C + \tfrac{2}{15}L^3C^2\omega^4 \ldots$$

For all practical purposes it is sufficient to use the first terms of these corrections. Thus readings of R are reduced by $(\frac{2}{3}RLC\omega^2)$, and those for L by $(\frac{1}{3}L^2C\omega^2)$. It will be seen that in both cases the percentage correction varies as the square of the length of the coil.

The value for C is evidently the capacity of one limb of the bifilar wound coil to the other. If the coil were in water this would be one-quarter of the capacity to earth of the whole coil; but as the test is usually carried out in air, the wire-to-wire capacity of the loop under these conditions must be known.

For example, if for a coil of length 2 nautical miles $C = 0{\cdot}1\ \mu$F, and the apparent values of R and L are $3{\cdot}5$ ohms and 200 mH, for $f = 100$ ($\omega = 628$), the true value of R is then $3{\cdot}50 - 0{\cdot}02 = 3{\cdot}48$ ohms, and of $L = 200 - 0{\cdot}5 = 199{\cdot}5$ mH, to a sufficient degree of accuracy. Such corrections are usually inappreciable for frequencies below 50 cycles per sec.

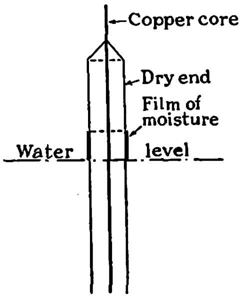

FIG. 9.

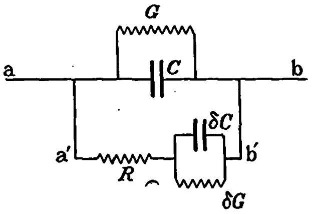

FIG. 9A.

The corrections for leakance and capacity are determined in a similar way by expanding coth Pl, for $Z = Z_0 \coth Pl$. They indicate that, to a first approximation, the apparent values of G and C are too high by $\frac{1}{3}\omega^2C(CR + 2GL)$, and by $\frac{1}{3}(\omega^2C^2L - 2RGC)$, respectively. In practice, the correction to G on a full length of core would be high enough seriously to prejudice the accuracy of the final result, and it is partly for this reason that leakance and capacity tests are taken only on short samples for which the corrections are negligible.

(*e*) *Tests under Pressure and at Low Temperature.*—The average depth to which a long submarine cable is submerged is between 2 500 and 3 000 fathoms, and at these depths pressures of 3 to $3\frac{1}{2}$ tons per sq. in., and a temperature of about 36° F., are experienced.

In order to ensure that pressure shall be transmitted uniformly to the strain-sensitive loading material, and shall not cause mechanical distortion, a layer of viscous compound is placed as a cushion between loaded conductor and insulator, the former being run through a bath of compound immediately before being covered with the latter. Pressure tests taken in the factory are of two classes:—(i) observations of inductance on lengths of a few yards to detect fall in permeability due to mechanical damage to the loading wire, and (ii) tests on longer coils to determine the variation of the primary constants with pressure and temperature.

While in the latter case the individual effects of the two independent variables are found to be additive, in the former this may not be so. For example, with a defective compound, inductance may be independent of pressure at normal temperatures, or of change of temperature at atmospheric pressure, but may vary considerably with pressure at 36° F. owing to changes in the viscosity of the compound with temperature. It is therefore necessary to bring the test specimens down to the low temperature before pressure is applied, the straight cylindrical tube in which they are placed being water-jacketed for this purpose. Normal procedure is to apply hydrostatic pressure in five or six equal increments from zero up to 3 tons per sq. in., and to observe the inductance at each increment. A drop of inductance will indicate that the compound is not sufficiently fluid, or has been irregularly applied; in the latter case there is usually a gradual recovery with time back to the normal value as the compound distributes itself more or less evenly under pressure; in the former case recovery may be slow, or may not take place at all. Normally, no change of inductance greater than 1 or 2 per cent is observed with pressure up to 4 tons per sq. in.

For the second class of tests, coils of about 100 yards in length are subjected to hydrostatic pressure in a small water-jacketed cylinder. With regard to inductance, with decreasing temperature there is a slight proportional decrease amounting to 2 per cent for a change of temperature from 75° to 35° F.; with pressure, the absence of variation observed on the shorter lengths is verified.

(*f*) *Variations of the Primary Constants with Frequency, Current, Temperature and Pressure. Experimental data.*— The tests described in Section (4) were taken on the Pacific Cable Board's Bamfield (Vancouver)–Fanning Island II (1926) cable,* and factory tests on the core for this cable will therefore be primarily considered. Tests on other cores of different dimensions are introduced in order to verify and amplify deductions made in particular cases.

Results throughout this paper will be referred to a length of 1 nautical mile, unless otherwise stated.

The conductor of the Bamfield–Fanning II cable consists of a round copper wire closely surrounded by 6 thin copper tapes, the whole being of diameter 0·185 in. and weighing 608 lb. per nautical mile. The loading is of high-permeability alloy known as "mumetal No. 6," in the form of a wire of average diameter 0·0108 in. This is applied to the conductor in one close continuous spiral, the weight of which is 114 lb. per nautical mile of conductor. The dielectric is of gutta-percha of radial thickness 0·130 in., weighing 370 lb. per nautical mile, and the layer of compound between conductor and dielectric is of radial thickness approximately 0·010 in.

From the above dimensions the following preliminary estimates may be made (for 1 nautical mile of core), using well-known formulæ:—

(i) D.C. resistance = 1·96 ohms at 75° F. for copper of 100 per cent standard conductivity, including an allowance of 1 per cent for the particular (taped) composition of the conductor.

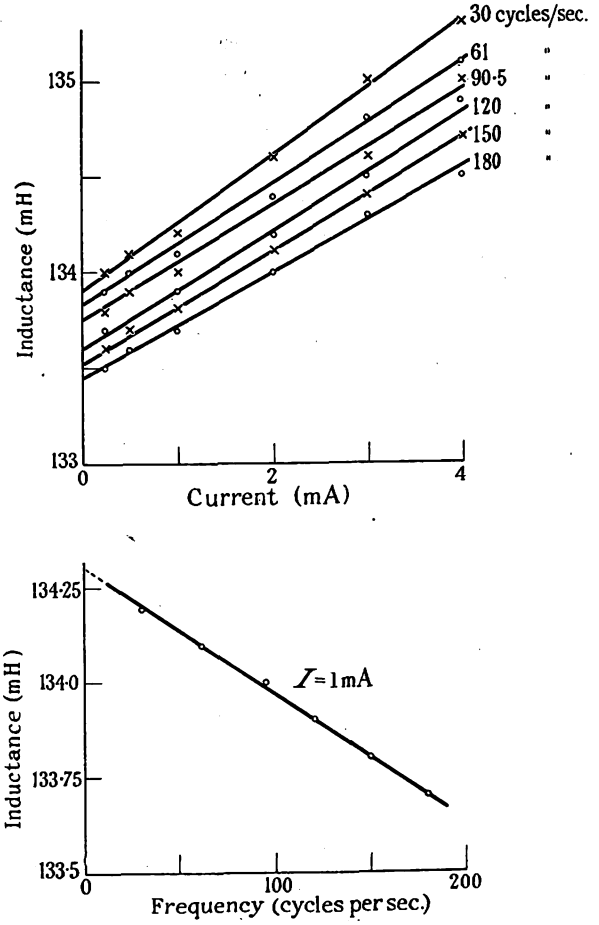

FIG. 10.

(ii) Capacity = 0·39 μF, taking the specific inductive capacity of gutta-percha and compound as 3·2.

(iii) Inductance (millihenrys) added by loading $(L_1) = 0\cdot0318\mu$, where μ = effective permeability of loading.

(iv) Geometric, or natural, inductance of core, when wound bifilar, $(L_g) = 0\cdot7$ mH.

(v) Added resistance due to eddy currents

$$(R_{ec}) = 8\cdot3\,\mu^2 f^2 10^{-12} \text{ ohms},$$

taking specific resistance of loading material as 45 microhms per cm^3.

The formulæ used in estimates (iii) and (v) do not take into account small corrections—inappreciable in this case—for variation with frequency due to eddy-current reactions and to the angle ϕ between the loading helix and a line through it parallel to the axis of the conductor.

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* E. S. HEURTLEY: *Electrician*, 1927, vol. 98, p. 348; also *Post Office Electrical Engineers' Journal*, 1927, vol. 20, p. 36.

The correction factors are given as

$(1 - \frac{1}{30}m^4d^4)\sin^2\phi$ for inductance, and
$\left\{1 - (17/420)m^4d^4\right\}\sin^2\phi$ for eddy-current resistance,[*]

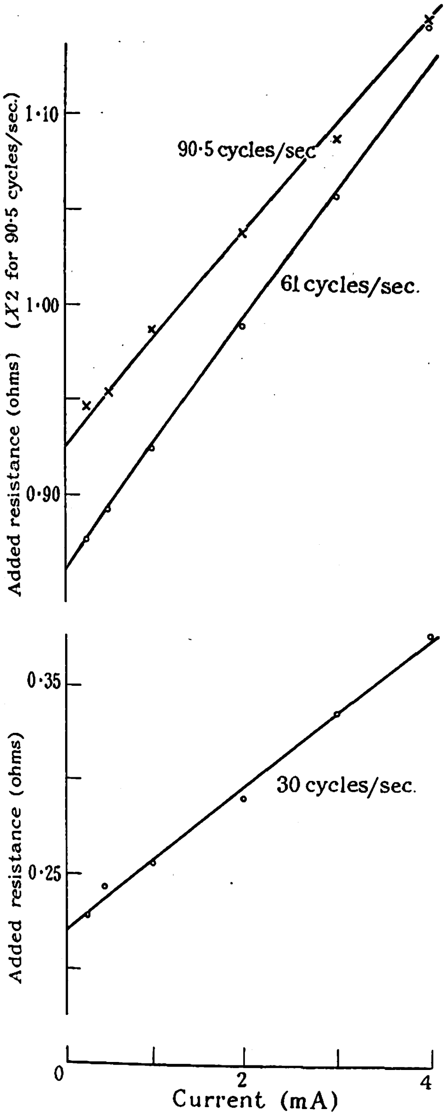

FIG. 11.

where $m = \sqrt{(2\pi\mu\omega/\rho)}$,
μ = permeability of loading material,
ρ = resistivity of loading material, and
d = diameter of loading wire.

It may be noted, however, that in practice the correction for inductance appears to depend on the first power, and not on the square, of the frequency. Fig. 10 shows a typical case.

The most important a.c. tests are those determining the variation of inductance (L) and added resistance (R_{ad}) (i.e. a.c. resistance—d.c. resistance) with current and frequency, as these largely determine the speed of the cable.

Variation of Inductance and Added Resistance with Current and Frequency.

(i) *For Light Currents, from Zero to about 5 mA.*—The variation with currents has in both cases been found to be linear, typical results being given for a sample marked X. 2989 in Figs. 10 to 13. It has generally been accepted that the added-resistance curves start parallel to the current axis, i.e. that there is no variation with currents near zero, but the author has found that accurate tests consistently give the linear variation. This characteristic has been noted by Jordan[†] from tests on iron-cored coils.

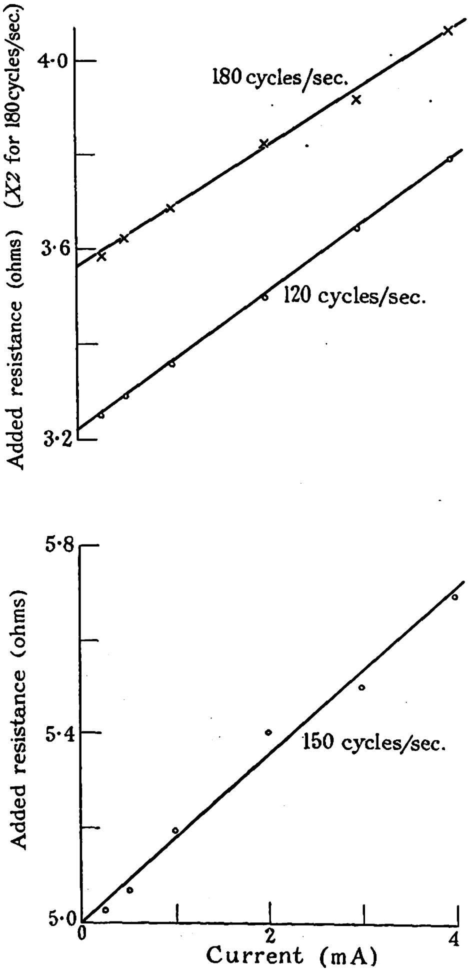

FIG. 12.

By repeating these tests at different frequencies, a combined current-frequency variation law may be determined.

In Fig. 13, values of R_{ad}/f are plotted against f, giving straight lines. The added resistances for zero currents (obtained by extrapolation from the current curves) when divided by f and plotted against f, show that an added resistance, varying linearly with f, exists

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[*] U. MEYER: *Elektrische Nachrichten-Technik*, 1924, vol. 1, p. 169; also *Elektrotechnische Zeitschrift*, 1925, vol. 46, p. 1033.

[†] H. JORDAN: *Elektrische Nachrichten-Technik*, 1924, vol. 1, p. 7.

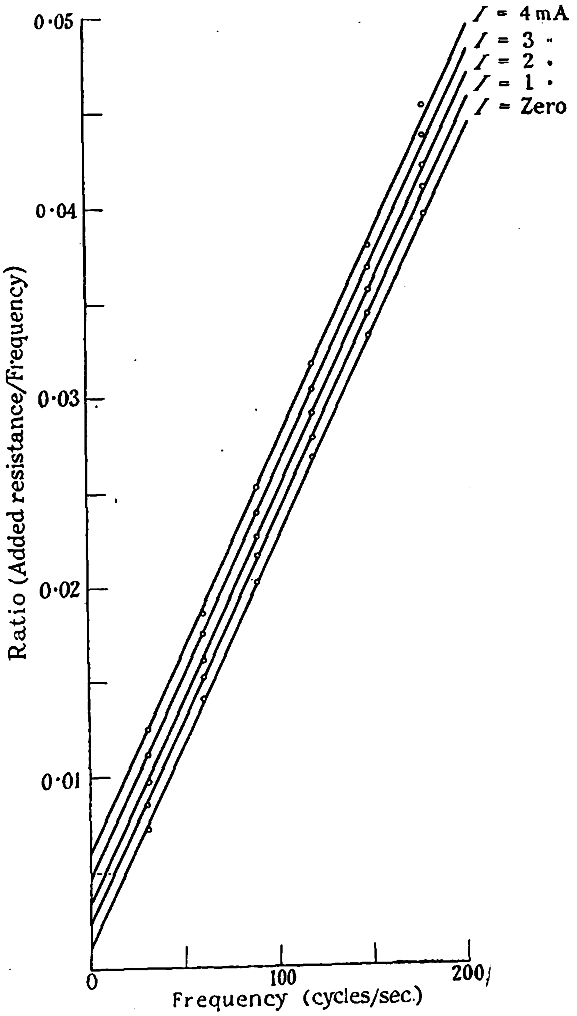

FIG. 13.

at zero current. This may also be obtained by extrapolation to zero of the curve connecting the coefficient of f with current (Fig. 13A). Hence we may write, for small currents,

$$R_{ad} = af(1 + cI) + bf^2$$

and

$$L = L_0 + dI,$$

where a, b, c and d are constants, I is the current and f the frequency. That part of the added resistance which varies as f^2 is due to eddy currents; of the part which varies as f, that remaining at zero current has been termed by Jordan "after-effect"; the other part, also varying with f, is due to hysteresis.

Allowance for after-effect in loaded cables does not appear to have been made hitherto, it having been assumed that there is no iron loss for currents near zero other than that due to eddy currents.*

The separate components of the added resistance for a given inductance (i.e. a given permeability of loading material) may be written thus:—

$$\left.\begin{aligned} R_{ae}\ (\text{after-effect}) &= af \\ R_h\ (\text{hysteresis}) &= acfI \\ R_{ec}\ (\text{eddy current}) &= bf^2 \end{aligned}\right\}\text{for small currents,}$$

and the following deductions may be made:—

$$\mu = \mu_0 + eI, \quad \text{and} \quad H = \text{magnetizing force} = kI,$$

where e and k are constants.

Flux, $B = \mu H = \mu_0 kI + ekI^2 \doteqdot \mu_0 kI$, or $I = (B/\mu_0 k)$.

Hysteresis loss $= R_h I^2 = acfI^3 = (acfB^3/\mu_0^3 k^3)$; that is, hysteresis loss varies as B^3. Similarly after-effect and eddy-current losses vary as B^2.

In the example given (Figs. 10 to 13) the laws of variation of inductance and added resistance for small currents are

$$L = 134 \cdot 3 - 0 \cdot 0033f + 0 \cdot 3I$$

$$R_{ad} = 0 \cdot 001f(1 + 1 \cdot 3I) + 213f^2 10^{-6}$$

I being expressed in milliamperes.

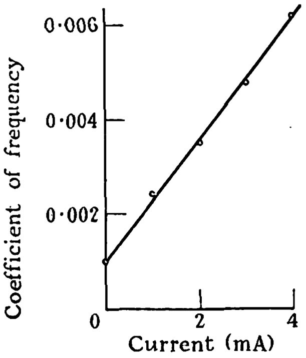

FIG. 13A.

TABLE 1.

Specimen number	Inductance†	Permeability † μ	Added resistance	$\left(\frac{\text{Coefficient of } f}{\mu^2}\right)$	$\left(\frac{\text{Coefficient of } f^2}{\mu^2}\right)$
	mH		ohms		
X. 3577	89·8	2 800	$0 \cdot 001f + 110f^2 10^{-6}$	$0 \cdot 13 \times 10^{-9}$	$14 \cdot 0 \times 10^{-12}$
P. 1282	100·4	3 130	$0 \cdot 0013f + 115f^2 10^{-6}$	$0 \cdot 13 \times 10^{-9}$	$11 \cdot 7 \times 10^{-12}$
X. 3605	115·3	3 600	$0 \cdot 0018f + 150f^2 10^{-6}$	$0 \cdot 14 \times 10^{-9}$	$11 \cdot 6 \times 10^{-12}$
X. 2989	134·2	4 200	$0 \cdot 0023f + 213f^2 10^{-6}$	$0 \cdot 13 \times 10^{-9}$	$12 \cdot 0 \times 10^{-12}$
P. 1321	137·2	4 300	$0 \cdot 0025f + 220f^2 10^{-6}$	$0 \cdot 14 \times 10^{-9}$	$11 \cdot 9 \times 10^{-12}$
P. 1903s.	153·7	4 820	$0 \cdot 0035f + 276f^2 10^{-6}$	$0 \cdot 15 \times 10^{-9}$	$12 \cdot 0 \times 10^{-12}$

† Inductance and permeability measured at 20 cycles per sec.

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* O. E. BUCKLEY: *loc. cit.*; also J. J. GILBERT: *Electrician* 1927, vol. 99, p. 191.

The relation between added resistance and permeability, at a current of 1 mA, is shown by the tests on specimens of different inductances set out in Table 1.

It will be seen that the coefficient of *n* varies approximately as the square of the permeability, discrepancies being attributed to differences in mechanical or thermal treatment. The coefficient of f^2 varies closely as μ^2, but the added resistance due to eddy currents is $R_{ec} = 12\cdot0\mu^2 f^2 10^{-12}$ ohms instead of the theoretical $8\cdot3\mu^2 f^2 10^{-6}$ ohms, i.e. the realized R_{ec} is 1·45 times the calculated value. This increase has been found to be dependent on the diameters of conductor and loading wires, and is probably due to the flux density over the cross-section of the loading wire not being uniform, as assumed in the theoretical consideration.

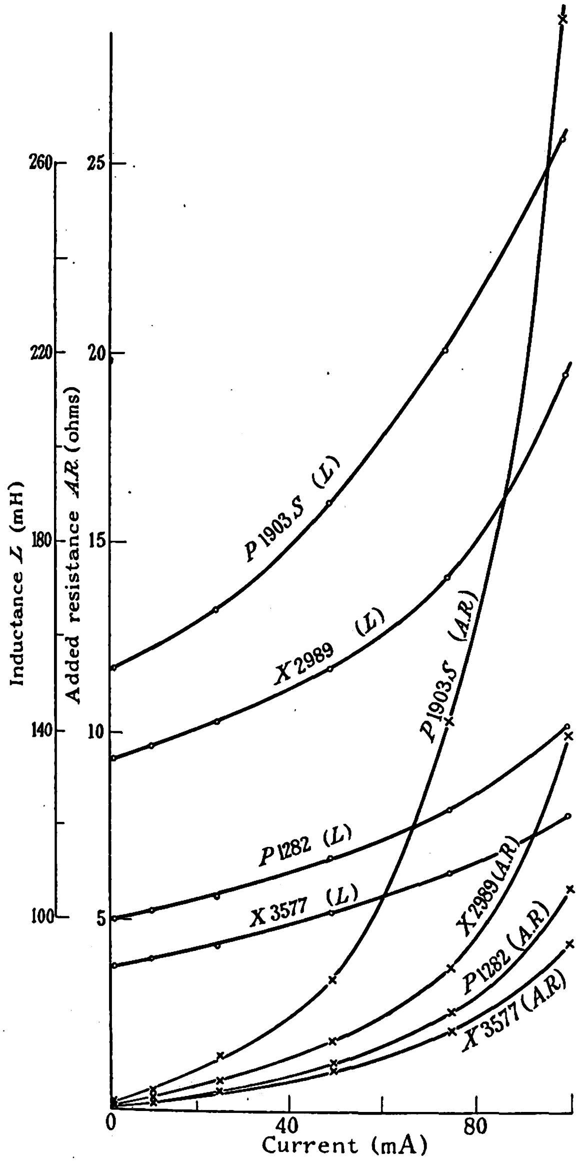

FIG. 14.

(ii) *For Currents up to* 100 *mA*.—As the normal sending current in a loaded cable is about 100 mA, the current tests must be extended up to that value. Typical results on four specimens of different initial inductance at 20 cycles per sec. are given in Fig. 14. Tests on one specimen at 20, 30 and 40 cycles per sec. are shown in Fig. 15.

It must here be noted that the tests determine the performance of the cable on alternating current of sinusoidal wave-form. Owing to non-linear variation of inductance with currents greater than a few milliamperes, the flux is not of sinusoidal wave-form, but, as the bridge detector is tuned to the fundamental frequency, the inductance and resistance measured are those due to the effective sine-wave component alone.

The inductance-current curves may be termed the magnetization curves of the cable and, while the maximum inductance usually occurs for a current above 100 mA, this may not always be the case. For a particular specimen marked X. 3446 the maximum is at approximately 100 mA, as will be seen from Fig. 16. In this case the mean diameter of the loading spiral, composed of 0·0108-in. wire as in the other cases, is 0·130 in. The shape of the magnetization curves depends on the composition of the alloy and its history, particularly with regard to thermal treatment, and these conditions for the best (i.e. the flattest) curve for any required initial inductance must be found by experiment. To a first approximation, however, with optimum conditions the rate of variation of inductance with current is a function of the square of the initial inductance.

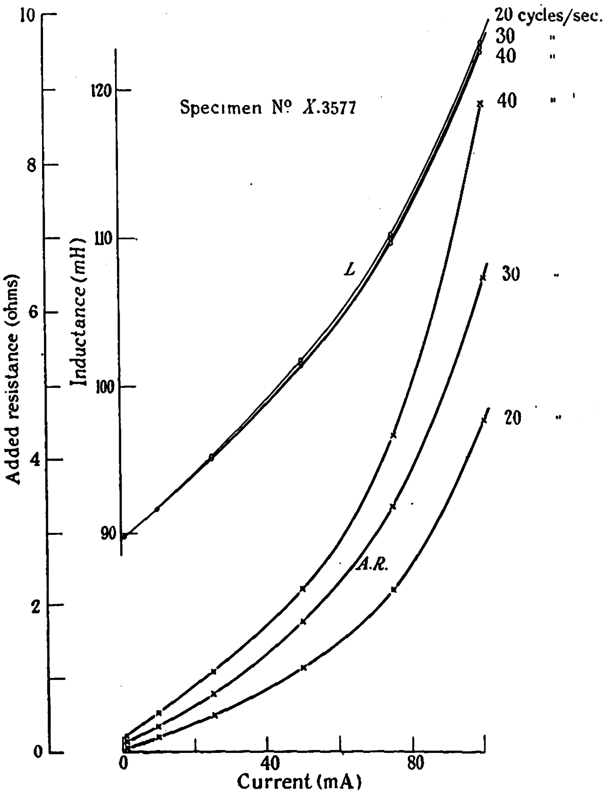

FIG. 15.

An examination of the tests illustrated in Figs. 14 to 16 enables an expression for hysteresis loss to be obtained in terms of inductance, and yields an approximation of the "after-effect" resistance (R_{ae}), given the eddy-current resistance (R_{ec}). The testing current is first converted into effective magnetizing force H, by the relation $H = (2I/10r)$ where r = mean radius of loading spiral in cm and I = current in amperes, R.M.S. values having been used in these computations. In the case of all samples except X. 3446, $2r = 0{\cdot}196$ in. and $H = 0{\cdot}80I$, while for X. 3446, $H = 1{\cdot}20I$. The effective permeability corresponding to each inductance is calculated from the dimensions of the core, and from this and H an effective value of flux density B is obtained for each current.

The added resistances less R_{ec} are then tabulated, R_{ec} being found by test or estimate at 1 mA and calculated for other currents. From these resistances is subtracted an estimated value for R_{ae}, this being, of course, invariable with current.

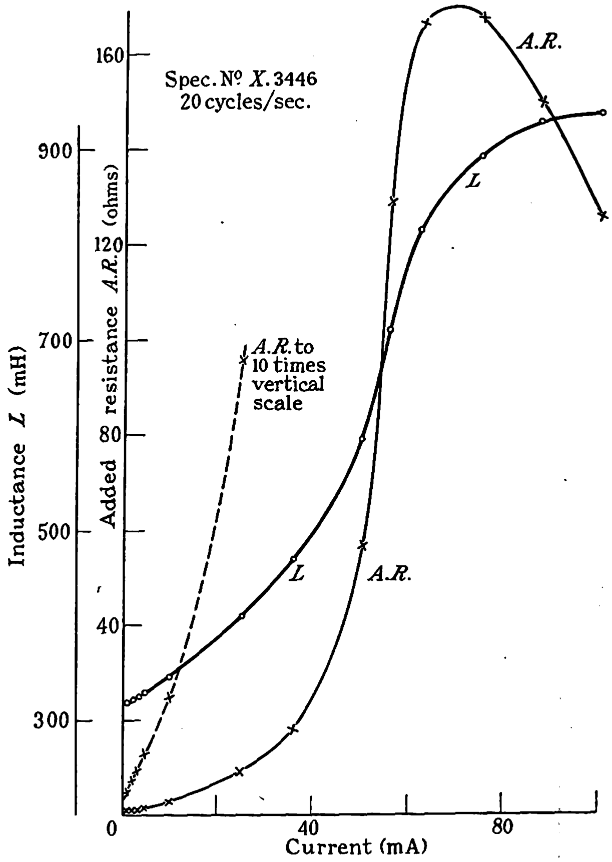

FIG. 16.

Thus the current test is reduced to three series of corresponding values: (i) currents, (ii) effective magnetizing forces and (iii) hysteresis resistances estimated by the method of taking differences just described. Series (iii) is then multiplied by the square of series (i) and plotted against series (ii)—that is, I^2R_h is compared with B. It is found that, with logarithmic scales, the variation gives a straight line, with possibly slight deviation for currents below a few milliamperes. This deviation may be eliminated by adjusting the original estimate of R_{ae}, which is an appreciable proportion of $(R_h + R_{ae})$ only for the lower currents. Thus R_{ae} is determined as that constant deduction from $(R_h + R_{ae})$, which allows a definite relation between hysteresis loss and flux density to be established.

The results of this analysis on the current tests plotted in Figs. 14 to 16 are shown in Fig. 17, from which it is seen that the dependence of hysteresis loss on the cube of the flux density holds for higher currents as well as for those of a few milliamperes. The curve for X. 3446 is not taken beyond I = 56 mA, above which current it departs from the straight line and shows that the exponent of B decreases as the saturation shown in Fig. 16 is approached. All other curves include the normal testing range up to I = 100 mA.

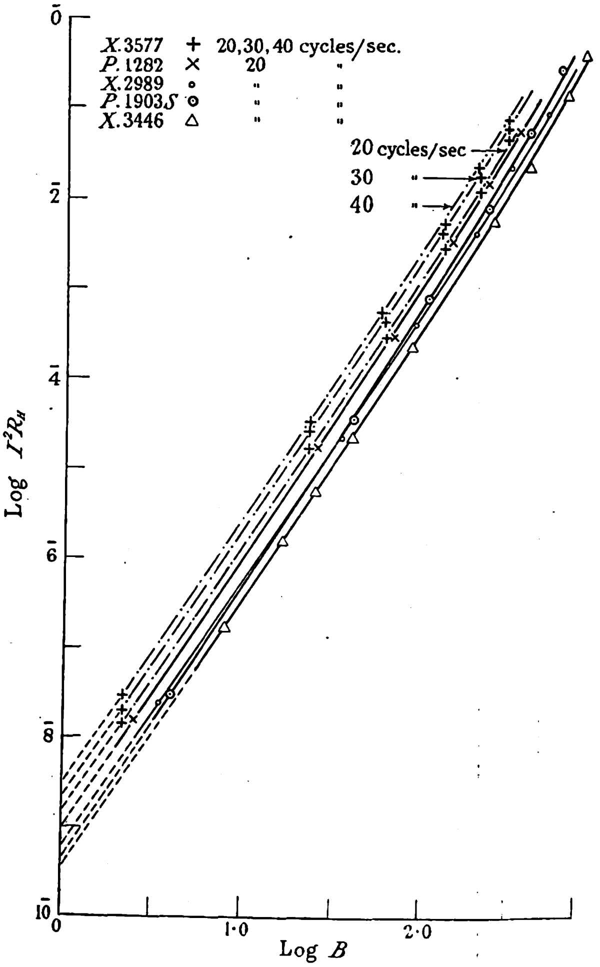

FIG. 17.

Table 2 gives values of R_{ae} and hysteresis loss determined from Fig. 17.

In the case of X. 2989, R_{ae} was also determined as shown in Figs. 13 and 13A. The correction to X. 3446 converts the results for mean diameter of loading spiral from 0·130 in. to 0·196 in.

These results enable the hysteresis loss of a length of loaded cable to be calculated, from the magnetization curve, for any current and frequency within the range covered, and show that with different specimens hysteresis loss may be expressed as $0\cdot 5 \times 10^{-3} f B^3/\mu_0^2$.

For a current of 1 mA ($H = 0\cdot 0008$), $B = \mu_0 H$ practically, and, at 20 cycles per sec.,

$$I^2 R_h = 0\cdot 01 \mu_0 H^3, \quad \text{and} \quad R_h = 5\cdot 1 \times 10^{-6} \mu_0.$$

TABLE 2.

Specimen number	Frequency	Initial μ (μ_0)	R_{ae}	Hysteresis loss	(Coefficient of B) × μ_0^2 for $f = 20$ cycles per sec.
	cycles/sec.			10^{-9}	
X. 3577	20	2 800	0·007	$1\cdot 4\ B^{3\cdot 0}$	0·011
X. 3577	30	2 800	0·010	$2\cdot 0\ B^{3\cdot 0}$	0·010
X. 3577	40	2 800	0·015	$2\cdot 8\ B^{3\cdot 0}$	0·011
P. 1282	20	3 130	0·01	$0\cdot 93 B^{3\cdot 1}$	0·009
X. 2989	20	4 200	0·02	$0\cdot 58 B^{3\cdot 0}$	0·010
P. 1903s.	20	4 820	0·04	$0\cdot 40 B^{3\cdot 1}$	0·009
X. 3446	20	6 520	0·07	$0\cdot 32 B^{3\cdot 0}$	—
X. 3446 (corrected)	20	6 520	0·105	$0\cdot 21 B^{3\cdot 0}$	0·009

Table 2A shows the variation of after-effect resistance R_{ae} in different samples, at 20 cycles per sec. and 1 mA, and shows the relationship between R_{ae} and μ_0.

TABLE 2A.

Specimen number	$R_h + R_{ae}$ from coefficient of f (Table 1)	$R_h = 5\cdot 1 \times 10^{-6}\mu_0$ (Table 2)	R_{ae} by difference	R_{ae} from Table 2	$0\cdot 065 \times 10^{-12}\mu_0^{3\cdot 2}$
X. 3577	0·02	0·014	0·006	0·007	0·007
P. 1282	0·026	0·016	0·010	0·010	0·010
X. 3605	0·036	0·018	0·018	—	0·016
X. 2989	0·046	0·021	0·025	0·02	0·026
P. 1321	0·050	0·022	0·028	—	0·027
P. 1903s.	0·070	0·025	0·045	0·04	0·040
X. 3446 (corrected)	—	0·033	—	0·105	0·105

TABLE 3.

Pressure	Temperature	G
tons per sq. in.	° F.	
0	36	$0\cdot 0054 f^{1\cdot 32}$
0·95	36	$0\cdot 0078 f^{1\cdot 28}$
2·1	36	$0\cdot 014 f^{1\cdot 21}$
3·0	36	$0\cdot 016 f^{1\cdot 20}$

The standard test at 1 mA and 20 cycles per sec. on all coils of core for the Bamfield–Fanning II (1926) cable gave the mean inductance as 118·3 mH, including the geometric, or natural, inductance of 0·7 mH. The corresponding permeability is 3 700. Hence the mean added resistance, from the data above, should be as follows:—

$$R_h = 5\cdot 1 \times 10^{-6}\mu_0 = 0\cdot 02 \text{ ohm}$$
$$R_{ae} = 0\cdot 065 \times 10^{-12}\mu_0^{3\cdot 2} = 0\cdot 02 \text{ ohm}$$
$$R_{ec} = 12\cdot 0 \times \mu^2 f^2 10^{-6} = 0\cdot 065 \text{ ohm}$$
$$\text{Total } R_{ad} = 0\cdot 002 f + 165 f^2 10^{-6} = 0\cdot 105 \text{ ohm}$$

The standard test gave the mean R_{ad} as 0·107 ohm at 65° F. The mean d.c. resistance of the cable at 75° F. was 1·967 ohms.

Variation of Leakance and Capacity with Frequency, Temperature and Pressure.—The following preliminary operations are necessary in testing:—

(i) The specimen is put under a pressure of 2 or 3 tons per sq. in. for a short time before zero pressure measurements are taken. As previously noted, this has the effect of smoothing out any irregular distribution of the compound—a condition which appears to result in increased leakance. If the precaution is omitted, the variation with pressure may not be consistent, and original zero pressure readings cannot be repeated. Although pressure normally increases the leakance, the application of the first step to an unprepared specimen may result in a slight drop, owing to the reduction resulting from even compound distribution being greater than the increase due to pressure.

(ii) The leakance of the standard condenser must be determined for all the test frequencies. The value of this condenser is usually 0·015 μF or more, owing to the length of cable necessary to obtain sufficient sensitivity, and for part of this a mica condenser of 0·010 μF has been used. The power factor of the 0·010 μF mica, plus that of the air condensers to make up 0·015 μF, has been found to increase largely with reduction in frequency. The combination used had a power factor

TABLE 3A.

Pressure	Temperature	G
tons per sq. in.	° F.	
0	75	$0\cdot 00077 f^{1\cdot 4}$
0	55	$0\cdot 0011 f^{1\cdot 5}$
0	36	$0\cdot 0061 f^{1\cdot 32}$
3·0	75	$0\cdot 00093 f^{1\cdot 5}$
3·0	55	$0\cdot 0065 f^{1\cdot 3}$
3·0	36	$0\cdot 025 f^{1\cdot 1}$

of 0·0004 at 1 000, of 0·0006 at 66, and of 0·0011 at 20 cycles per sec., the corresponding leakances being 0·03, 0·003, and 0·0017 μmho. As these corrections change with temperature and humidity, they must be frequently checked, and their application is essential if consistent results are to be obtained.

Variation of leakance and capacity of a typical specimen with pressure is shown in Fig. 18. The value of the leakance-frequency variation is shown in Fig. 19, from which the laws given in Table 3 are deduced.

Further tests on a specimen of different dimensions are given in Figs. 20 and 21, which include variation due to temperature. The results are set out in Table 3A.

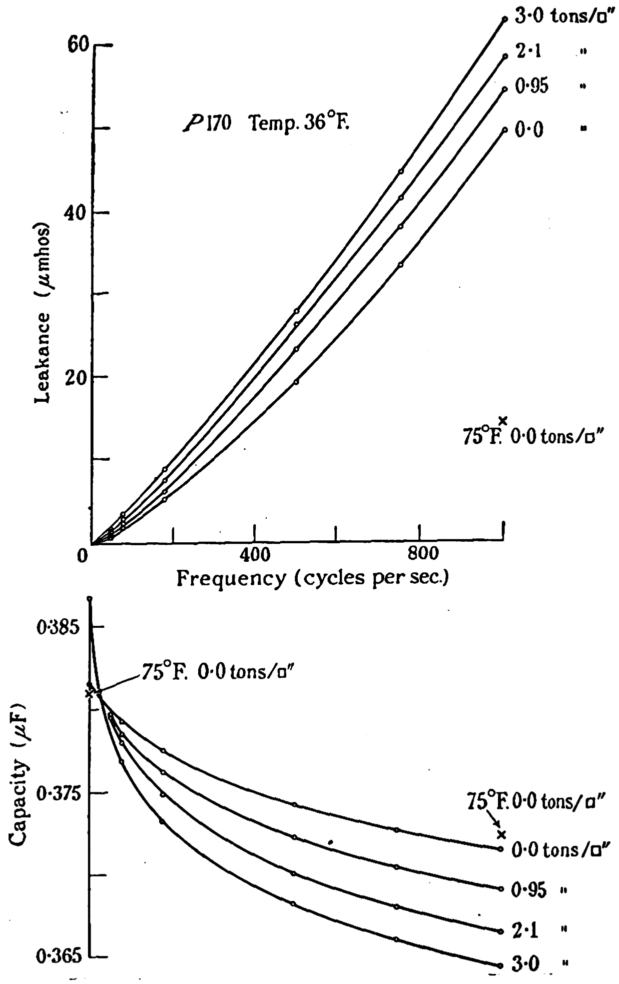

FIG. 18.

From extended tests it has been found that the changes shown in these tables are permanent, i.e. there is no tendency to recover with time while the test conditions of temperature and pressure are maintained.

It will be seen that the effects of increasing pressure and of reducing temperature are similar, i.e. leakance, and the rate of increase of capacity with the reduction of frequency, are increased.

In general, the tests follow Schweidler's * theory, except that the exponent of frequency is greater than unity.

No variation of leakance or capacity with voltage up to 60 volts has been found.

The standard test at 1 000 cycles per sec., 75° F. and atmospheric pressure gave the mean leakance of the cable as 14·4 μmho and the mean capacity as 0·382 μF.

The mean d.c. capacity was 0·393 μF at 75° F. and atmospheric pressure.

Leakance and capacity at 36° F. and 3 tons per sq. in. may thus be taken from Fig. 18, making allowance for the capacity of the specimen (P. 170) being 3 per cent lower than the mean under the same conditions of temperature and pressure.

(*g*) *Prediction of Attenuation and Head-End Loss from Factory Tests.*—It is convenient to divide the attenuation of a loaded cable into two parts: (i) attenuation for currents at which resistance and inductance may be considered invariable, and (ii) extra attenuation, termed "head-end loss," due to increase of resistance (chiefly hysteresis) and inductance with currents up to the normal sending value of about 100 mA. In order to estimate both these parts, assumptions must be made with regard to the influence on the constants of mechanical handling during laying. This will not appreciably affect leakance or capacity, but will reduce the permeability of the strain-sensitive loading material and consequently affect inductance and resistance. A reduction in initial permeability of 15 per cent will be assumed, this figure being indicated by strain tests in the factory. Added resistance will be correspondingly reduced by the laws determined in the last section of this paper, but an increase of eddy-current resistance must be allowed for,

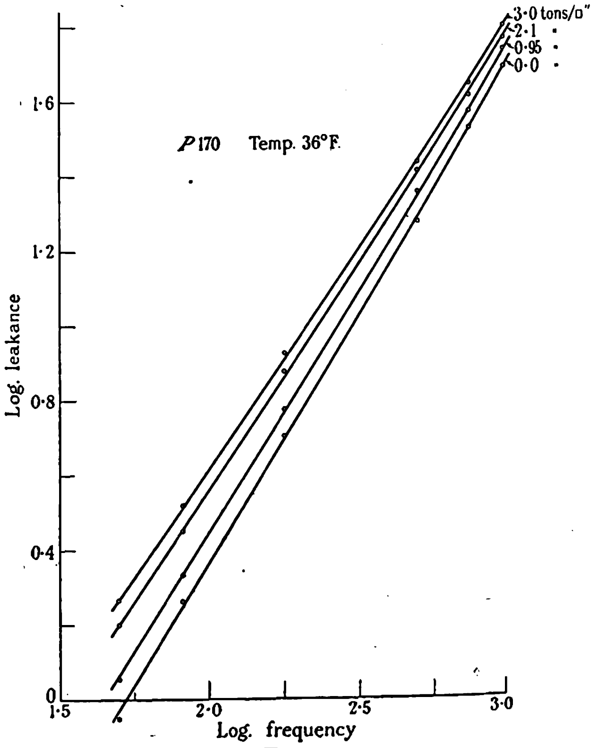

FIG. 19.

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* SCHWEIDLER: *Annalen der Physik*, 1907, vol. 24, p. 742; also L. HARTSHORN: *Journal I.E.E.*, 1926, vol. 64, p. 1152.

owing to a decrease in the specific resistance of the loaded material with temperature.

For mumetal No. 6 the temperature coefficient is 0·0008 per deg. F., giving an increase in R_{ec} from 65° F. to 36° F. (estimated sea-bottom temperature) of 2·5 per cent. At the latter temperature the d.c. resistance may be expected (from the mean at 75° F.) to be 1·80 ohms. It is now necessary to allow for additional resistance and inductance due to the fact that the return circuit consists of a concentric ring of armouring and sea-water outside the insulator of the cable. The values shown in Fig. 22, calculated from formulæ deduced from tests on an unloaded cable,* are provisionally used. The average sea-bottom pressure is estimated from chart soundings as 3 tons per sq. in., using the relation 1 000 fathoms depth = 1·19 tons per sq. in. pressure. The estimate of primary constants for currents near zero is given in Table 4.

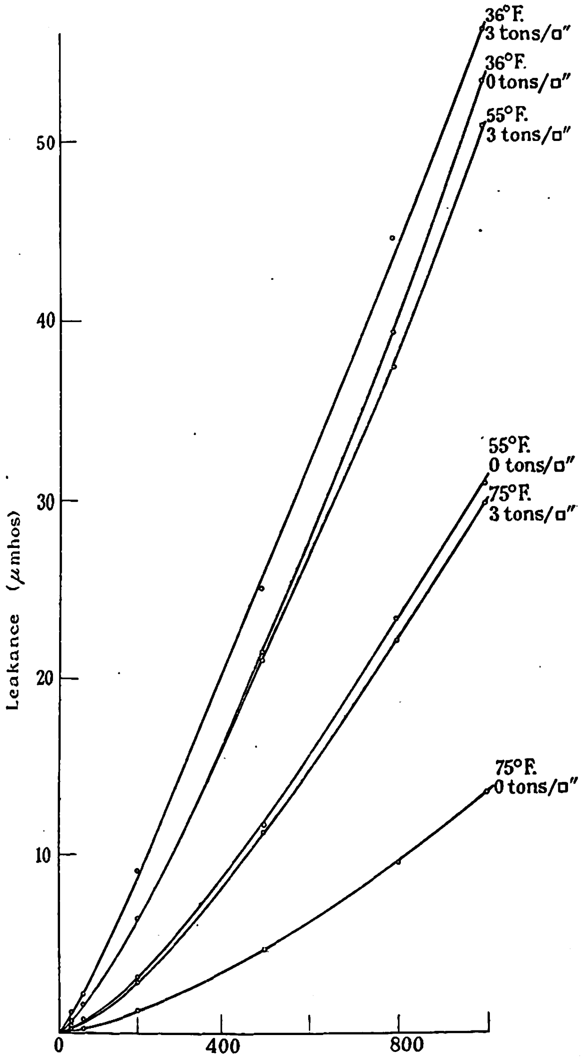

FIG. 20.

Head-end loss is calculated from tests determining variation of inductance and effective resistance with current. In certain magnetic alloys of relatively low initial permeability (about 1 000) these variations can be expressed as definite functions of current, and the transmission formulæ modified accordingly. Thus Salinger * has assumed variations of the form

$$L = L_0\epsilon^{kI}, \quad \text{and} \quad R = R_0\epsilon^{\frac{1}{2}kI},$$

while Meyer † has taken the linear variation,

$$L = L_0(1 + \lambda I) \quad \text{and} \quad R = R_0 + rI,$$

and in both cases formulæ have been derived for the calculation of head-end loss.

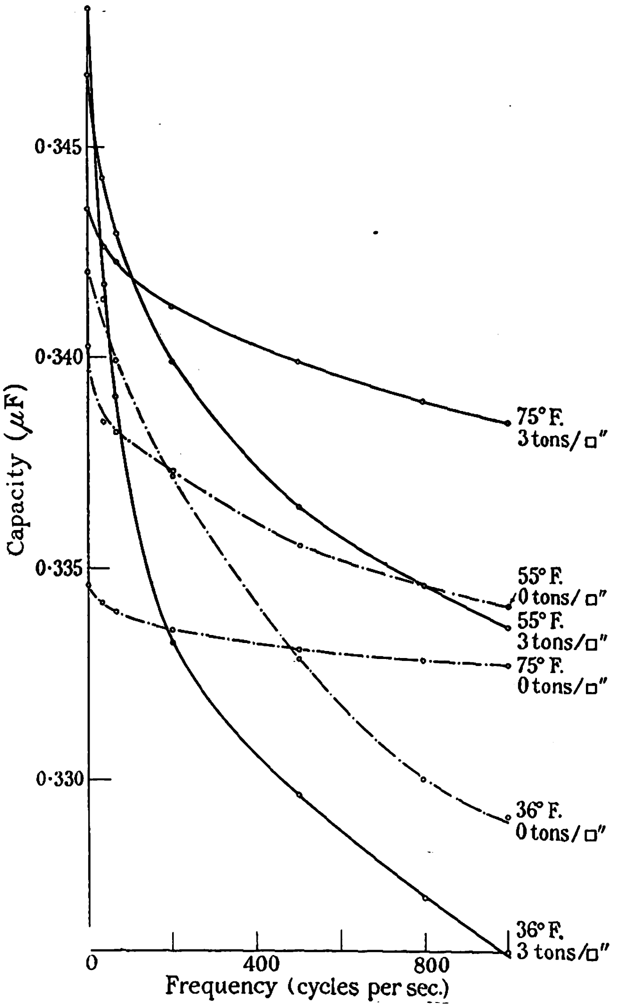

FIG. 21.

In the case of the higher-permeability alloys used for loading telegraph cables, however, no simple consistent relations exist between current, inductance and resistance, and the estimate has to be made by summing the attenuations of cable sections of such length that the current in them may be considered constant—the current in the next section being determined by the attenuation of the section so considered. In a previous description of this method ‡ the calculation has been commenced at an assumed sending current of 100 mA and carried down in steps to a current of 1 mA, below which value "zero attenuation" (i.e. attenuation at zero current) has been used. The author considers it better to start with the lowest current and to work upwards, as this enables the variation of head-end loss with current to be predicted. Further, a current below 1 mA should be worked to, as "zero attenuation" in most cases differs materially from attenuation at 1 mA. Preferably the calculation should start at 0·2 mA. The basis of the calculations are the current tests shown in Figs. 14 and 15.

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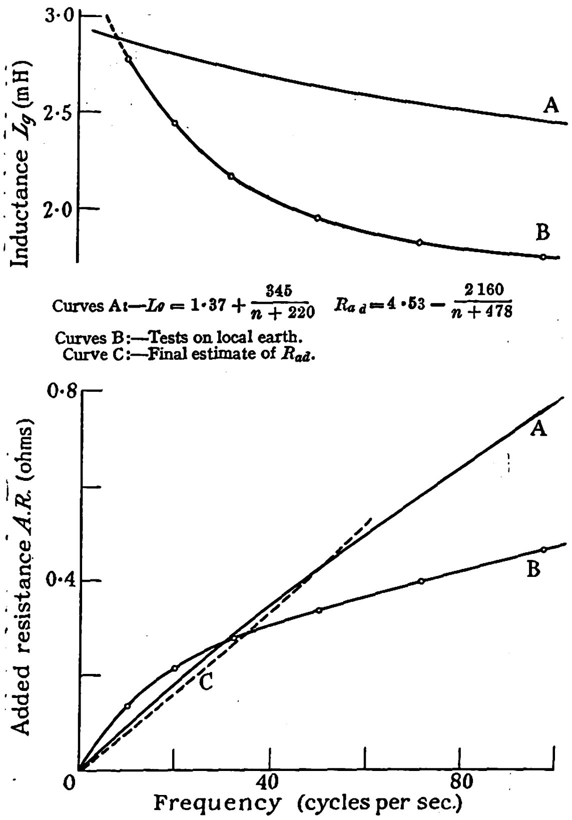
* F. E. PERNOT: *Journal of the Franklin Institute*, 1920 vol. 190 p. 323.

* H. SALINGER: *Archiv für Elektrotechnik*, 1923, vol. 12, p. 268.
† U. MEYER: *Elektrische Nachrichten-Technik*, 1926, vol. 3, p. 33.
‡ R. L. HUGHES: *Journal I.E.E.*, 1928, vol. 66, p. 155.



Curves A:—$L_0 = 1\cdot37 + \frac{345}{n+220}$ $R_{ad} = 4\cdot53 - \frac{2\,160}{n+478}$

Curves B:—Tests on local earth.
Curve C:—Final estimate of R_{ad}.

FIG. 22.

After the application of suitable corrections to allow for sea-bottom conditions, these test values were used to obtain curves of the *increase* (due to the preponderating effect of hysteresis loss) of attenuation with current. The excess attenuation, due to current in excess of 0·2 mA, was calculated for the head-end of the cable, section by section. Results obtained are shown in Fig. 23. As it was considered that the inductance of the head-end of the cable when laid would approximate to that of specimen X. 3577, a head-end loss at 20 cycles per sec. of about 0·6 could be anticipated for a sine-wave current of R.M.S. value 100 mA.

(4) TESTS ON CABLE AFTER LAYING.

(*a*) *General.*—Before a.c. testing is detailed it is necessary to note (i) the final laid length of the cable and earth lines, and the distribution of inductance, (ii) tests of resistance by direct current, and (iii) the equipment used in obtaining a.c. power.

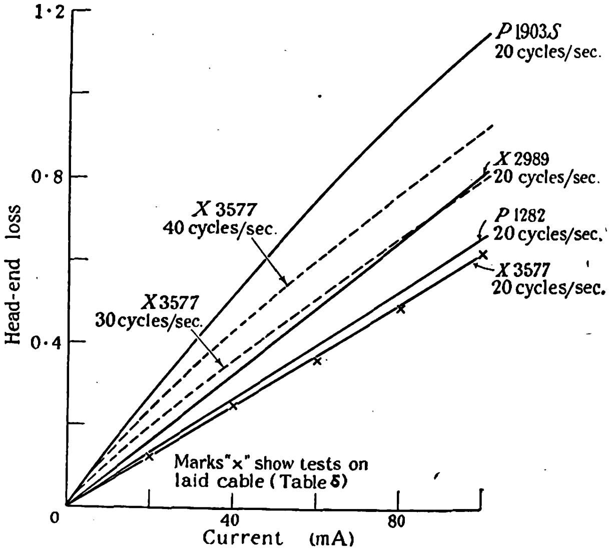


FIG. 23.

(i) The laid length of the Bamfield–Fanning II (1926) cable was 3 467 nautical miles. The Bamfield shore end consisted of 3 cores enclosed within the same sheathing,

TABLE 4.

Frequency	Resistance *				Inductance			Leakance $0\cdot016f^{1\cdot2}$	Capacity	Attenuation constant $\alpha_0 \times 10^3$
	R_{ae}	R_{ec}	Sea return	Total	Added by loading	Sea return	Total			
cycles/sec.	ohms	ohms	ohms	ohms	mH	mH	mH	μmho	μF	
5	0·00	0·005	0·05	1·855	100·0	2·9	102·9	0·11	0·385	1·76
12·5	0·01	0·02	0·12	1·95	100·0	2·8	102·8	0·33	0·383	1·94
20	0·015	0·05	0·18	2·045	100·0	2·8	102·8	0·58	0·382	2·11
30	0·02	0·11	0·27	2·20	100·0	2·8	102·8	0·94	0·3805	2·36
40	0·03	0·19	0·35	2·37	99·9	2·7	102·6	1·34	0·3795	2·63
50	0·045	0·30	0·43	2·575	99·9	2·7	102·6	1·74	0·379	2·94

* D.C. resistance = 1·80 ohms.

viz. the main (loaded) core; the sea-earth (loaded) core, terminated at a distance of 53·0 nautical miles by a resistance of 470 ohms; and the local-earth (unloaded) core, terminated at 3·92 nautical miles by direct connection to the sheathing. The inductance of the main core was graduated, as evenly as possible from the factory tests, in sections of approximately 250 nautical miles, the mean inductance of sections rising from 95 mH at the shore ends to 144 mH in the centre. The inductance of the sea-earth core was matched as nearly as possible with that of the main core running with it. The conductor weight of the unloaded local-earth core was 700 lb. per nautica mile, while that of the other two cores, as already noted, was 608 lb.

(ii) The d.c. resistance of cable and sea earths was measured by the "false zero" method, ordinary laboratory methods being inapplicable owing to interference from earth currents. Cable and earth are connected to an ordinary Wheatstone bridge, and the deflection of the galvanometer is noted with a resistance equal to that of the battery substituted for the battery itself. This is the "false zero," and when the battery is replaced the standard resistance is adjusted till this deflection is obtained. The initial condition is then restored in order to check possible variation of earth currents during the test, which must be repeated if the "false zero" has changed. If a time is chosen when earth currents are constant the test can be repeated without variation of result and an accuracy of 0·2 or 0·3 per cent is obtainable.

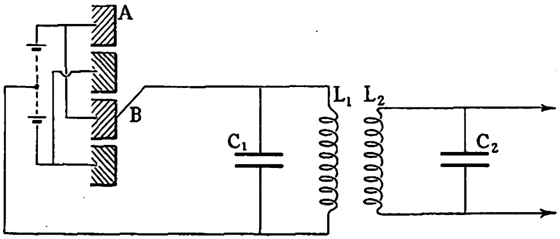


FIG. 24.

The results of the test were as follows:—

Main cable, 6 204 ohms = 1·789 ohms per nautical mile.
Resistance-terminated sea-earth, 569·5 ohms.
Local earth, 6·25 ohms = 1·59 ohms per nautical mile.

(iii) The equipment used in obtaining a.c. power consisted of a d.c.–a.c. motor-alternator, the speed of the alternator being controlled by shunt and series regulators on the d.c. motor and a variable gear-ratio between the two machines. The frequency was determined by a speed indicator on the alternator shaft. This was used for transmitting in attenuation measurements, and for impedance testing with currents up to the normal sending value of 100 mA. For impedance testing at 1 mA, and for the small voltage required for calibration in attenuation measurements (to be described later) a supply of sine-wave current was obtained by filtering reversals of direct current. Alternate segments of a 10-segment commutator, part of which is indicated at A in Fig. 24, were connected through slip-rings to the positive and negative poles of a battery. Connections from the centre of the battery and the brush B were taken to a condenser C_1 and inductance L_1 in parallel. A second inductance L_2 with parallel condenser C_2 was loosely coupled to L_1. Both inductances were flat "ironless" coils of inductance 1 henry, having resistances of about 30 ohms. With the condensers set for resonance at the frequency of the reversals, a small output of very nearly sinusoidal wave-form was obtained from the coupled circuit L_2C_2, with a battery of 8 or 10 volts. As the commutator was directly geared to a phonic motor driven by a vibrating tuning-fork, a constant and accurate frequency was obtained, this feature being the chief advantage of the arrangement. With the particular fork and motor available the commutator could be run at speeds giving frequencies up to 100 cycles per sec. For frequencies above this the filter was tuned to the third harmonic of the reversal, condenser C_1 being placed in series with primary coil L_1 instead of in parallel. With the low battery voltage used sparking at the commutator was not excessive, and the wave-form remained practically sinusoidal as long as the load was substantially non-inductive and of resistance not less than about 500 ohms.

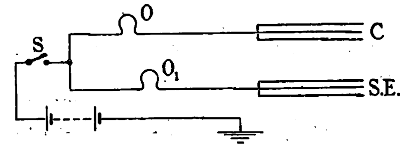


FIG. 25.

(b) *Measurement of Impedance.*—A series of impedance tests on a laid cable is of use—other than for the obvious purpose of applying Ohm's law to sending voltage and current—in indicating the inductance near the sending end (capacity being assumed), the position and extent of irregularities in the loading, and the degree to which the resistance-terminated sea-earth balances the cable for the object described on page 449.

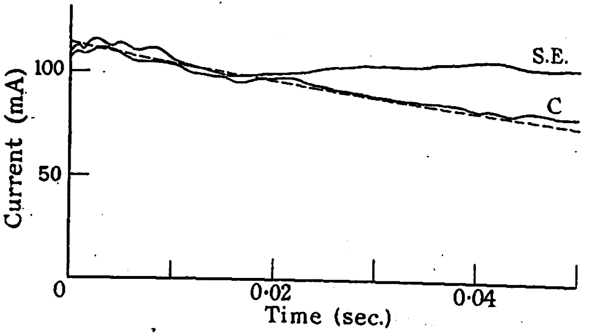


FIG. 26.

Before impedance determination by bridge methods is described, a more general and less direct test will be dealt with, i.e. the recording of current entering cable and sea earth. For this purpose the circuit shown in Fig. 25 was used, current from a battery being applied by the closing of switch S to cable C and sea earth SE simultaneously, through separate vibrators of an oscillograph, O and O_1. The vibrators recorded on the same paper, starting from the same zero line, the paper being time-marked by the control of a beam of light by a vibrating tuning-fork. Results obtained are shown, referred to the current and time calibrations of the apparatus, in Fig. 26, which is about 0·7 times the size of the original record. The far end of the cable was earthed for the test, and the applied voltage was 60·0 volts.

The oscillograph vibrators were of resistance 5 ohms, so that the sending impedance was small compared with the cable impedance.

It will be seen that the currents entering cable and sea earth (and hence their impedances) begin to deviate appreciably after about 0·02 sec., but it may be said that the resistance-terminated sea earth simulates the cable, for the purpose required, closely for disturbances of frequency above 50, and approximately for frequencies down to about 20 cycles per sec.

The currents in the cable and sea earth ultimately approach the steady values $V_s/6\,204 = 9\cdot7$ mA and $V_s/569\cdot5 = 105$ mA respectively. Deviations from smoothness are due to irregularities in loading.

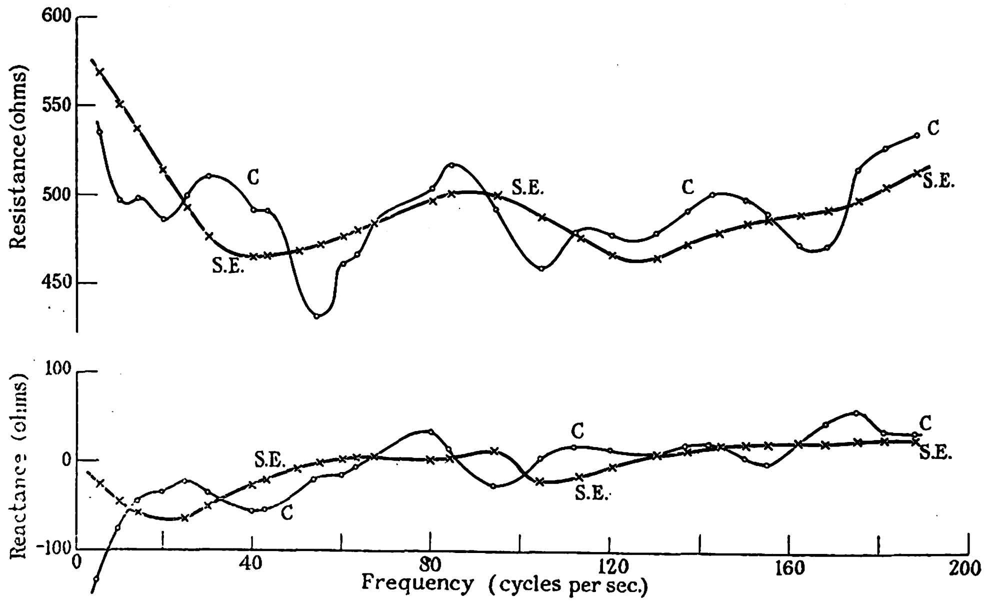


FIG. 28.

The current in the cable is theoretically *

$$I_s = E\sqrt{\left(\frac{C}{L}\right)}\epsilon^{-at}I_0(at)$$

$$= E\sqrt{\left(\frac{C}{L}\right)}\left[1 - at + \frac{1.3}{(2!)^2}(at)^2 - \frac{1.3.5}{(3!)^2}(at)^3 + \dots\right]$$

where $a = R/2L$ and $I_0(at)$ is the " zero-th "o rder non-oscillating Bessel function.

Values of capacity are taken from factory tests already given, including variation with frequency, as shown in Table 5.

If an inductance of 100 mH is assumed, the dotted curve in Fig. 26 is obtained from the above formula, taking R as the measured value 1·79 ohms. The close agreement between this and the experimental record indicates that the effective inductance to a direct current of 110 mA at the end of the cable is 100 mH.

For bridge measurements of characteristic impedance the arrangement shown in Fig. 27 was used.

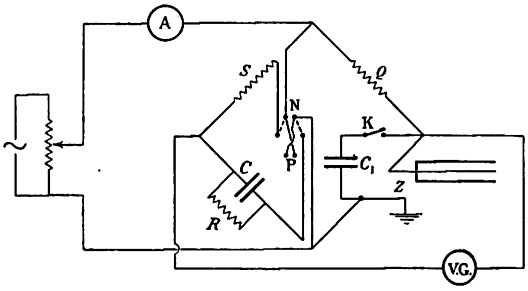


FIG. 27.

With the change-over switch in the position N (as shown dotted) the arrangement is a Wien bridge for use when the angle of Z is negative, in which case $1/Z = (1/R) + j\omega C$, with $Q = S$. With the switch in position P—Maxwell bridge *—balance may be obtained when Z has a positive angle, the equation being $Z = SQ\{(1/R) + j\omega C\}$. Although the angle of the

TABLE 5.

T	Capacity C
sec.	μF
0	0·364
0·005	0·373
0·01	0·376
0·02	0·379
0·03	0·380
0·04	0·381
0·05	0·382

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* H. W. MALCOLM: *loc. cit.*, p. 298.

* J. MAXWELL: *loc. cit.*, p. 425.

characteristic impedance of the cable is theoretically negative at all frequencies, it actually may become positive owing to reflections consequent on irregularities of loading. As an alternative to using the Maxwell bridge in such cases a condenser, capacity C_1, may be paralleled with the cable by closing the key K, and balance may be obtained with the Wien arrangement. This obviates a change in the operation of working out results (an appreciable advantage if many tests are taken), but the current to line is no longer one-half the total current recorded by the meter A. The difference, however, does not exceed 0·5 per cent in any case here recorded, and the standard method has been the Wien bridge (change-over switch in position N) for both negative and positive angles.

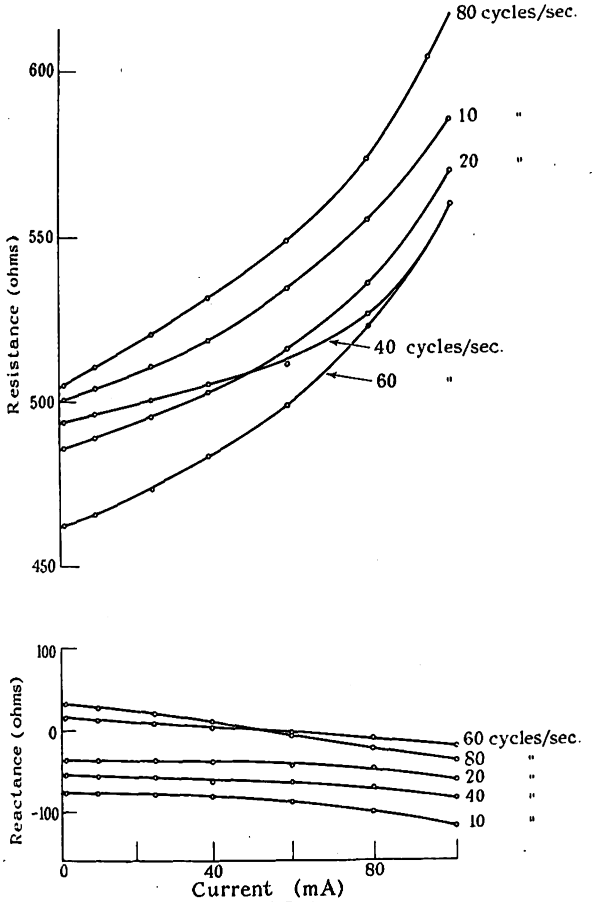

FIG. 29.

The variation of impedance (Z_0, ϕ) of cable and sea earth with frequency at 1 mA is shown in Fig. 28, in which results are expressed in terms of resistance ($Z_0 \cos \phi$) and reactance ($Z_0 \sin \phi$).

The impedance of the cable varies about a mean value of approximately 490 ohms, and if an average capacity of 0·38 μF is assumed the inductance, derived from the relation $\sqrt{(L/C)} = 490$, is 91 mH total, or about 89 mH added by the loading. The irregular shape of the curve is the result of the superposition of several regular variations, each due to one particular reflection, and the position of these reflections may be obtained by dividing the velocity of propagation by twice the frequency interval between successive maxima.* Thus in the "cable" curve of resistance, primary maxima occur at 30, 85 and 144 cycles per sec., or at average intervals of 57 cycles per sec. Secondary maxima appear at intervals of approximately 30 cycles per sec., starting at 14. The average velocity of propagation near the end ($L = 91$, $C = 0 \cdot 38$) being 5 400 nautical miles per sec., the main reflection is located at a distance of 47 nautical miles and a secondary reflection at about 90 nautical miles from the end.

The "sea earth" curve indicates a variation of periodicity about 85 cycles per sec.—i.e. an irregularity 32 nautical miles from the end. The length of the earth line to the terminating resistance was 53 nautical miles, and disturbance from this point would result in successive maxima at intervals of about 51 cycles. The absence of these is further evidence of the closeness of simulation of the cable impedance by the terminating resistance.

Variation of impedance of cable with current is shown in Fig. 29, similar curves being obtained for the sea earth. The fact that the slopes of the curves are irregular with respect to frequency shows that the location of irregularities changes with current and that they are therefore due to inductance, and not to capacity. The average impedance at 100 mA is 580 ohms, giving an inductance of 127 mH total, or 125 mH added. The average slope thus compares fairly well with that of the inductance of X. 3577 tested in the factory (Fig. 15).

The impedance of the local earth was measured by the Anderson bridge † as shown in Fig. 30.

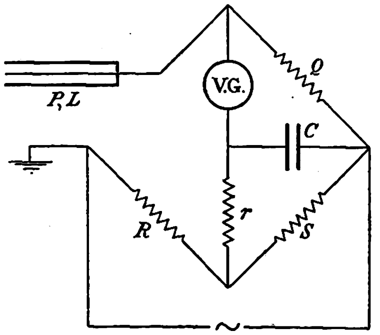

FIG. 30.

This core being unloaded and of relatively short length, the impedance gave resistance (P) and inductance (L) direct from the bridge equations $P = QR/S$, and $L = CQ[r(1 + R/S) + R]$.

Results are shown in Fig. 22, the d.c. resistance of the core having been subtracted. The sheathing up to the end of the local earth was composed, for the most part, of 23 No. 1 iron wires, while that of the main cable was chiefly 20 No. 14 steel wires. Differences in permeability, specific resistance and thickness of sheathing may be expected to have considerable influence on the resistance and inductance of the return path, and the results are

* WEINBACH: "Principles of Transmission in Telephony," ch. 16 (New York, 1924).

† E. B. ROSA and F. W. GROVER: *Bulletin of the Bureau of Standards*, 1905, vol. 1, p. 291.

therefore not applicable to the main cable, as will be shown experimentally in Section (4) (*e*).

(*c*) *Measurement of Attenuation and Head-End Loss.*—The attenuation of a long submarine cable is determined for any frequency by measuring the received current or voltage when a periodic e.m.f. of the required frequency and of known voltage is applied at the sending end. The applied e.m.f. need not be sinusoidal as long as the value of the fundamental is known, as, owing to the increase of attenuation with frequency, only the fundamental arrives (practically speaking) at the receiving end, the harmonics having been attenuated to negligible magnitude in transmission.

It is desirable to test attenuation with sending voltages down to 2 or 3 volts, and as the ratio of received to sent voltage (or current) of a cable with a total attenuation of 9, when terminated by its characteristic impedance, Z_0, is about 1/10 000, the quantities to be measured are very small. Three methods of test will be described.

(i) The Sumpner dynamometer is of sufficient sensitivity, and may be used as shown in Fig. 31. With the change-over switch on T (test) as shown, current from the cable passes through condenser C' in series with the moving coil, M, of the instrument. In parallel with this combination is the resistance R. R and C' are preferably adjusted so that the receiving impedance is equal to the characteristic impedance, Z_0, of the cable, i.e. $(1/R) + j\omega C' = 1/Z_0$, the impedance of the moving coil being small enough to be omitted from the calculation. The field coils, F, are excited from a local a.c. source of frequency differing from that transmitted through the cable by about 1 cycle per minute. The moving coil thus deflects periodically on either side of zero in 1-minute beats, a time of about this length being necessary in order that deflections shall not be affected by the damping of the moving coil. A series of extreme deflections, which occur when the currents in M and F are in phase or 180° out of phase, is noted, and the switch is then moved to C (calibrate). Steady deflections of required values can then be obtained by varying r, reversal of direction being obtained by reversal of the moving-coil connections.

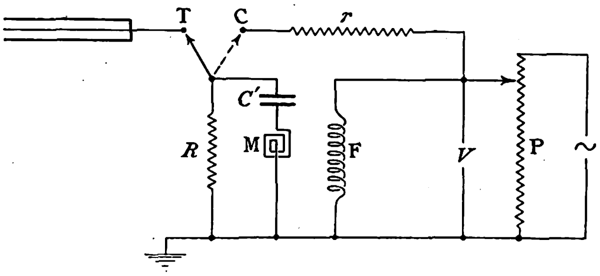

FIG. 31.

Let the impedance of the field coils F be $A\underline{/90^\circ - \theta}$, and that of the moving coil M and condenser C′ be $B\overline{\backslash 90^\circ - \theta_1}$. The currents in F and M are then out of phase, for the same applied voltage, by $180^\circ - (\theta + \theta_1)$. The steady deflections to be obtained are therefore the extreme deflections of the beat corrected for this deficiency $(\theta + \theta_1)$, i.e. multiplied by $\cos(\theta + \theta_1)$. This correction is small but not always negligible. In a particular instrument used the impedance of F at 40 cycles per sec. was $13{\cdot}4\underline{/83^\circ\,8'}$ ohms. The resistance of M was 40 ohms, and the impedance of moving coil and condenser was $3\,980\overline{\backslash 89^\circ\,25'}$ ohms, the capacity of the latter being 1 μF. The correcting factor was thus $\cos(6^\circ\,52' + 0^\circ\,35') = 0{\cdot}99$.

The potentiometer P regulates the sensitivity of the apparatus by controlling the voltage, V, across the field coils, which is also (conveniently) the calibrating voltage. The resistance r must be high compared with the impedances of V, P, and F.

The total impedance of the calibrating circuit is $r + Z_0\overline{\backslash\phi} = (r + Z_0)\overline{\backslash\text{zero}}$, nearly. The voltage across the series combination C′ and M is thus $(VZ_0\overline{\backslash\phi}/(r + Z_0)$, and the component of this voltage in phase with V is $(VZ_0 \cos\phi)/(r + Z_0)$ or $(VR\cos^2\phi)/(r + Z_0)$. This is equal to the voltage drop Vr across Z_0 due to the current from the cable, and the attenuation is determined from the relation:—

$$Vr = \frac{V_s}{\cosh Pl + (Z_0/Z_r)\sinh Pl} = \frac{2V_s\epsilon^{-Pl}}{1 + (Z_0/Z_r)} = V_s\epsilon^{-Pl}$$

for a long cable when $Z_r = Z_0$.

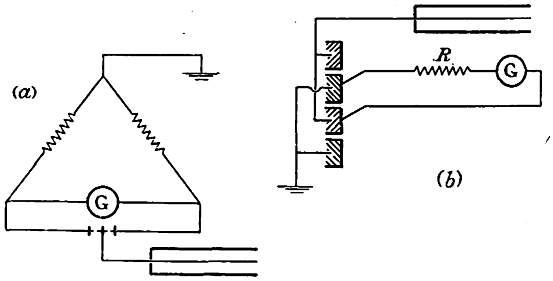

FIG. 32.

(ii) *Measurement by Rectification.*—A method has been described * in which the incoming sinusoidal current is rectified by means of a synchronously running relay, and measured on a d.c. galvanometer. The circuit diagram is given in Fig. 32 (*a*).

The author uses a modification of this arrangement in which, in place of a relay, a 10-segment commutator having 2 brushes spaced an odd number of segments apart is used [Fig. 32 (*b*)]. With this is used a single receiving circuit, consisting of resistance, R, in series with d.c. galvanometer, G, instead of the bridge necessary in the other case. The commutator is run at nearly the same reversal-speed as the frequency of the incoming current so that maximum deflections occur periodically, as in the case of the Sumpner dynamometer test. The galvanometer indicates the average value of the half sine-waves, i.e. the value $(1/\pi)\int_0^\pi \sin x\,dx = 2/\pi$, and the ratio of this to the R.M.S. value is $2\sqrt{2}/\pi = 0{\cdot}90$.

If I_r is the galvanometer current, then for a long cable

$$I_r = \frac{V_r}{Z_r} = \frac{2V_s\epsilon^{-Pl}}{Z_r + Z_0},$$

and

$$\epsilon^{Pl} = \frac{2V_s \times 0{\cdot}90}{I_r(Z_r + Z_0)} = \frac{1{\cdot}80\,V_s}{I_r(Z_r + Z_0)}$$

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* E. S. HEURTLEY: *loc. cit.*

This test has the great advantage of utilizing the high sensitivity obtainable with d.c. reflecting galvanometers. The resistance R should be made high so that the impedance of the galvanometer may be taken as its d.c. resistance without the introduction of appreciable error.

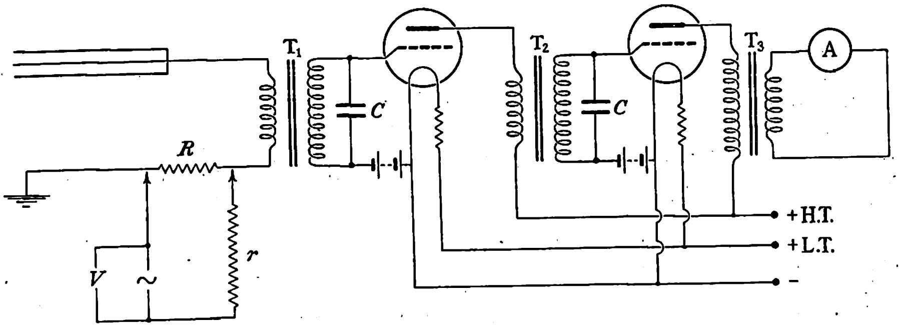

FIG. 33.

For the higher voltages at low frequencies the received current is frequently large enough to give sufficiently accurate readings on a direct-reading microammeter. This method is not subject to disturbance from earth currents, which are commutated into ineffective reversals.

(iii) *Measurement by Substitution and Amplification.*—In both the methods just described, the requirement that the period of the deflection shall be not less than about 1 minute makes each test comparatively long, as several complete swings must be observed and the necessarily close frequency adjustment takes some time. In addition, method (i) suffers from the disadvantage that corrections must be applied and the result is not given in simple terms of the variables employed, and method (ii) tends to give high results at the higher frequencies owing to imperfect commutation. The characteristic impedance of the cable must be known in both cases.

In the third method results are quickly obtained and worked out, and the impedance of the cable need not be known. The circuit is shown in Fig. 33.

Current from the cable passes to earth through the primary of a transformer T_1 and a variable resistance R, and is amplified by a 2-stage transformer-coupled amplifier as shown, the output being applied through a step-down transformer T_3 to a thermal milliammeter A. A local calibrating circuit consisting of a low-voltage a.c. supply with a thermal voltmeter and series high resistance r adjustable up to 10 000 ohms, can be switched across resistance R. The secondaries of transformers T_1 and T_2 are tuned by condensers C. The test procedure is as follows:—

The distant station transmits continuously and the ratios of the transformers are adjusted so that a convenient deflection is obtained on A. The secondaries of T_1 and T_2 are tuned by adjusting the condensers for maximum output. The local supply is then switched across R and the beat of the two frequencies is observed by the periodic change of the deflection of A. If this shows that the frequencies are in sufficiently close agreement (within 0·2 per cent) a prearranged series of voltages is applied to the far end, each voltage for three 1-minute periods with 1-minute intervals between. During the transmission periods the deflection on A is noted with the local circuit off, and when the distant station is not sending the local circuit is switched on, and R is adjusted until the same deflection is obtained. Thus for each voltage 3 tests and 3 calibrations are taken, the cable being left in circuit the whole time.

It is convenient to work with a calibrating voltage of about 1·5 volts, as the thermal voltmeter is then readily checked by a single primary cell standardized by a d.c. voltmeter.

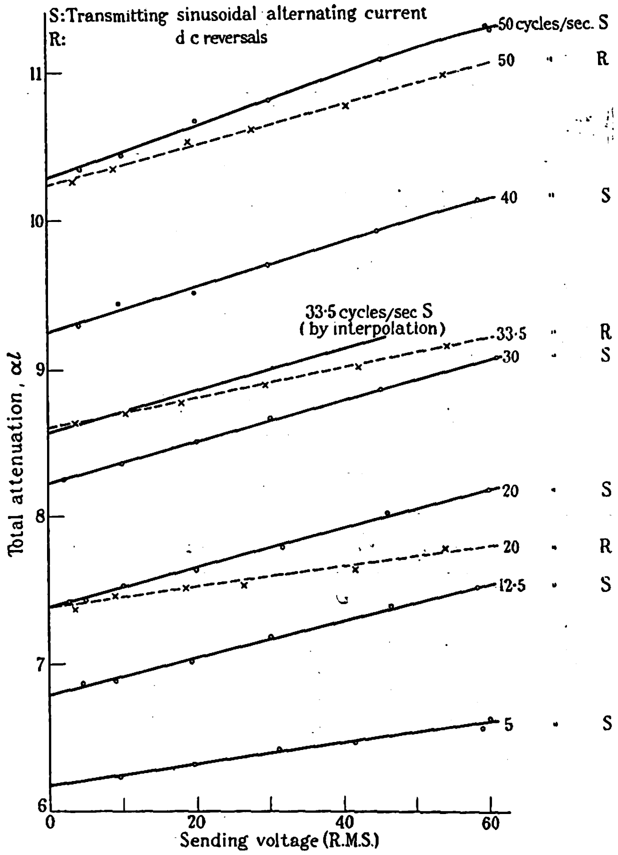

FIG. 34.

If I_r is the current in the primary of T_1 resulting in the deflections for test and calibration thus adjusted to equality, and if the impedance of the receiving circuit is Z_r, for test, $I_r = (2V_s\epsilon^{-Pl})/(Z_r + Z_0)$, for a long cable, and for calibration, $I_r = \{VR/(r + R)\}\{1/(Z_r + Z_0)\}$.

Hence $VR/(r+R) = 2V_s\epsilon^{-Pl}$ = received voltage for open-circuited receiving end. In practice the value of r is conveniently between 3 000 and 10 000 ohms, while that of R varies up to about 300 ohms.

The voltage V must of course be read with the calibrating circuit on. It is adjusted by changing the coupling of the coils L_1 and L_2 in Fig. 24. An advantage of the method is that interference from earth currents is minimized by the double tuning of the circuit, and is the same for both test and calibration.

The results of attenuation tests, which were all taken by this method, are shown in Fig. 34, tests at 20 cycles per sec. being verified by method (ii). The extrapolation of the curves to zero voltage, and division by the length, give the initial attenuation constant, a_0. The variation with frequency of a_0, and head-end loss for $V_s = 60$ volts, are given in Fig. 36.

The results obtained are, from the equations above, voltage attenuations, and the relation between voltage and current head-end loss must here be noted.

Let the former be written h_1 and the latter h_2.

If the effective impedance of the cable with sending voltage V_s is Z_e, then the attenuation of current is given by

$$I_r = I_s\epsilon^{-(a_0l+h_2)} = \frac{V_s}{Z_e}\epsilon^{-(a_0l+h_2)},$$

where a_0 = attenuation constant for currents near zero.

Also, attenuation of voltage is

$$V_r = V_s\epsilon^{-(a_0l+h_1)}, \quad \text{whence} \quad I_r = \frac{V_s}{Z_0}\epsilon^{-(a_0l+h_1)}$$

where Z_0 is the initial value of Z_e.

$$\text{Thus} \quad \frac{\epsilon^{-h_1}}{Z_0} = \frac{\epsilon^{-h_2}}{Z_e}, \quad \text{and} \quad h_2 = h_1 - \frac{\log(Z_e/Z_0)}{\log\epsilon}$$

In Table 6 the voltage head-end loss at 20 cycles per sec. from Fig. 34 is converted into current head-end loss by the use of the 20-cycle per sec. impedance-current test ($Z_0 = 487$). Variation of h_2 with I_s is plotted with the factory estimates in Fig. 23.

TABLE 6.

I_s	Z_e	$V_s(=I_sZ_e)$	h_1	h_2
mA				
20	494	9·9	0·14	0·12
40	504	20·2	0·28	0·25
60	517	31·0	0·42	0·36
80	537	42·9	0·59	0·49
100	572	57·2	0·78	0·62

Attenuation tests were also taken with d.c. reversals transmitted by the commutator at 20, 35·5 and 50 cycles per sec. In Fig. 34 the attenuations are plotted against the R.M.S. voltage of the fundamental frequency, i.e. d.c. voltage × 0·90. Comparison of these with results for sine-wave transmission shows that attenuations for zero voltage agree within 0·5 per cent. Head-end losses are lower, as shown in Table 7, the reduction being attributed to the suppression of part of the hysteresis loss of the fundamental by the harmonics of the reversals —this effect decreasing as frequency increases and length of line over which harmonics are effective decreases.

TABLE 7.

Frequency	Head-end loss (60 volts R.M.S.)		
	Sinusoidal (S)	Reversals (R)	Ratio R/S
cycles/sec.			
20	0·82	0·44	0·54
33·5	0·865	0·64	0·74
50	1·02	0·85	0·83

(*d*) *Measurement of Propagation Time.*—The wavelength constant of the loaded cable, from equation (13), reduces to

$$\beta = \left[\left\{\tfrac{1}{2}R\sqrt{(C/L)} - \tfrac{1}{2}G\sqrt{(L/C)}\right\}^2 + \omega^2CL\right]^{\frac{1}{2}}$$

on the same assumptions that lead to the short formula for a [equation (18)].

In the present case, from Table 4, at 30 cycles per sec.,

$$\left\{\tfrac{1}{2}R\sqrt{(C/L)} - \tfrac{1}{2}G\sqrt{(L/C)}\right\}^2 = 3\cdot6 \times 10^{-6},$$

while $\omega^2CL = 1\cdot35 \times 10^{-3}$.

Hence, at 30 cycles per sec., $\beta = \omega\sqrt{(CL)}$ to within 0·2 per cent, and the time of propagation $T = \beta l/\omega = l\sqrt{(CL)}$ practically.

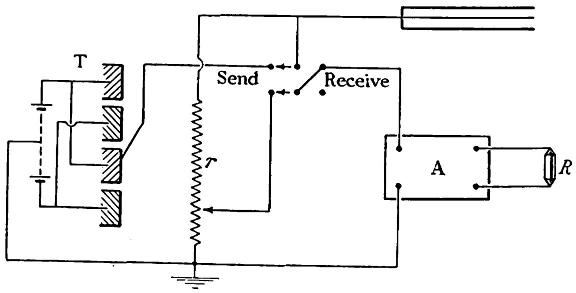

FIG. 35.

The method of measurement is to transmit a signal from station A to station B, and as soon as possible a reply from B to A. Then if at A the time between sending the signal and receiving the answer is t_1, and at B the time between receiving and answering is t_2, $T = \frac{1}{2}(t_1 - t_2)$. Circuits for recording both signals and the timing impulses to enable t_1 and t_2 to be evaluated, have been given by Gilbert * and Salinger.†

In the latter case, sent impulses operate a recorder connected directly between cable and earth, but received signals pass through a condenser mesh and an amplifier before being recorded. A correction must therefore be applied to allow for the resultant phase displacement of these signals. The former arrangement eliminates this error, both sent and received signals being recorded *after* amplification. The amplifier is sensibly distortionless, and records the sent signals (square-topped reversals through a condenser) as distorted reversals, thus—

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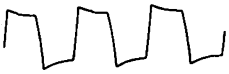
* J. J. GILBERT: *Electrician*, 1927, vol. 99, p. 249.

† H. SALINGER: *Elektrische Nachrichten-Technik*, 1928, vol. 5, p. 130.



The necessity of measuring to zero phase of the fundamental, which occurs somewhat earlier than zero phase of these signals, is pointed out.

The author uses the circuit shown in Fig. 35. T and A are the commutator and the 2-stage (tuned) transformer-coupled amplifier previously referred to in connection with attenuation measurements. R is a recorder, and *r* a resistance of about 10 000 ohms. The transmitter T runs continuously, and while the double-pole change-over switch is on "send," reversals are transmitted to line and are applied to the amplifier by a tapping across a small part of *r*. Owing to the tuned couplings of the amplifier the record is of sinusoidal form, and the zero phase time-difference between the distorted reversals and the fundamental is thus corrected for. After a few reversals (conveniently 10) have been transmitted, the switch is moved to "receive," when the answering signal is amplified and recorded, having received the same phase displacement in the amplifier as effected the record of the sent signal. The timing impulse is taken from a contact on the tuning-fork driving the transmitter motor, and is preferably marked by a separate recorder alongside the sent and received impulses. It is checked up with the impulse at the other end of the cable by observing beats between the two sources as in attenuation testing, and must be accurate to a few parts in 10 000. The number of reversals transmitted is controlled by a rotary make-and-break contact driven by the transmitter motor through reduction gearing at such a speed as to close the battery circuit of the transmitter, for the time of 10 reversals, at conveniently short intervals of about 2 seconds. The send-receive switch, operated by hand, is put to "send" only for a sufficient time to allow 1 complete operation of the contact to send the 10 reversals to line. The time-intervals at both stations are counted from the same point in the train of reversals, this being generally the start of the 8th reversal. Specimen records are shown in Fig. 37.

The propagation time of the Bamfield–Fanning II cable was found to be 0·67 sec. at 30 cycles per sec., no difference being found (within the experimental error of 0·005 sec.) with voltages of 15, 30 and 60 volts.

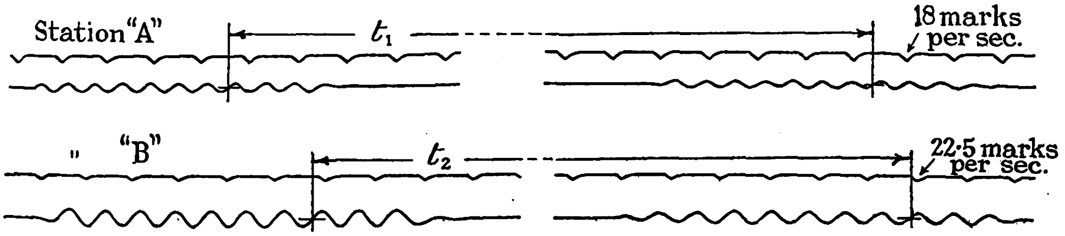


FIG. 37.

(*e*) *Method of Determining Constants.*—From the attenuation tests taken on the laid cable, recorded in Section (4) (*c*), the values per nautical mile at zero voltage obtained (Fig. 36) are as set out in Table 8, col. 2.

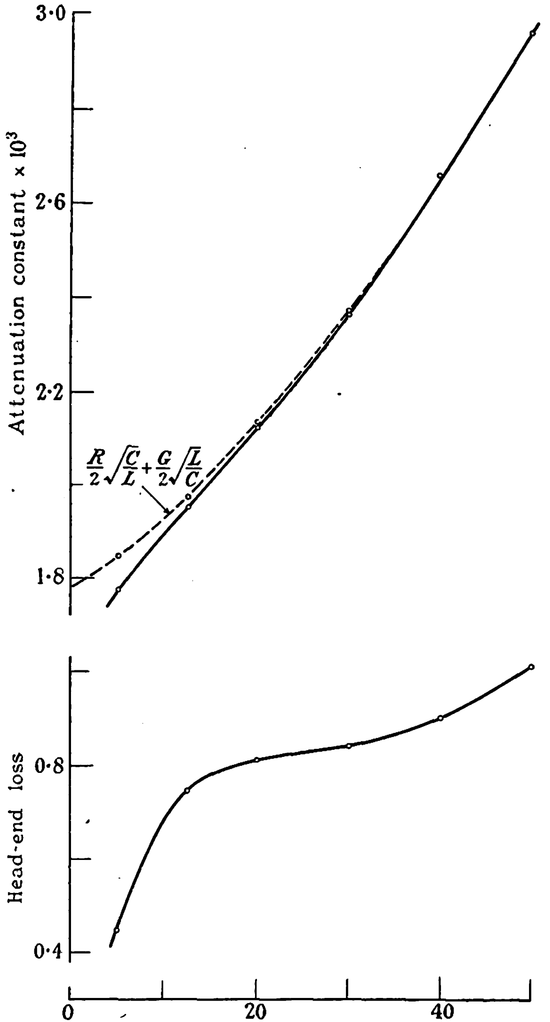


FIG. 36.

Numerical values of the primary constants *R*, *L*, *G* and *C*, are required which will give these attenuations and be consistent with the propagation time at 30 cycles per sec.—viz. 0·67 sec. The method of determining these is as follows:—

A series of values of the expression

$$\tfrac{1}{2}R\sqrt{(C/L)} + \tfrac{1}{2}G\sqrt{(L/C)} = a_1$$

is found from the estimated constants in Table 4. The difference between these and the attenuation, calculated by equation (13), decreases as frequency increases (and ωL and ωC become greater in comparison with R and G) as shown in Table 8, col. 3.

TABLE 8.

Frequency	$a_0 \times 10^3$	$(a_1 - a_0) \times 10^3$
cycles/sec.		
5	1·78	0·07
12·5	1·96	0·02
20	2·13	0·01
30	2·375	0·005
40	2·67	0·00
50	2·97	0·00

For a series of constants near those in Table 4 these differences will be the same. Therefore, if they are added to the attenuations found by test and the curve extrapolated to zero frequency, a value for

$$\tfrac{1}{2}R\sqrt{(C/L)} + \tfrac{1}{2}G\sqrt{(L/C)}$$

at zero frequency may be found. In the present case this is $1{\cdot}78 \times 10^{-3}$ (Fig. 36).

But, for this condition, R = d.c. resistance = 1·79 ohms, and $\tfrac{1}{2}G\sqrt{(L/C)}$ = zero, so that, at zero frequency, $\sqrt{(C/L)} = 1{\cdot}99 \times 10^{-3}$. Now from the propagation time test, $\sqrt{(CL)} = 1{\cdot}93 \times 10^{-3}$ at 30 cycles per sec., or, applying a correction for variation of capacity with frequency from Fig. 18, at zero frequency

$$\sqrt{(CL)} = 1{\cdot}95 \times 10^{-3}.$$

From these values of $\sqrt{(C/L)}$ and $\sqrt{(CL)}$, $L = 98{\cdot}0$ mH, and $C = 0{\cdot}388$ μF. Table 4 may now be amended as shown in Table 9 to give a second approximation of the constants of the laid cable.

The differences between the resultant attenuations and the results of tests may be reduced by altering original assumptions of either added resistance or leakance, but the change will be made in the sea-return resistance as there is less experimental data on this factor than on the others. The use of the trial curve C (Fig. 22) results in the final estimate given in Table 10.

TABLE 9.

Frequency	Total resistance *	Total inductance	Leakance	Capacity	Resultant attenuation $a_0 \times 10^3$	(Test value—calculated value of attenuation) $\times 10^3$
cycles/sec.	ohms	mH	μmho	μF		
5	1·845	98·0	0·11	0·386	1·79	− 0·01
12·5	1·94	98·0	0·33	0·384	1·98	− 0·02
20	2·03	98·0	0·58	0·383	2·145	− 0·15
30	2·19	98·0	0·94	0·3815	2·395	− 0·02
40	2·36	97·9	1·34	0·3805	2·67	± 0·00
50	2·565	97·9	1·74	0·380	2·98	− 0·01

* D.C. resistance = 1·79 ohms.

TABLE 10.

Frequency	Resistance †				Inductance			Leakance $0{\cdot}016f^{1{\cdot}2}$	Capacity	Resultant attenuation $a_0 \times 10^3$	Test attenuation $a_0 \times 10^3$	Difference (col. 12—col. 11) $\times 10^3$
	R_{ae}	R_{ec}	Sea return	Total	Total	Sea return	Added by loading					
1	2	3	4	5	6	7	8	9	10	11	12	13
cycles/sec.	ohms	ohms	ohms	ohms	mH	mH	mH	μmho	μF			
5	0·00	0·005	0·04	1·835	98·0	2·9	95·1	0·11	0·386	1·78	1·78	0·00
12·5	0·01	0·02	0·10	1·92	98·0	2·8	95·2	0·33	0·384	1·965	1·96	−0·005
20	0·015	0·05	0·16	2·015	98·0	2·8	95·2	0·58	0·383	2·13	2·13	0·00
30	0·02	0·11	0·25	2·17	98·0	2·8	95·2	0·94	0·3815	2·375	2·375	0·00
40	0·03	0·19	0·34	2·35	97·9	2·7	95·2	1·34	0·3805	2·655	2·67	+0·015
50	0·045	0·30	0·43	2·565	97·9	2·7	95·2	1·74	0·380	2·97	2·97	0·00

† D.C. resistance = 1·79 ohms.

The constants of the laid cable thus compare with factory tests and estimates as follows:—

Resistance.—Measurements and estimates of d.c. resistance are summarized as follows:—

(i) Original estimate, from actual weight of conductor, with 1 per cent allowance for composite (taped) structure, 1·96 ohms at 75° F.

(ii) Realized from factory tests, 1·967 ohms at 75° F.

(iii) Estimate for laid cable from (ii), using coefficient 0·00238 per deg. F., 1·80 ohms at 36° F.

(iv) Realized from tests on laid cable, 1·79 ohms.

The difference between (iii) and (iv) is not likely to be due to an inaccurate estimate of sea-bottom temperature, as the cable follows the route of the Bamfield–Fanning (1902) unloaded line, for which the temperature is given by soundings and by final resistance tests as 36° F. It is probably connected with the allowance referred to in (i). This assumes partial contact between tapes and centre wire, which was probably not realized to the degree anticipated, owing to the penetration of the liquid compound beneath the tapes. This would account for the difference between (i) and (ii). It is probable, however, that the contact improved under pressure at sea-bottom. Hence (iv) is consistent with (i) rather than with (ii). This effect has also been noticed with other loaded cables.

With regard to added resistance, it has already been shown that no alteration in the estimates made from factory tests was necessary, as discrepancies could be eliminated by a small change in the assumed values of sea-return resistance.

Inductance.—The mean inductance added by the loading fell from 117·6 mH demagnetized (factory) to 95·2 mH (laid), a decrease of 19 per cent. Table 9 shows curve B (Fig. 22) for sea-return inductance to be inapplicable, as it would result in inductance due to loading increasing substantially with frequency.

Leakance.—No alteration in factory estimates was required.

Capacity.—Practically no alteration required. Tests on the laid cable do not necessarily check the assumed variation of capacity with frequency, but there is no reason to suppose any departure from the factory tests, as specimens were kept under observation for possible change with age over the period of time between factory and final tests.

(5) ARRIVAL CURVES.

For an ideal heavily-loaded cable having constants invariable with frequency and current, and with negligible leakance, no current arrives at the receiving end until a time $T = \sqrt{(CL)}l$ after the commencement of the transmitted impulse. The signal head then rises abruptly to the value

$$I_r = 2E\sqrt{(C/L)}\epsilon^{-(R/2)\sqrt{(C/L)}}$$

(in the case where the terminating impedance is zero); after which the received current increases with time until the sent impulse is discontinued or the limiting value $I_r = E/Rl$ is reached.

In the practical case the dependence of the constants on frequency and current prevents the initial abrupt rise from being realized. Records of arrival curves are of use in estimating whether the deviation of the signal head from a vertical straight line is due to head-end loss (i.e. to variations of the constants with current) or to the change in the characteristics of the cable with frequency. Further, the possibility of constructing message signals from a given arrival curve, and the effect of the impedance of the end apparatus, may be tested.

Arrival curves for an ideal cable for the case where the sending impedance is zero, and the receiving impedance a non-reactive resistance r, were calculated, using the following constants:—

$$R = 1{\cdot}79 \text{ ohms} \qquad = 3\,467 \text{ nautical miles}$$
$$L = 98{\cdot}0 \text{ mH} \qquad \sqrt{(L/C)} = 505 \text{ ohms}$$
$$C = 0{\cdot}384\ \mu\text{F} \qquad \sqrt{(CL)}l = 0{\cdot}67 \text{ sec.}$$

For $G = 0$, and a steady sending voltage E, the sum of the original and first reflected waves is given by Heaviside * as

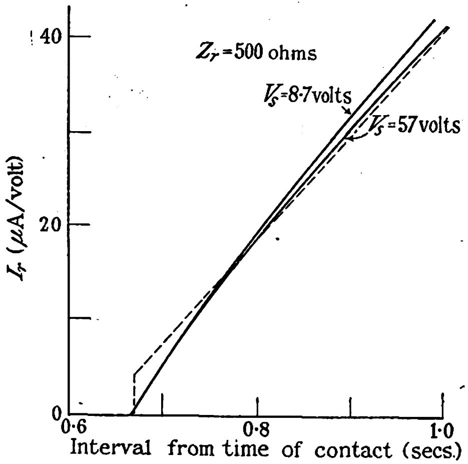


FIG. 38.

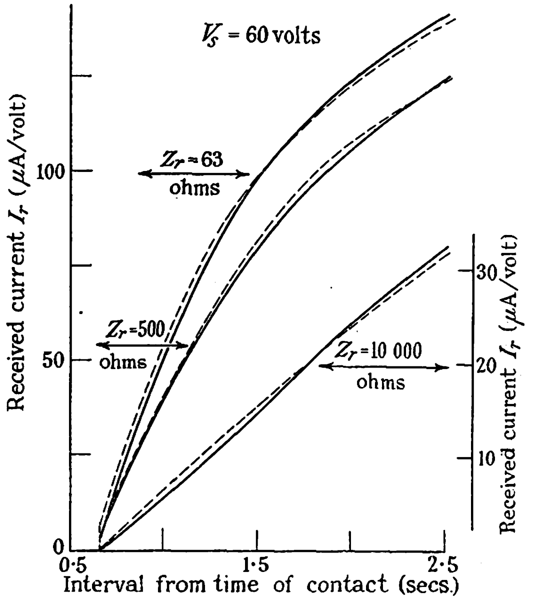


FIG. 39.

$$I_r = E\sqrt{(C/L)}\epsilon^{-at}\Big[(1 + c)I_0(z) + (1 - c^2)\Big\{(w/z)I_1(z) - (cw^2/z^2)I_2(z) + \dots\Big\}\Big]$$

where

$$a = R/2L, \quad c = \Big\{\sqrt{(L/C)} - r\Big\}/\Big\{\sqrt{(L/C)} + r\Big\}$$
$$w = a\Big\{t - \sqrt{(CL)}l\Big\}, \quad z = a(t^2 - CLl^2)^{\frac{1}{2}}$$

and $I_m(z)$ is the mth order non-oscillating Bessel function.

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* O. HEAVISIDE: "Electromagnetic Theory," vol. 2, p. 389 (1899).

In special cases the following simplifications occur:—

If $r = 0$, $c = 1$

$$I_r = 2E\sqrt{(C/L)}\epsilon^{-at}I_0(z)$$

If $r = \sqrt{(L/C)}$, $c = 0$

$$I_r = E\sqrt{(C/L)}\epsilon^{-at}\left[I_0(z) + (w/z)I_1(z)\right]$$

If r is large, c approaches -1.

Writing $k = 1 + \sqrt{(L/C)}/r$

$$I_r = (E\epsilon^{-at}/r)\Big[(2/k)I_0(z) + (4/k^2)\Big\{w/zI_1(z) - (cw^2/z^2)I_2(z) + \dots\Big\}\Big]$$

As the propagation time $\sqrt{(CL)}l$ is 0·67 sec., these expressions should be exact to $t = 2\cdot01$ secs. when the second reflected wave arrives at the receiving end. As a check, the arrival curve for $r = 0$ was also evaluated from the formula *

$$I_r = \frac{E}{Rl}\left[1 - \epsilon^{-2at} + 4\epsilon^{at}\sum_{m=1}^{m=\infty}\frac{\cos m\pi \sinh at\sqrt{\left(1 - \frac{4m^2\pi^2L}{CR^2l^2}\right)}}{\sqrt{\left(1 - \frac{4m^2\pi^2L}{CR^2l^2}\right)}}\right]$$

The calculated curves for $r = 63$, 505, and 10 000 ohms are shown by the dotted lines in Figs. 38 and 39.

The experimental curves in these diagrams were obtained by means of an oscillograph, the received signal being first amplified by a substantially distortionless thermionic amplifier. The cable was earthed through a non-inductive resistance of the required value, r, and the voltage across an adjustable part of this was applied to the amplifier. Calibration was afterwards performed by applying known voltages across r (with cable disconnected) and observing the resultant deflections of the oscillograph vibrator.

The chief experimental difficulty was interference from earth currents, which, being of similar nature to the currents to be recorded, could not be eliminated.

The inflection of the curve for $r = 10\ 000$ megohms (Fig. 39) is attributed to this cause.

In general, the test curves follow the theoretical ones after the first 0·1 sec. In the most important region (the first 0·05 sec.) there is marked deviation. As shown in Fig. 38, no difference was found in the initial shape for sending voltages of 57 and 8·7 volts. That is, the influence of head-end loss (which in the first case was 6 times as great as in the second) on the shape of the head of the signal was not discernible. The shape of the signal head must, therefore, be attributed to the variation of attenuation with frequency.

Records were also taken of the signal " understand " (marking 50 per cent) without sending apparatus [Fig. 40 (A)], and with a sending condenser of 5 μF [Fig. 40 (B)]. The dotted line in the first case is the signal built up from the arrival curve in Fig. 38. It consists of the algebraic sum of a number of these arrival curves, all continued to the end of the signal, a new one commencing with each change of sent impulse, and corresponding in sign to the direction of the change.

Thus on the original positive curve are superimposed, at corresponding time-intervals, positive curves representing impulses c, e, h, and j [Fig. 40 (C)], and negative curves representing impulses b, d, f, g and k.

The similarity of the original and the built-up curve indicates the possibility of predicting the shape of a signal from the arrival curve by the method used.

The starting time of all arrival curves is taken as 0·67 sec. from the result of the propagation-time test.

(6) TRANSMISSION CAPACITY OF THE CABLE.

The transmission of signals was tested over a range of speeds from 1 600 to 6 000 centre-holes, or elements, per minute. At the sending end a suitable shaping mesh * was interposed between the transmitter and the cable. At the receiving end the cable was earthed through a shunted condenser in series with a resistance, variable up to 1 000 ohms. The voltage-drop across the resistance was applied to the input circuit of a thermionic amplifier, the output circuit of which actuated a high-speed siphon recorder.

Test messages were sent by means of punched tape in an automatic transmitter driven by a phonic motor, and the shaping meshes were adjusted by trial for optimum shape, and uniformity in size, of signals.

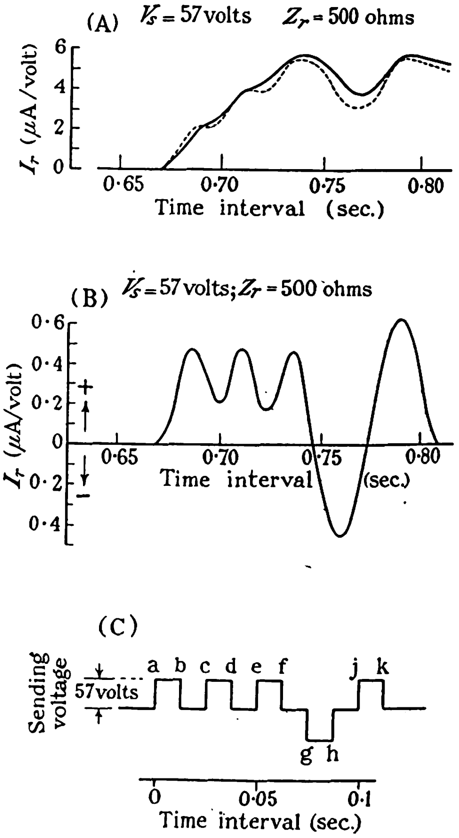

FIG. 40.

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* O. HEAVISIDE: *loc. cit.*, p. 381; and H. W. MALCOLM: *loc. cit.*, pp. 498 and 512.

* E. S. HEURTLEY: *loc. cit.*

For the purpose of verifying the assumption made in Section (2) (*c*) with regard to permissible attenuation for satisfactory working, three tests will be considered, the results of which are shown in Fig. 41.

The records are of signals (the letters of the alphabet) received at speeds of (*a*) 4 000, (*b*) 4 800 and (*c*) 5 200 centre-holes per minute. The sending voltage was 60 volts, and block signalling (in which successive impulses in the same direction are run together and there is no earthing interval) was used in all cases.

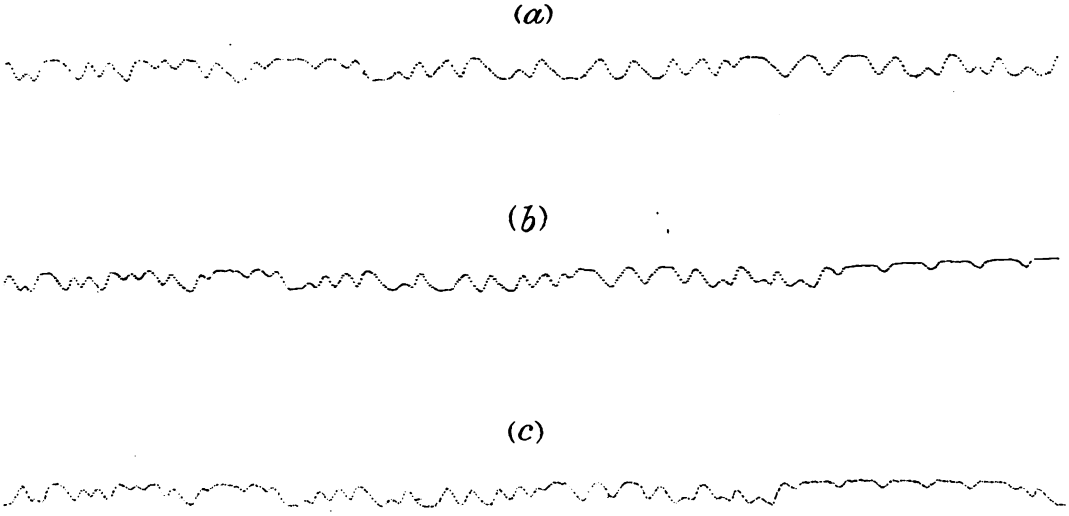

FIG. 41.

The overall attenuations of the cable for the fundamental reversal frequencies corresponding to the transmission speeds are computed as shown in Table 11.

TABLE 11.

Record	Speed	Reversal frequency	Corresponding attenuation		
			$a_0 l$ from Fig. 36	Head-end loss	Total
	centre-holes/min.				
(*a*)	4 000	33·5	8·60	0·64	9·24
(*b*)	4 800	40·0	9·25	0·72	9·97
(*c*)	5 200	43·5	9·60	0·77	10·37

The head-end loss was taken (by interpolation) from Table 7 for reversals at 60 volts.

By inspection of Fig. 41, conditions sufficiently favourable for recorder working with code messages are indicated by (*b*), and those suitable for the transmission of plain language by (*c*). That is, for recorder working, an attenuation of 10 is allowable and the attenuation of 9·3 implied in the guarantee (page 450) is amply safe.

Record (*a*) shows signals suitable for relay operation, for which the assumed criterion (attenuation = 9) is justified.

The author understands that relay working at 4 000 centre-holes per minute was successfully carried out at the far end of the cable at Fanning Island.

(7) CONCLUSIONS.

The chief processes of this investigation may be summarized as follows:—

(i) Theoretical and practical considerations show the transmission speed of a loaded telegraph cable to be limited by its attenuation, and hence allow its performance to be determined in terms of its alternating-current characteristics.

(ii) An inquiry into the nature of the required tests, and the different conditions under which they must be performed, is made. Test methods are examined and the precautions necessary for consistent results are stated. From test data obtained during the process of manufacture, the effective characteristics of the laid cable are predicted.

(iii) These characteristics are then determined by attenuation and propagation-time tests, and small discrepancies between them and the predictions are accounted for. The results of impedance tests, and records of departure and arrival curves, are shown to be consistent with these determinations.

(iv) Finally, the procedure is justified by the realization of a transmission speed in accordance with the criteria adopted.

It has been shown that the limiting reversal frequency is that for which the total attenuation is 9, or 10, according to the method of working. The attenuation has been treated as the sum of two parts, (i) the value for currents near zero, and (ii) extra attenuation at the head end due to the increase of losses in the loading with current. It has been shown that both these factors may be closely estimated from factory tests, and the importance of the tests discussed in Section (3) (*f*), and their generalization for use in designing other cables, is thus apparent.

The least certain of the predictions made is that of the inductance of the laid cable. It is difficult in the factory to simulate, even approximately, the mechanical stresses to which the cable is subjected in the process of laying, and, owing to variable influences such as weather conditions and depth of sea-bottom, the stresses in no two cases are exactly alike. It may be stated, however, that the drop of inductance due to mechanical handling will be between 10 and 20 per cent, and that an average estimate of 15 per cent will not be greatly in error. It has been shown that a considerable range of values of the effective permeability of the loading material is obtainable, and in any particular case the optimum for the laid cable must be calculated and the required factory value thus obtained.

The great importance of resistance measurements is shown in these calculations, for which the added resistance must be known in terms of frequency, current and initial permeability. If attenuations are then calculated for several assumed (increasing) values of initial permeability, it will be found that an optimum attenuation is reached, above which the increase of added resistance preponderates adversely over the increase of initial permeability.

Thus added resistance controls the performance of a loaded cable by limiting the inductance which may be usefully employed.

The influence of leakance on attenuation, expressed by the factor of $\frac{1}{2}G\sqrt{(L/C)}$, is similar to that of added resistance, but to a smaller degree. If, however, future improvements enable substantial reduction of added resistance to be obtained, leakance may become the predominating limiting factor unless produced *pro rata*.

With the dielectric at present used, changes in capacity with frequency, temperature, pressure and age are relatively small and affect the final attenuation in a minor degree only. If, however, the variations which do occur are established, the capacity of the laid cable may be predicted with considerable accuracy and a sound basis for the estimates of the other constants may thus be obtained.

In the design of cables a factor of safety must necessarily be introduced, but by the use of accumulated test data such as have been incorporated herein a close approximation to predicted results should be realized.

The author wishes to express his thanks to the management of the Telegraph Construction and Maintenance Co., Ltd., for permission to make use of the matter incorporated in this paper.

A METHOD OF MEASURING THE OVERALL PERFORMANCE OF RADIO RECEIVERS.

By H. A. Thomas, M.Sc., Associate Member.

[From the National Physical Laboratory: communicated by permission of the Radio Research Board.]

(*Paper first received* 20*th June*, 1929, *and in final form* 13*th March*, 1930; *read before the* Wireless Section 15*th January*, 1930.)

Summary.

The paper describes researches which have been carried out at the National Physical Laboratory for the Radio Research Board. An improved method of measuring the amplification of a radio receiver is described, together with the manner in which this method can be applied to practical cases, particularly at short wavelengths. The apparatus covers a wavelength range of from 15 to 30 000 metres, and is capable of dealing with inputs of from 0·25 to 1 000 mV over this range. After describing in detail the construction and operation of the apparatus in Section (1), the results of tests on four receivers of widely different types are given in Section (2), and some general deductions are obtained from the properties of these receivers. In conclusion, suggestions are made in Section (3) for a possible means of classifying receivers for different purposes.

Table of Contents.

Section (1).—Method of measurement.
- (*a*) Introduction.
- (*b*) The construction of the screened cabin for the oscillator.
- (*c*) The construction of the screened input resistance.
- (*d*) The input oscillator.
- (*e*) The measurement of the output voltage.
- (*f*) The complete circuit arrangements.

Section (2).—Examples of measurements upon various types of receivers.
- (*a*) Introduction.
- (*b*) A 4-valve receiver (200–16 000 m).
- (*c*) A commercial short-wave receiver (15–60 m).
- (*d*) A screened short-wave receiver (15–80 m).
- (*e*) A supersonic-heterodyne receiver with frame aerial (50–500 m).

Section (3).—Suggestions for specifying the performance of receivers.

Section (1).—Method of Measurement.

(*a*) *Introduction.*—The aim of all measurements of the constituent parts of a radio receiver is ultimately to obtain a characteristic relationship between the input supplied to the receiver and the output voltage given by the receiver, together with an analysis of the behaviour of the individual portions of the apparatus. Such a measurement is the most important of all those that can be obtained, and at the same time is the most difficult. The difficulty lies in the fact that the output quantities are in general very large compared with the input quantities, so that the slightest form of accidental coupling between the input and the output circuits introduced by the measuring apparatus may completely modify the behaviour of the receiver. Another difficulty lies in the fact that the input and output frequencies are dissimilar.

Most of the early attempts to obtain the overall characteristics of a receiver were based on an assumption that the overall performance could be represented in terms of the product of the performances of the separate components. If this assumption were valid, the problem would be simple, but, unfortunately, the effects due to the input impedance of an amplifying stage, together with the various forms of retroaction, render this assumption unjustifiable in all but the very simplest cases.

Due to the difference in frequency between the input and output, the large magnitude of the step-up ratio, and the retroaction effects, substitution, bridge and comparison methods are difficult to employ. The input must be supplied by means of an artificially generated signal, the form of which must be such that the results obtained can be readily applied to the actual conditions met with in practice.

The relatively large output must also be measured by a method which in no way disturbs the normal operation of the receiver.

An overall performance measurement implies the inclusion of the input tuned circuit, the antenna or frame-coil, whichever is used in practice with the receiver. The problem of applying a known e.m.f. to this tuned circuit may be solved in one of the following three ways:—

- (i) By inducing the e.m.f. into the main tuning inductance by means of a known mutual inductance, the current in the primary of which is known.
- (ii) By passing a known current through a condenser of known value which forms part of the tuning capacity.
- (iii) By inserting in series with the tuned circuit a small non-inductive resistance or a small inductance carrying a known current.

The first method has been used,* but it involves the measurement of a mutual inductance of large ratio at radio frequencies. It is difficult to make such measurements with any accuracy, and also the tuning circuit of the receiver must always include, or consist of, this secondary circuit of the calibrated mutual inductance, which must always be carefully screened from the rest of the receiver. The method is therefore inapplicable as a general method of testing receivers in which the tuned circuit forms part of the complete arrangement.

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* T. A. Smith and G. Rodwin: "Notes on Radio Receiver Measurement," *Proceedings of the Institute of Radio Engineers*, 1927, vol. 15, p. 387.

In the second method, since the value of the tuning condenser is specified by the wavelength range, the e.m.f. which can be applied can only be controlled by the current passed through this condenser and supplied by the main oscillator. Consequently the possible range of the input e.m.f. is very limited. For the smallest measurable radio-frequency current, the value of this condenser must be very large if the e.m.f. across it is to be of the right order.

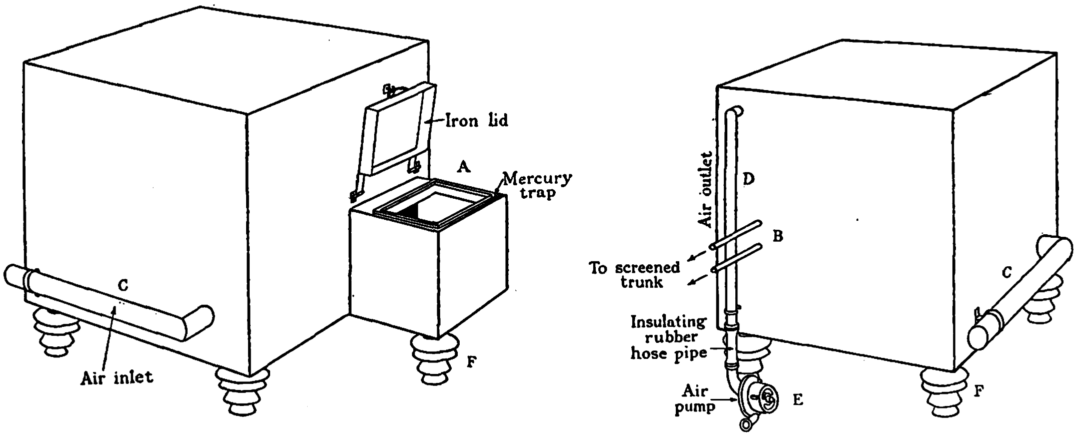

FIG. 1.—Screened oscillator cabin.

The third method has been adopted to a greater extent than the previous methods,* owing to its more general application and its comparative independence of frequency. Small non-inductive resistances can be made within fairly wide limits and, with a reasonable range of current, can be used for a wide range of input voltage. A radio-frequency oscillation, modulated to a known extent at an audio frequency, supplies current to these resistances. The prevention of direct magnetic and electric induction from the oscillators and leads to the resistance demands the most elaborate screening of these components. This is effected by enclosing the oscillators in a completely screened metal room and screening the leads to the resistance. The amplifier, too, must be housed in a screened room to prevent induction from external sources. Refinement in measurement is dependent upon the efficacy of these screens, and practically nothing except complete shielding is permissible.

The screened resistance takes the form of a straight resistance wire with a concentric return, by which means complete shielding is effected. If the resistance wire is tapped at various points, e.m.f.'s of known magnitudes are obtained. At very high radio frequencies it is important that the current through the wire should be measured at a point as near to the tapping as possible. If the filament of the amplifier is connected to the joint between the resistance wire and the concentric return, the batteries will be connected to the amplifier screen which is at earth potential, which condition is required for the imitation of the normal operation of the receiver. It is important that this battery earthing connection be adhered to, otherwise the capacities to the screen may modify the measured performance. If the amplification is very large, the resistance wire becomes very short and at very high frequencies its inductance becomes important. This inductance is too small to measure and must be calculated from the known dimensions of the wire.

In practice, the only factors limiting the accuracy of the measurement are:—

(i) The impossibility of measuring the effective impedance of the screened input resistance, and the consequent dependence of this value upon the calculated value of the inductance of the wire. The possibilities of error, however, are small.

(ii) The difficulty of measuring the current in the resistance at very high radio frequencies. At present a non-contact thermo-junction ammeter is used, and the assumption is made that its d.c. calibration is valid at all frequencies.

This limitation is, however, imposed on many other measurements at high radio frequencies at the present time. A better method of measuring very high radio-frequency currents would naturally improve the accuracy of the measurements at such frequencies.

(*b*) *The Construction of the Screened Cabin for the Oscillator.*—A perspective view of the completed oscillator cabin is shown in Fig. 1. The screened cabin is a 6½ ft. cube and consists of a wooden skeleton covered with No. 22 S.W.G. tinned iron sheet. Great care was taken to solder over every joint, and the completed box was hermetically airtight. Previous experience with screened doors had shown the difficulty of making them sufficiently effective, and consequently a mercury-sealed trap door (shown at A) was adopted.* The seal consists of a welded angle-iron frame dipping into a channel-shaped iron frame containing mercury. This door has been tested and found to be entirely satisfactory, but it has been found important to maintain the portion of the iron frame immersed in the mercury in a thoroughly clean condition. The output current leads are taken through seamless steel tubing (shown at B).

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* H. A. THOMAS: "The Performance of Amplifiers," *Journal I.E.E.*, 1926, vol. 64, p. 253; E. KLOTZ: "The Quantitative Measurement of Receivers," *Telefunkenzeitung*, 1927, vol. 8, p. 54; H. D. OAKLEY: "Quantitative Determination of Radio Receiver Performance," *Journal of the American I.E.E.*, 1927, vol. 46, p. 498.

* R. L. SMITH-ROSE: "On the Electromagnetic Screening of a Triode Oscillator" *Proceedings of the Physical Society of London*, 1922, vol. 34, p. 127.

The ventilation of such a box presents some difficulty, the method here adopted making use of two long copper pipes C and D, provided with three copper-gauze baffles which give adequate screening while permitting a sufficient passage for air. Pipe D is connected by an insulating rubber hose-pipe to a centrifugal pump E, and pipe C is the inlet. The diameter of pipe D is much smaller than that of C, so that the air pressure inside the box is only slightly lower than that of the outer atmosphere. The complete box is insulated from earth by means of the five large insulators F.

The output pipes B are insulated from the connecting trunk G, Fig. 2 (*a*), by a method, shown in detail in Fig. 2 (*b*), which gives good insulation and at the same time effective screening. Tests made with the completed box have shown that it is sufficiently screened for the purposes required.

(*c*) *The Construction of the Screened Input Resistance.*—Since the radio-frequency current is taken through the trunks to cabin A containing the amplifier, the radio-frequency resistance needs to be very efficiently screened.

For short-wave work, usually below 40 m, the inductance of the resistance wire is not negligible and consequently it was decided to use a screened straight wire in which the inductance was calculable. Such an arrangement would take the form shown in Fig. 3 (*a*), the current passing through the central wire and back through the screening cylindrical tube. The external field would be negligible, and if a certain length of wire l_1 were used the potential difference across this length could be applied to the amplifier.

The input lead B would have a length l_2 equal to the radius of the cylinder in the magnetic field due to the inner wire, and an e.m.f. could be induced in this wire. The construction Fig. 3 (*b*) is better, since the length of unscreened lead B is now materially reduced. However, the distance *d* must be reduced to a minimum if the capacity between the wire and the screen is to be negligible, such capacity acting as a shunt to the resistance, but this distance *d* also affects the capacity of the tapping lead to the screen; a compromise is therefore necessary which gives a new minimum capacity shunt effect. Since one lead A of the potentiometer is connected to the screen, it follows that this lead is effectively earthed and is connected to the main screen of cabin A. In all tests this lead is connected to the filament of the amplifier, thus "earthing" all batteries, which condition is normal. Therefore lead Y, Fig. 2, is connected to the screen and need not really be used, but in certain special cases, such as the input to a push-pull stage, no earth is required, and then the lead Y can be disconnected from the screen by the switch and the lead brought out of the screen.

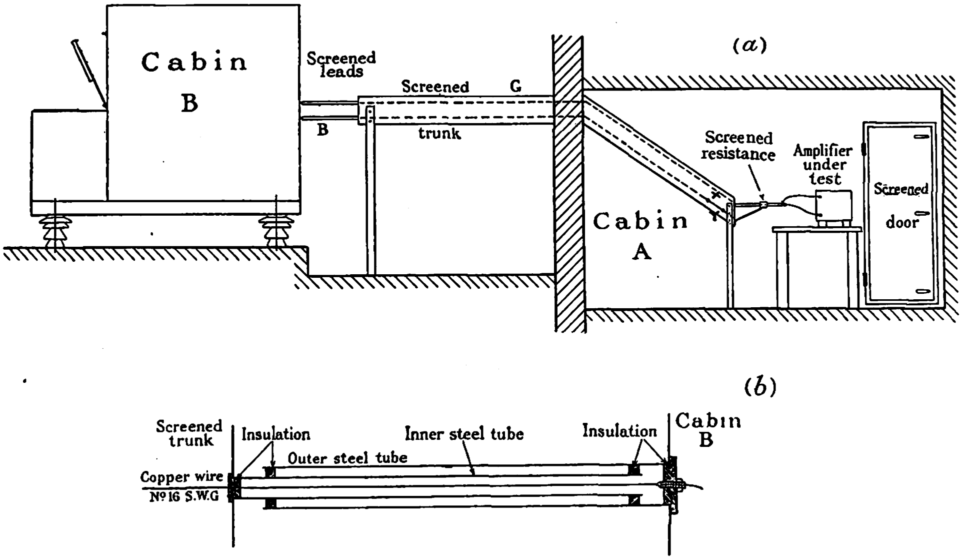
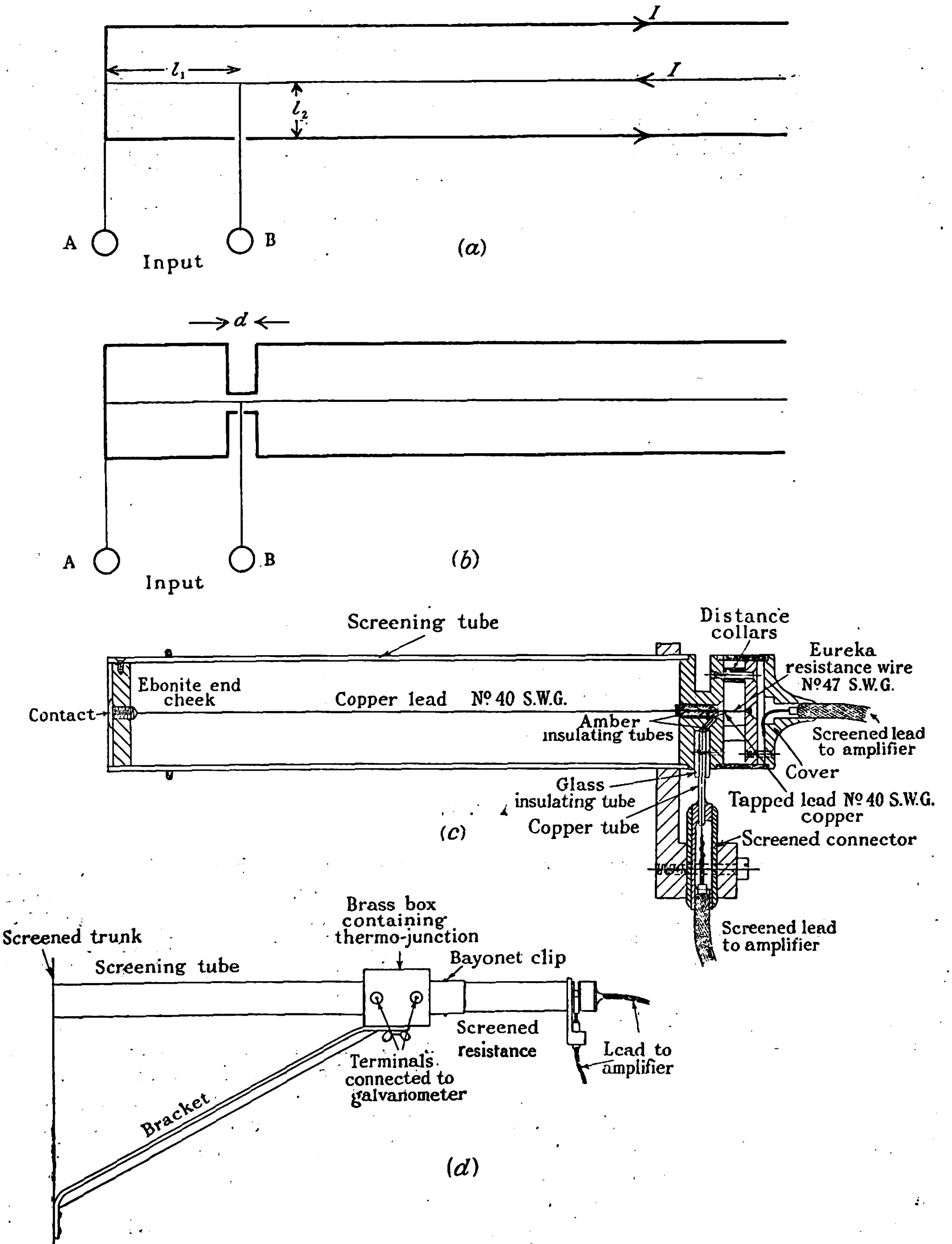


FIG. 2.

The final arrangement adopted for the input resistance is shown in Fig. 3 (*c*). No. 47 S.W.G. eureka wire is used as the resistance, and No. 40 S.W.G. copper wire is used to connect to the wire X, Fig. 2. The details of the insulation and screening are clearly shown in the diagram. Six such resistances have been made, having values of 0, 0·76, 0·96, 5·139, 11·23 and 27·86 ohms respectively. The resistance was measured by a potentiometer, this obviously being more satisfactory than a bridge resistance measurement, owing to the unknown electrical nature of the soldered joints. The inductance of the six wires was calculated and was found to be 0, $1 \cdot 39 \times 10^{-3}$, $3 \cdot 39 \times 10^{-3}$, $25 \cdot 98 \times 10^{-3}$, $60 \cdot 45 \times 10^{-3}$ and $176 \cdot 5 \times 10^{-3}$ μH respectively, these figures being obtained from the lengths of the eureka resistance wire measured by a travelling microscope.

The screened resistance can be plugged into a bayonet socket adjacent to the screened vacuum junction, as shown in Fig. 3 (*d*). This junction is of the non-contact type and measures the current within a few inches of where it passes through the resistance wire; this point is of importance since, at very high frequencies, the current varies along the trunk leads.

resistance, but lead B is connected to the screen end of the wire. This resistance is used to ascertain whether any electric or magnetic induction effects are present. Using this resistance, no output should be given if there are no induction effects.



I
I
l_1
l_2
A
B
Input
(a)
d
A
B
Input
(b)
Screening tube
Distance collars
Eureka resistance wire Nº47 S.W.G.
Ebonite end cheek
Copper lead Nº 40 S.W.G.
Contact
Amber insulating tubes
Screened lead to amplifier
Cover
Glass insulating tube
Tapped lead Nº 40 S.W.G. copper
Copper tube
Screened connector
(c)
Screened lead to amplifier
Brass box containing thermo-junction
Screened trunk
Screening tube
Bayonet clip
Screened resistance
Terminals connected to galvanometer
Lead to amplifier
Bracket
(d)

FIG. 3.—Details of screened resistance for supplying known potential differences to a wireless receiver.

The two input leads are screened up to the terminals of the amplifier, the capacity of these leads being insufficient to alter appreciably the impedance of the resistance even at frequencies corresponding to wavelengths [in the neighbourhood of 30 m (10 megacycles per sec.). The zero-resistance wire has a construction identical with that of the 0·76-ohm screened

The inductive reactance of the resistances is negligible at frequencies below 10 megacycles, and at frequencies above this value the reactance can easily be calculated. These resistances appear to be quite satisfactory and have been used on wavelengths of 15 m (20 megacycles per sec.).

(*d*) *The Input Oscillator.*—Various types of radio-frequency oscillator have been tried, the push-pull type being used for the preliminary work. It has been found, however, that the series-fed Hartley oscillator with grid condenser and leak gives the best results, as this oscillator will work satisfactorily with a 2-volt low-impedance valve and a high-tension supply of 20 volts. Using this circuit arrangement, an oscillator has been built which will cover all wavelengths down to 5 m (60 megacycles per sec.).

In the early work, capacitative coupling to the input screened leads and resistance was adopted, a variable condenser connected between the free potential lead and one end of the oscillating coil being used, while the earthed lead was connected to the centre tapping. The adjustment of this condenser provided a very simple means of varying the current, but unfortunately this type of coupling exaggerates the harmonics and, since the thermo-junction measures the R.M.S. value of the current in the resistance, has been abandoned. The present arrangement employs a tuned circuit inductively coupled to the oscillator, the screened resistance being in series with this circuit. Although not so simple to operate, the purity of wave-form obtained by this method compensates for the increased practical difficulties.

The audio-frequency oscillator consists of a push-pull arrangement with a tuned output circuit in series with the anode feed to the radio-frequency oscillator. The wave-form obtained with this arrangement is sufficiently good for most measurement purposes. The modulation percentage was originally measured by means of an electrostatic voltmeter, but this instrument has now been replaced by a valve voltmeter owing to the sluggishness of the electrostatic instrument. The complete oscillator unit is carefully screened and consists of the audio-frequency oscillator, a modulator unit, the modulation measuring voltmeter, the radio-frequency oscillator and the coupling unit. The complete circuit arrangements are dealt with later in sub-section (*f*).

(*e*) *The Measurement of the Output Voltage.*—Most types of receiver give an output at an audio frequency, and in the early work a vibration galvanometer was used to measure this output. Such an instrument is eminently suitable for the measurement of very small outputs such as those given in telephones but, with more modern receivers, outputs of loud-speaker intensity are more common and the potential on the grid of the power stage is of the order of several volts.

Since the power stage must always be looked upon as a converting mechanism, the amplification must be expressed in terms of the voltage output delivered to the grid of the power stage with respect to some input voltage. To measure reasonably large outputs it is usual to use a valve voltmeter connected across the grid and filament of this stage, but difficulties have been encountered with the use of a valve voltmeter connected in this manner, owing to the large shunt load imposed by this instrument. This effect is illustrated by the results given in Fig. 4, the output as measured by a valve voltmeter being plotted against the input supplied to a 2-stage resistance-capacity amplifier. In curve A, the valve voltmeter was connected directly across the input of the power valve and it is seen that, as the input is increased, the output appears to reach a saturation value due to the load of the voltmeter. If, however, the voltmeter is connected across a 100-ohm resistance inserted in the anode circuit of the power valve, the characteristic is given by curve B, which shows a linear relationship between the input and the output. This low anode-circuit resistance is negligible in comparison with the loud-speaker impedance and consequently its effect, considered as a modifying element in the circuit arrangement, is negligible. The amplification will appear to be higher than that obtained when the voltmeter is connected directly across the input of the power stage when very small outputs are being obtained, as shown by the tangent drawn to the lower part of curve A. Since the modulation percentage never exceeded 15, the only important harmonic produced due to rectification is the second, and this can never produce an error greater than 3 per cent in the output measurement.* In all measurements, therefore, the voltmeter was connected across a low non-inductive resistance in the anode circuit, and the power stage was calibrated by supplying an audio-frequency oscillation directly to the grid and filament by means of a high-resistance potentiometer. By this means the actual voltage on the grid of the power valve can be obtained by noting the deflection of the valve voltmeter connected in the anode circuit.

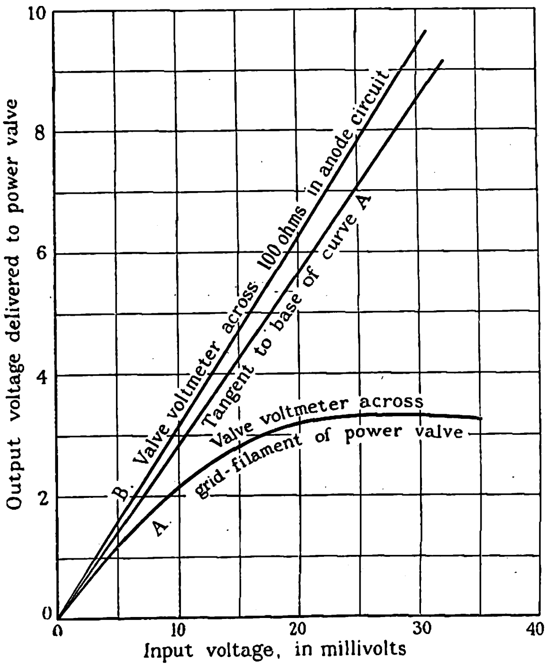


Fig. 4.

(*f*) *The Complete Circuit Arrangements.*—Fig. 5 shows the completed arrangement of the apparatus. The radio-frequency oscillation is modulated by means of the screened audio-frequency oscillator and the modulator. By means of a variable coupling between the audio-frequency tuned coupling circuit and the oscillator, and also by shunts across the output transformer of the modulator valve, the modulation percentage may be varied.

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* W. B. Medlam and V. A. Oschwald: "The Performance of Valve Detectors," *Journal of the Institute of Wireless Technology*, 1928, vol. 1, p. 147.

It has been found that the output current given by the radio-frequency oscillator is sensibly proportional to $(V - K)$, where V is the high-tension d.c. voltage and K is an experimental constant. If the R.M.S. voltage of the modulator output is E, then the modulation percentage is given by

$$\frac{\sqrt{2}\,E}{V-K} \times 100 \text{ per cent}$$

An inductively-coupled tuned system supplies the screened resistance, the current in which is measured by the non-contact thermo-junction Q. A second junction P is inserted inside the oscillator cabin so that the operator can tune the circuits, but no measurements of current are taken on this instrument. With the switches in cabin A at position (1), the input is normally applied to the amplifier and the negative filament leg is connected to the screens and may be earthed if required; at position (2) the power stage is calibrated with an audio-frequency input by means of a high resistance. The milliammeter in the anode circuit of the power stage is used as an indicator to obtain the same grid bias under both conditions, the bias voltage being controlled by a potentiometer as shown in the diagram.

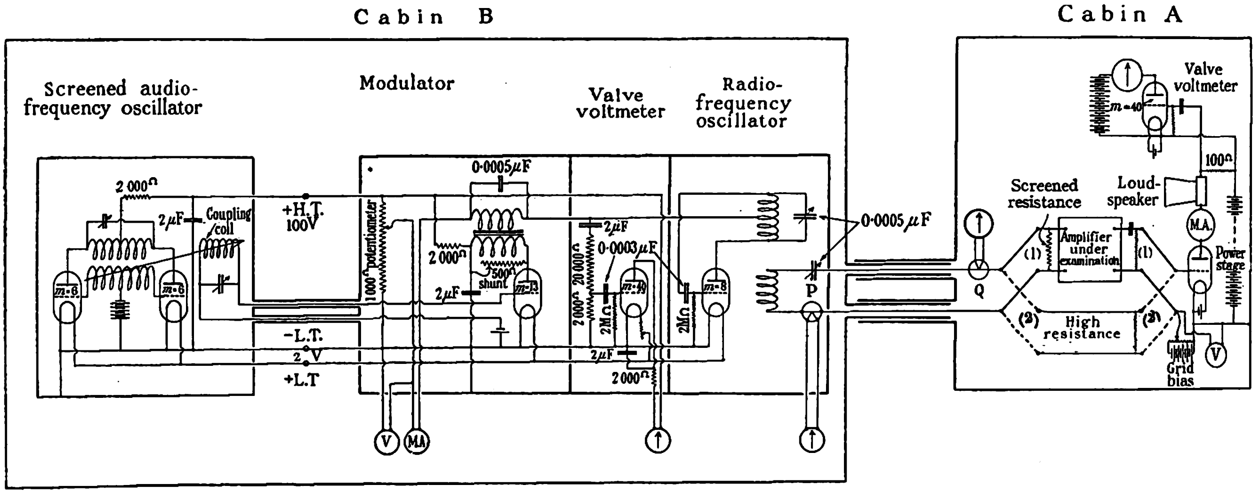
Cabin B
Cabin A
Screened audio-frequency oscillator
Modulator
Valve voltmeter
Radio-frequency oscillator
2 000Ω
2μF
Coupling coil
+H.T. 100V
m=6
m=6
-L.T.
2V
+L.T
0·0005μF
1000Ω potentiometer
2 000Ω
500Ω shunt
2μF
m=13
2μF
0·0003μF
2 000Ω
20 000Ω
2MΩ
m=40
2MΩ
m=8
2μF
2 000Ω
P
0·0005μF
V
MA
Valve voltmeter
m=40
100Ω
Screened resistance
Loud-speaker
Amplifier under examination
(1)
(1)
M.A.
Power stage
Q
(2)
High resistance
(2)
Grid bias
V

FIG. 5.—Circuit diagram of apparatus for testing the performance of radio receivers.

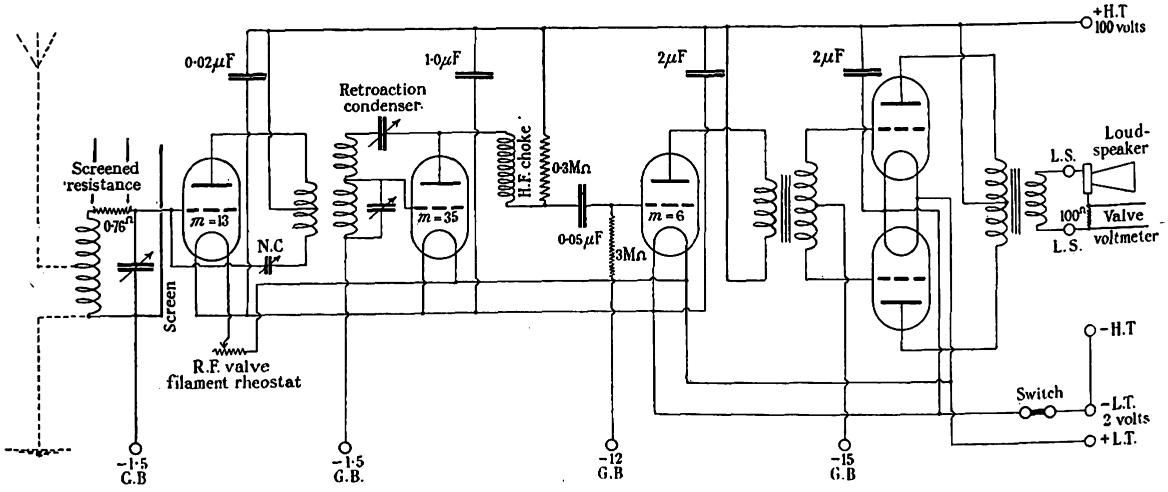
+H.T 100 volts
0·02μF
1·0μF
Retroaction condenser
2μF
2μF
Screened resistance
0·76Ω
m=13
N.C
m=35
H.F. choke
0·3MΩ
0·05μF
3MΩ
m=6
Loud-speaker
L.S.
100Ω
Valve voltmeter
L.S.
Screen
R.F. valve filament rheostat
-H.T
Switch
-L.T. 2 volts
+L.T.
-1·5 G.B
-1·5 G.B.
-12 G.B
-15 G.B

FIG. 6.—Circuit diagram of receiver, showing method of measurement.

The apparatus is capable of giving an input range of 0·25–1 000 mV at any wavelength from 5–30 000 m (20–0·01 megacycles per sec.), and an output range of 20–6 000 mV at any audio frequency.

SECTION (2).—EXAMPLES OF MEASUREMENTS UPON VARIOUS TYPES OF RECEIVERS.

(*a*) *Introduction.*—Having described the principal features of the measuring apparatus, some results of tests performed upon various types of receivers will now be given. The object of these tests was essentially to demonstrate the utility and range of the apparatus, and, although the results show the properties of the different receivers tested, no mathematical analysis of them has been attempted. For the purpose of analytical work, special amplifiers would need to be built and their constants would require exact measurement. The results, however, demonstrate the types of overall characteristic likely to be obtained from receivers of a similar type to those employed.

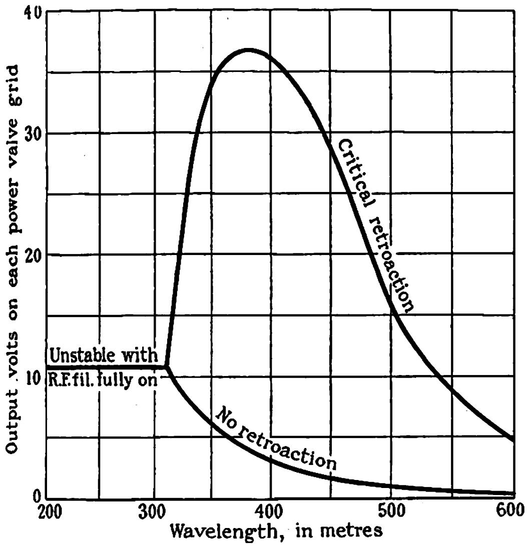

FIG. 7.

The receivers used for the tests were deliberately selected to cover several usual types, and, since the apparatus has been proved satisfactory for measuring the performance of these essentially different types, such measurements constitute a reasonable ground for believing that the apparatus can be employed to examine practically any type of receiver.

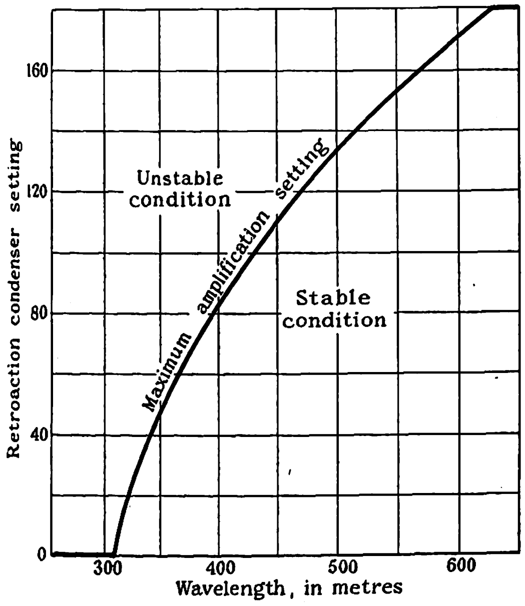

FIG. 8.

(*b*) *A 4-valve Receiver* (200–16 000 *m*).—A typical modern 4-valve receiver was examined. The particular receiver chosen had one radio-frequency stage, an anode-current rectifier with resistance-capacity coupling to the first audio-frequency stage, a transformer-coupled audio-frequency stage, and finally a push-pull output stage. The circuit arrangement is shown in Fig. 6. The radio-frequency stage is neutrodyned and a tapped secondary winding on the radio-frequency transformer provides the retroaction. The rectifier has a choke in series with the anode resistance, and the normal aerial and earth connections are shown by the dotted lines. For the purposes of the test the normal earth connection was taken to the screen, which was effectively earthed, and the known input voltage was applied to the tuned circuit as shown.

The valve voltmeter was connected across a 100-ohm resistance in series with the loud-speaker. To calibrate the push-pull output valves, the tapped secondary was removed and a tapped non-inductive resistance was substituted, the middle point being earthed. The audio-frequency oscillator fed this resistance and gave the output on the valve voltmeter.

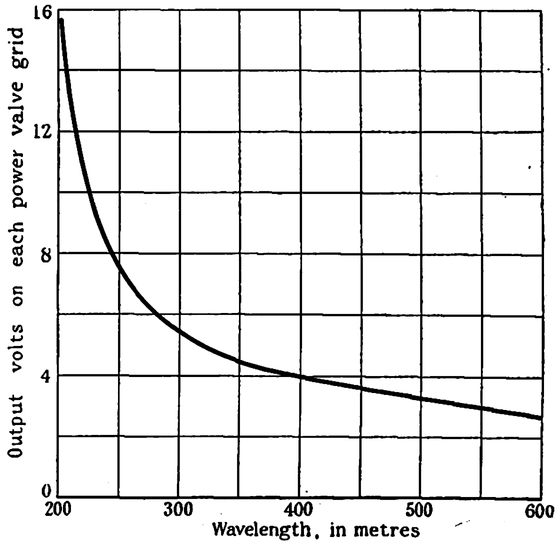

FIG. 9.

An earthed screen is used to prevent retroaction between the two radio-frequency circuits. The current in the filament of the radio-frequency valve is adjustable by means of a rheostat, this being used as a volume control and also as a stabilizer at certain wavelengths where the neutrodyne arrangement is not satisfactory.

A constant input of 5 mV modulated 15 per cent at 1 000 cycles per sec. was applied to the tuned circuit at various frequencies, and the R.M.S. output voltage delivered to either grid of the push-pull output valves was measured with the filament current of the radio-frequency valve at maximum and with the retroaction condenser at zero. This characteristic is shown in Fig. 7. At a wavelength of 310 m the receiver became unstable, and at any wavelength below this the radio-frequency valve filament-current had to be reduced to maintain stability. The amplification at these lower wavelengths could not be raised above the value given at 310 m. At wavelengths above 310 m the retroaction condenser was now adjusted to the threshold of oscillation and the output was measured. It will be seen from Fig. 7 that the maximum amplification occurred at a wavelength of 380 m. Any point lying between the two curves represents a possible stable condition depending upon the setting of the retroaction condenser. The actual settings of this condenser are shown in Fig. 8. Below 310 m the receiver is unstable with maximum filament current in the radio-frequency valve, even with the retroaction condenser at zero, whereas above 625 m the receiver is stable when all the extra retroaction is inserted. All points lying below the curve represent a condition of stability, and all points above the curve one of instability.

The next test was made at the constant wavelength of 370 m with a constant modulation of 10 per cent but with variable input. The relationship between the output and the input was found to be very nearly that of a square law. This test was made at different wavelengths and always gave a similar relationship, from which we deduce that this characteristic represents the property of the rectifier, since the radio-frequency and audio-frequency portions of the receiver sensibly obey a linear law.

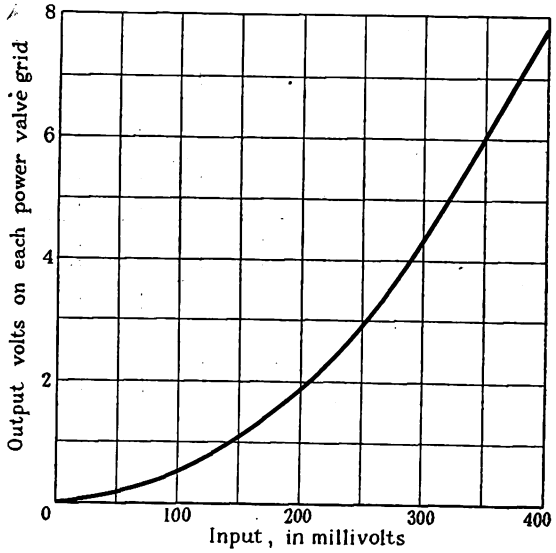

FIG. 10.

It was found that if the output exceeds about 4 volts on each power-valve grid, the relationship between the output and the modulation percentage departs from a linear law. This has been found to be generally true, irrespective of wavelength, and is clearly due to some saturation effect.

A constant input of 70 mV was now applied directly to the radio-frequency stage and the circuit was tuned to give the maximum amplification with no extra retroaction and with the full filament current at each wavelength. The output is plotted in Fig. 9 and it is seen that the radio-frequency stage is stable down to a wavelength of 200 m. The rectifier characteristic obtained by applying the known e.m.f. to the rectifier grid is shown in Fig. 10, the input being applied directly to the rectifier. The relationship between the input and output voltages for a definite modulation percentage is a perfect square law. From these two characteristics, Figs. 9 and 10, the amplification of the radio-frequency stage can be obtained and is plotted in Fig. 11. An examination of this figure shows that the amplification of the radio-frequency stage rises from about 3·2 at 600 m to nearly 9 at 200 m. The receiver is unstable at this wavelength if an input circuit is connected before the radio-frequency stage, but the figure represents the stable condition with no input circuit. Since the voltage factor of the radio-frequency valve is 13, this amplification figure is very low. Tests on other radio-frequency amplifiers have given similar low values, and, where high values are obtained approaching the valve voltage-factor, retroaction is usually responsible for such values.

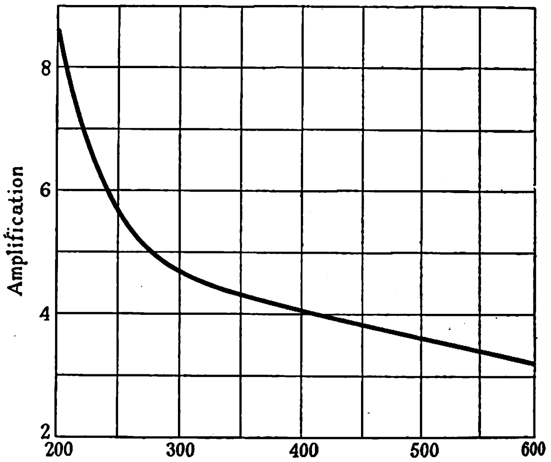

FIG. 11.

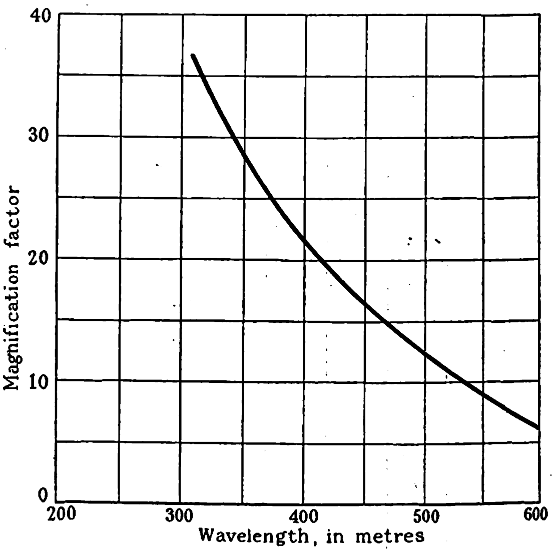

FIG. 12.

By combining the overall performance characteristic obtained by supplying the tuned input circuit with a known signal, and the radio-frequency valve characteristic, we can obtain a figure for the magnification factor or coil factor of the tuned input circuit; this is shown in Fig. 12. In the absence of all loading and retroaction effects, this characteristic should be given by $\omega L/R$, where L and R are respectively the inductance and radio-frequency resistance of the input tuned circuit.

An attempt was made to reconcile the experimental figures for the amplification of the radio-frequency stage and the magnification factor of the input circuit with the theoretical figures obtained by a cursory examination of the circuit. The radio-frequency resistance of the input circuit and the radio-frequency stage load circuit was obtained by measurement, together with the inductance and self-capacity of the coils used in these circuits. The simplest examination of these figures revealed the serious discrepancy between the experimental results and the results obtained by any simple theoretical calculation which neglects the effects due to retroaction and input impedance: not only are both experimental figures far lower than the predicted figures obtained by such a simple analysis, but the form of the curves is different. The departure in form shows that a proportionately higher figure is obtained as the frequency is raised, which is undoubtedly due to retroaction effects at the higher frequencies. It is clear that the input impedance and retroaction effects are very serious and no useful results would be obtained by a closer examination of the characteristics, as the receiver is one in which no special precautions have been taken to prevent stray retroaction. The results given are of considerable interest, in that they demonstrate the general properties obtained with a typical receiver, but a closer examination would be impossible on account of the numerous unknown quantities involved.

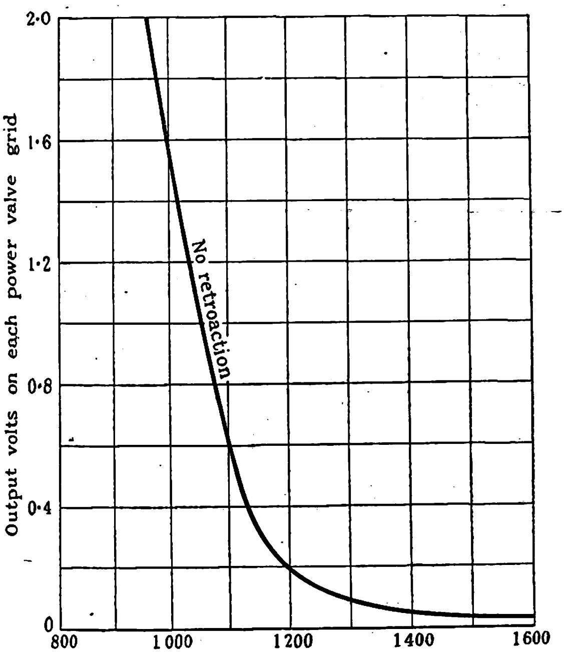

FIG. 13.

The properties of the receiver on long waves, using two different coils, are shown in Figs. 13, 14 and 15. In Fig. 13 the overall performance characteristic is given with no extra retroaction, while Fig. 14 shows the effect of retroaction. In this case a much greater increase of amplification is possible by the use of retroaction, but the best performance is only slightly better than in the medium wavelength case. This effect is due, no doubt, to the much smaller inherent retroaction at the longer wavelengths, the curves for "no retroaction" showing a much reduced amplification. Again, the rapid rise in amplification at the lower wavelength end and the instability coupled with it are to be noted. The critical retroaction setting is shown in Fig. 15, from which it will be noticed that the receiver can be rendered unstable at all wavelengths with a smaller

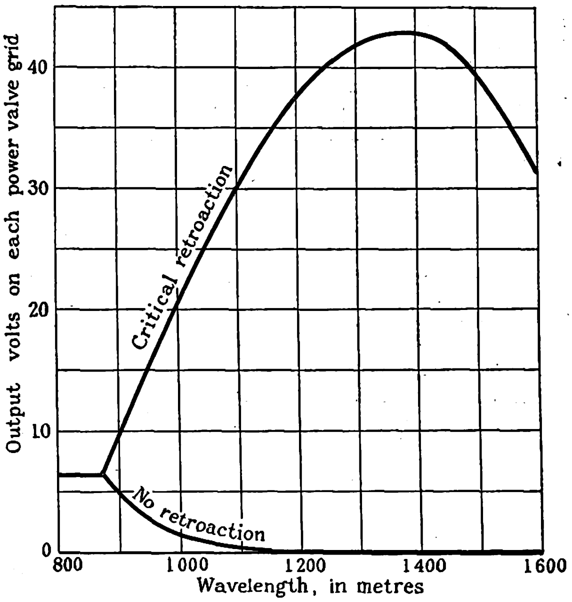

FIG. 14.

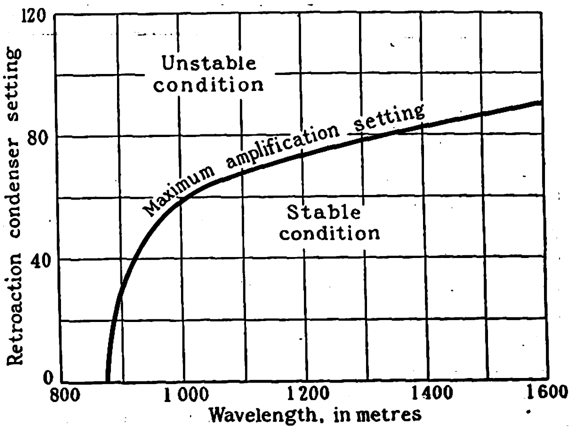

FIG. 15.

retroaction setting than in the previous medium-wave case, but, as before, it is unstable below a critical wavelength. In both cases the neutrodyne condenser was set to give balance by the usual audibility method, but no guarantee can be given that this setting was absolutely exact.

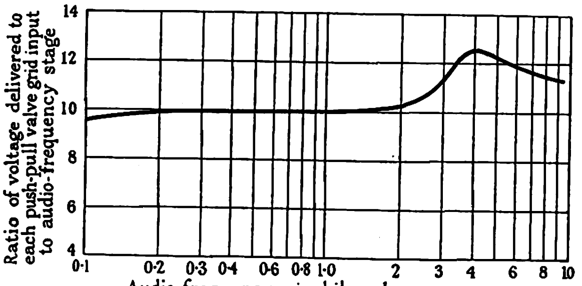

FIG. 16.

It is to be noticed that several characteristics show output voltages of 40 or so. It is to be realized that, where such points occur, they are obtained by calculation only. For instance, if a characteristic is being obtained on the basis of a constant input of 5 mV and an output of 2 volts is obtained at a certain wavelength, another wavelength may require only 1 mV to give the same output. Making use of the known overall properties, the output is then computed in terms of a 5-mV signal. Such computation is permissible and renders the curves more useful, but at no time during the tests did the output exceed the limit of linearity of the output stage characteristic.

The last test performed upon this receiver consisted in maintaining a constant input and modulation while varying the modulation frequency. In this way the audio-frequency characteristic of the amplifier stage preceding the output valves was obtained and is shown in Fig. 16.

(*c*) *A Commercial Short-Wave Receiver* (15–60 *m*).—To examine the utility of the apparatus at short waves, an examination of a standard short-wave receiver employing one stage of radio-frequency amplification was undertaken.

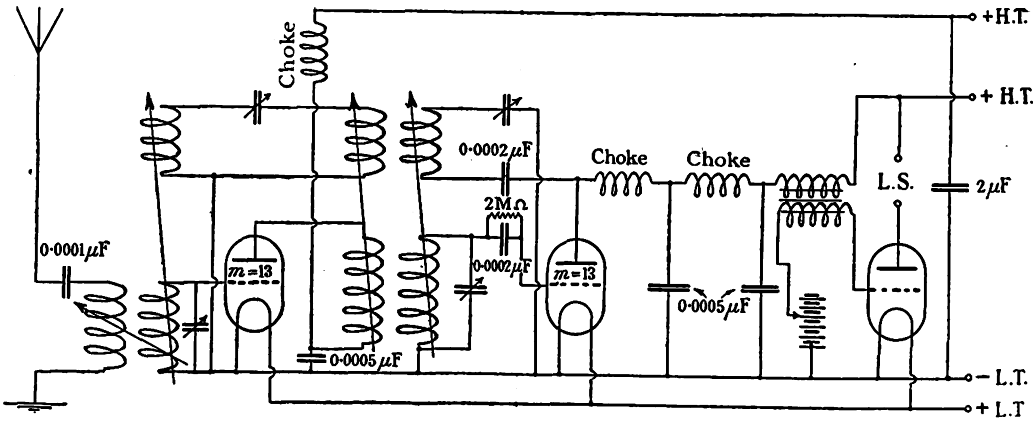

FIG. 17.—Circuit diagram of commercial short-wave receiver (15–60 metres).

The receiver circuit diagram is given in Fig. 17. There is one stage of radio-frequency amplification, the valve used having a voltage factor of 13 with an internal resistance of 30 000 ohms, followed by a rectifier valve with the same voltage factor and internal resistance, and lastly any normal output valve. Since the receiver is designed for use with weak telephonic outputs, the valve voltmeter was connected directly across the telephones and the power stage was calibrated with this connection. The known input voltage was supplied to either the input tuned circuit, the grid of the radio-frequency valve or the rectifier grid, by which means the performance of each part of the receiver could be analysed. Two tests were carried out at all wavelengths, namely, one with a variable modulation at a definite input, and the other with a variation of the input at a definite modulation. The modulation frequency was 1 000 cycles per sec. throughout, representative of an average audio-frequency in telephones with heterodyne reception of continuous waves.

The rectifier was calibrated at 30 and 60 m and found to be sensibly independent of frequency and to obey approximately a square-law relationship. By the use of this characteristic, together with those obtained by supplying the input tuned circuit or the radio-frequency stage, an analysis of the radio-frequency circuits was rendered possible. It is only possible to separate the coil and radio-frequency stage factors for the no-retroaction condition, since the amplification

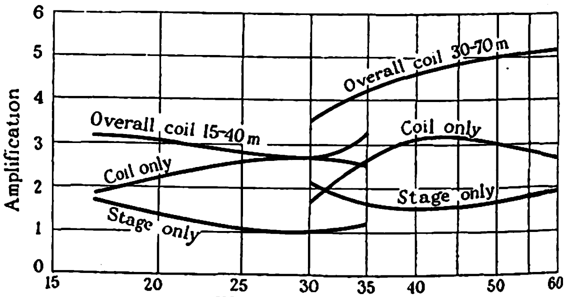

FIG. 18.

given when considerable retroaction is present is produced by the product of the two augmented values of both the coil factor and the radio-frequency stage factor. It is impossible to separate these two under critical conditions, owing to the modifying effect of the input resistance upon the circuits.

Within the limits of experimental accuracy, the output was found to obey a linear relationship with respect to the modulation percentage for constant input. With outputs greater than 0·3 volt on the power-valve grid the departures from this law were never greater than 5 per cent, and in the cases when the output was of the order of 0·1 volt they were much less.

It was found that the form of the input-output characteristic with constant modulation was independent of the frequency. For output voltages exceeding 0·1 this relationship was linear, but below this output voltage the characteristic was curved in a similar manner to the lower bend of a rectifier characteristic. The test made on the rectifier gave a somewhat similar curve, but the difference between the two was sufficient to suggest that a small amount of rectification was taking place in the radio-frequency stage. With critical retroaction the form of this input-output characteristic becomes saturated. This is due to the more critical retroaction setting possible with the weaker inputs, the larger inputs tending to throw the receiver more readily into oscillation. If the retroaction condenser had been adjusted for stability with a large input and left unaltered for the weak signals, this effect would have disappeared, but in the curves giving critical retroaction conditions the retroaction was adjusted for each measurement to give the greatest possible amplification. Owing to the difficulty of obtaining a critical setting, these characteristics have an accuracy of not more than 10 per cent.

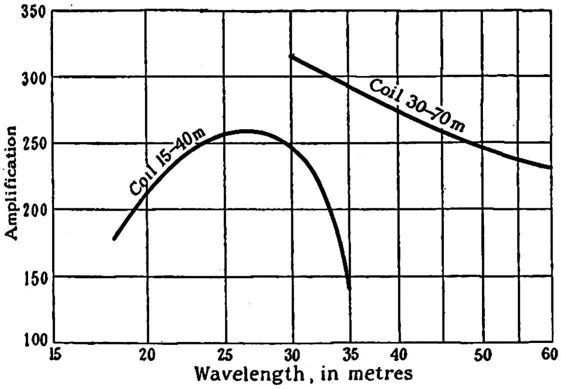

FIG. 19.

The receiver is provided with two sets of coils to cover the wavelength band of 17–60 m. The overall radio-frequency amplification obtained by the input tuned circuit and the stage of amplification before the detector is shown in Fig. 18 with no retroaction, and the critical retroaction case is given in Fig. 19. In the former figure the overall amplification has been resolved into its two components, namely, the coil factor and the audio-frequency stage factor.

The general properties to be noticed by an examination of these results are that, owing to capacity shunting effects, the sensitivity falls as the frequency rises in the no-retroaction case; this is clearly shown in the case of the coil having the range 30–60 m (Fig. 18). The other effect of raising the frequency is to increase the retroaction, resulting in greater amplification. This is particularly noticeable below 30 m where the sensitivity is maintained. This characteristic agrees with the results obtained on the previous amplifier. In the critical retroaction case, where the input voltage is 1 mV the sensitivity increases as the wavelength is reduced, owing to the greater retroaction effect on the shorter waves, but it appears that at wavelengths below 25 m the retroaction condenser cannot be set so critically and a loss of sensitivity takes place.

In the critical retroaction case the measured performance given in Fig. 19 is valid only for inputs not exceeding 1 mV, for with greater inputs the amplification is found to be materially reduced. It would appear at first sight that this behaviour is due to amplitude distortion, but on examination it is found to be due to the inability of obtaining so critical an adjustment of the retroaction condenser for the higher inputs. The results obtained on larger inputs suggest that the amplification with very weak inputs may be greater than that shown for an input of 1 mV in Fig. 19. The most striking feature of the results is the very poor amplification of the radio-frequency stage. This gives an amplification which never exceeds 2·1 and is only 1 at a wavelength of 28·5 m. It is interesting to note that the maximum coil factor is obtained at the same wavelength as the minimum radio-frequency stage factor for both ranges, and also that the maximum amplification obtained by the use of critical retroaction is obtained at the wavelength corresponding to the minimum radio-frequency stage factor. Since the use of retroaction is responsible for such a large increase in amplification, and since the radio-frequency stage appears to help to such a small extent, one arrives at the conclusion that methods of critical retroaction adjustment are more important than amplification at the high radio frequency by separate stages. Later experiments have confirmed this view. To illustrate

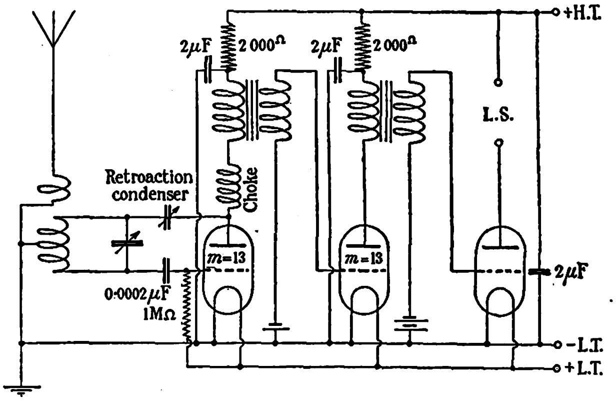

FIG. 20.—Circuit diagram of screened short-wave receiver (15–80 metres).

this point more fully, the next test was made upon a short-wave receiver covering the same wavelength range but employing no radio-frequency amplification.

(*d*) *A Screened Short-Wave Receiver* (15–80 *m*).—The circuit arrangement of this receiver is shown in Fig. 20. Each stage was screened, and the coils used were made with bare copper wire well spaced, and with merely a skeleton frame to support them, so that the losses were reduced to a minimum. Two coils are required to cover the wavelength range from 15 to 80 m. It was found that this type of circuit was more easily adjusted than the previous one, largely owing to there being only two condensers, one of which controls the retroaction, whereas the previous circuit had three condensers, two of which were tuning controls.

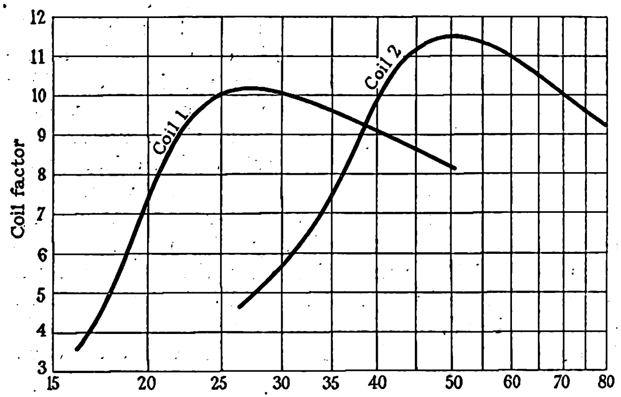

FIG. 21.

By comparing these results with those of the previous receiver, Figs. 18 and 19, it is seen that a similar overall performance can be obtained by the use of a retroactive rectifier circuit, and that the predominant factor is the retroaction.

The radio-frequency stage in the previous amplifier was contributing but slightly to the overall result, and there appears to be little justification for the greater complexity of the controls and circuit involved by the use of a radio-frequency stage when a simple retroactive system can give the same performance.

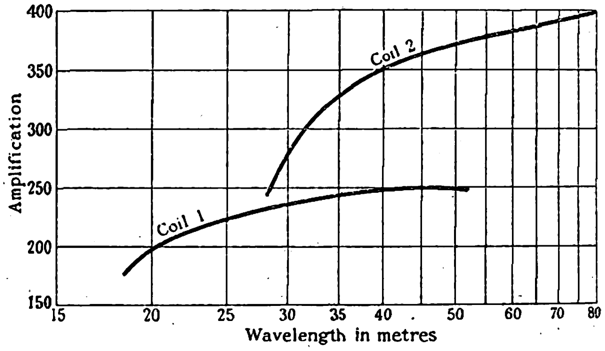

FIG. 22.

(*e*) *A Supersonic-Heterodyne Receiver with Frame Aerial* (50–500 m).—Finally, a complete examination of the properties of a supersonic-heterodyne receiver was made, and the results are expressed in such a manner as to be of direct application to the practical use of such receivers.

The receiver used was partly built up from commercial components, but was somewhat modified to suit the needs of a portable direction-finding receiver. The circuit arrangement is shown in Fig. 23. There is a separate oscillator having various coils to cover the required ranges, a 3-stage intermediate-frequency amplifier inductively coupled to the first rectifier, a second rectifier and an output stage. The voltage factors and internal resistances of the various valves are shown in Fig. 23.

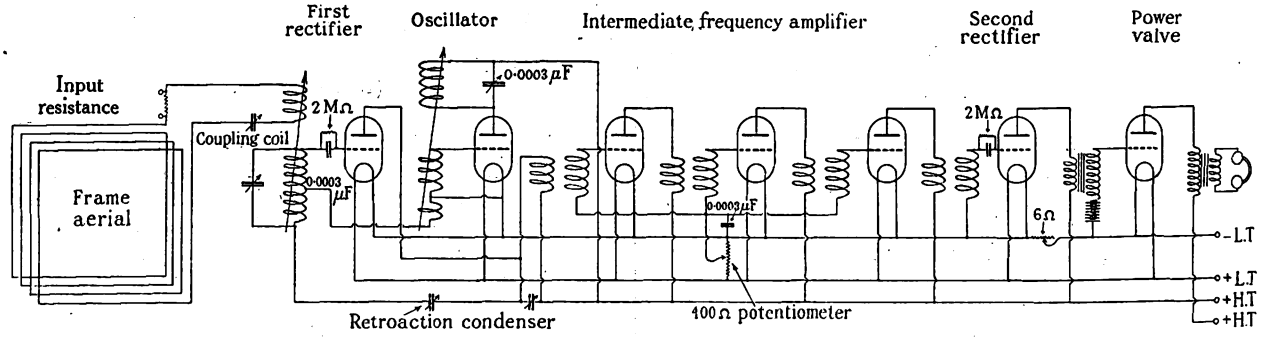

FIG. 23.—Circuit diagram of supersonic heterodyne receiver (50–5 000 metres).

By applying the known e.m.f. to the input tuned circuit and obtaining the audio-frequency output, and then by applying the e.m.f. directly to the rectifier, the coil factor can be obtained without deliberate retroaction. This characteristic is shown in Fig. 21, from which it will be noticed that the step-up due to the coil alone is much superior to that obtained in the previous case. This is largely due to the superior coils and also to the smaller load thrown upon the input circuit by the impedance of the rectifier valve circuit. By the use of retroaction, a greatly improved performance is possible, as shown in Fig. 22, the performance being similar with the two coils, namely, a fall in amplification with rise in radio frequency.

The first characteristic to be obtained was the amplification of the three stages comprising the intermediate-frequency amplifier. This is given in Fig. 24, the potentiometer control of the grid bias to the second valve being so adjusted that the system was just stable and giving its maximum amplification. For this test the input resistance was connected directly to the grid of the first intermediate-frequency stage, and the characteristic shown in Fig. 24 represents the ratio of the voltage delivered to the second rectifier to the input voltage applied to the first intermediate-frequency stage. The type of characteristic obtained is a very general one for an intermediate-frequency amplifier and many similar characteristics have been obtained previously.* Owing to the inductive coupling between the first intermediate-frequency stage and the first rectifier, this latter characteristic does not represent the true selectivity of the intermediate-frequency section. To obtain this selectivity we must include the coupling between the first rectifier and the first intermediate-frequency stage. The input at the intermediate frequency was now applied to the first rectifier and a characteristic obtained between the voltage delivered to the second rectifier and the voltage applied to the first rectifier. Since the frequency of the applied voltage was that corresponding to the intermediate-frequency amplifier, such a test does not truly represent the conditions existing on the first rectifier, but it does give the true selectivity of the intermediate-frequency stages. This characteristic is shown in Fig. 25 and can be used to calculate the selectivity of the input circuit at any desired frequency.

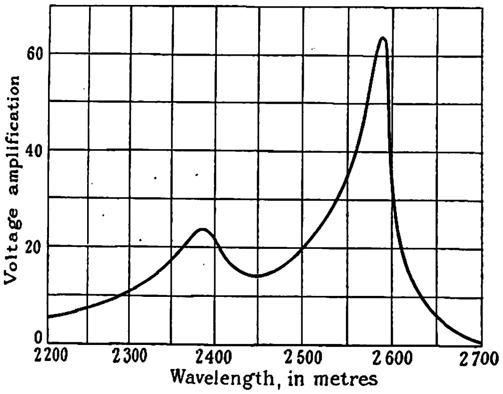

FIG. 24.

Using this characteristic, the selectivity of the receiver has been calculated for the particular wavelength of 325·7 m and is plotted in Fig. 26. By applying the known modulated e.m.f. to the frame-aerial circuit, an experimental selectivity characteristic was obtained and is plotted alongside the theoretical curve for comparison. The agreement between the two curves is considered to be good enough for most general purposes.

The overall characteristic was now obtained. Tests were made to find the relation between the output audio-frequency voltage delivered to the grid of the power valve in terms of the voltage applied to the frame aerial by means of the screened resistance. This resistance had a value of 0·76 ohm, and consequently the effective resistance of the frame aerial was slightly increased by this amount. However, the error introduced by this factor is small. To cover the wavelength range of 50–500 m two different frame aerials were needed, together with various coils for tuning the frame circuit and the secondary circuit (see Fig. 23). The various oscillator coils were marked to signify the approximate range of wavelength as follows:—Ultra-short, 100–200, 250–800, and the coils are referred to in the final results in this manner. Each wavelength can be received with two settings of the oscillator, one corresponding to the high setting of the oscillator condenser, and therefore to an oscillator frequency lower than that of the incoming signal, and the other corresponding to the low setting, in which case the oscillator frequency is higher than that of the incoming signal. These two conditions are referred to as the "high" and "low" settings respectively.

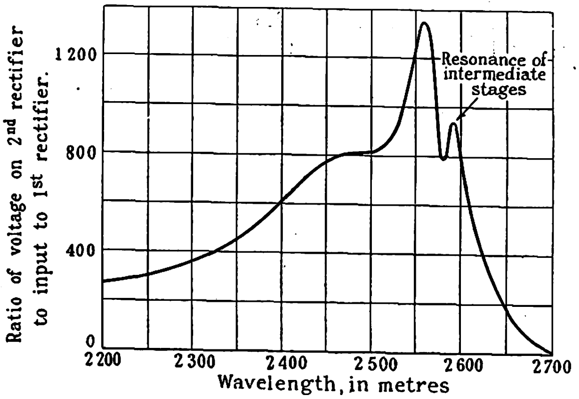

FIG. 25.

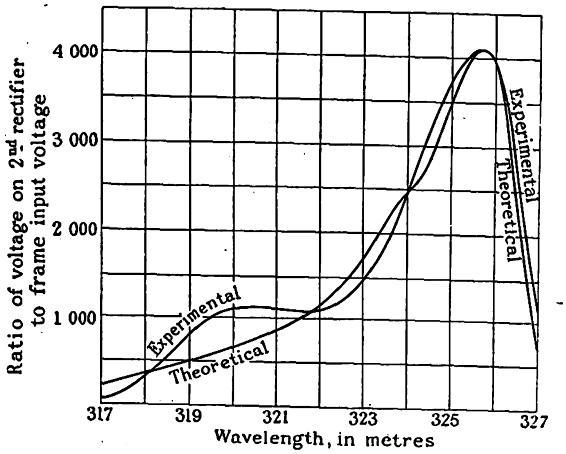

FIG. 26.

For the purpose of expressing the results in the most useful form, a constant output signal has been taken, corresponding to average telephone strength. This was found to be given by a voltage of 3 mV on the grid of the power valve. Accordingly all the measurements have been referred to this value. In Fig. 27 the e.m.f. required in the frame aerial at a modulation percentage of 100 to give the standard output of 3 mV is plotted against the wavelength for the different ranges and oscillator coils. For other modulation percentages the output is found to be proportional to the modulation percentage and would thus be reduced proportionately. The large difference in sensitivity between the two oscillator settings is most marked, particularly at the longer wavelengths. The current in the oscillator was found to rise almost proportionately with the wavelength. With the long-range oscillator coil (250–800) the sensitivity is far greater on the low setting, i.e. with a weaker local heterodyne, and the shape of the curve suggests that the sensitivity falls as the local heterodyne is increased with increase in wavelength. The obvious conclusion to be drawn from the form of this characteristic is that the local heterodyne is too strong. This could be improved by weakening the coupling to the frame aerial. On the other hand, the form of the remaining three sets of curves suggests that the local signal is too weak, since the maximum sensitivity always occurs when the oscillator wavelength is high, i.e. the local signal is large. It is well known that there is an optimum intensity for the local oscillation, and since no control is provided, it is not surprising that the optimum has not been obtained in this particular case. The two conditions, above and below this optimum, represented by the long and short oscillator coils illustrate the utility of such characteristics as a guide to improving the design of a receiver. The difference between the sensitivity characteristics for the high and low oscillator settings is small at the short wavelengths owing to the small difference between the condenser settings and consequently the small difference in the strength of the local signal, whereas at higher wavelengths the difference is very large.

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* H. A. THOMAS: "The Performance of Amplifiers," *Journal I.E.E.*, 1926, vol. 64, p. 253.

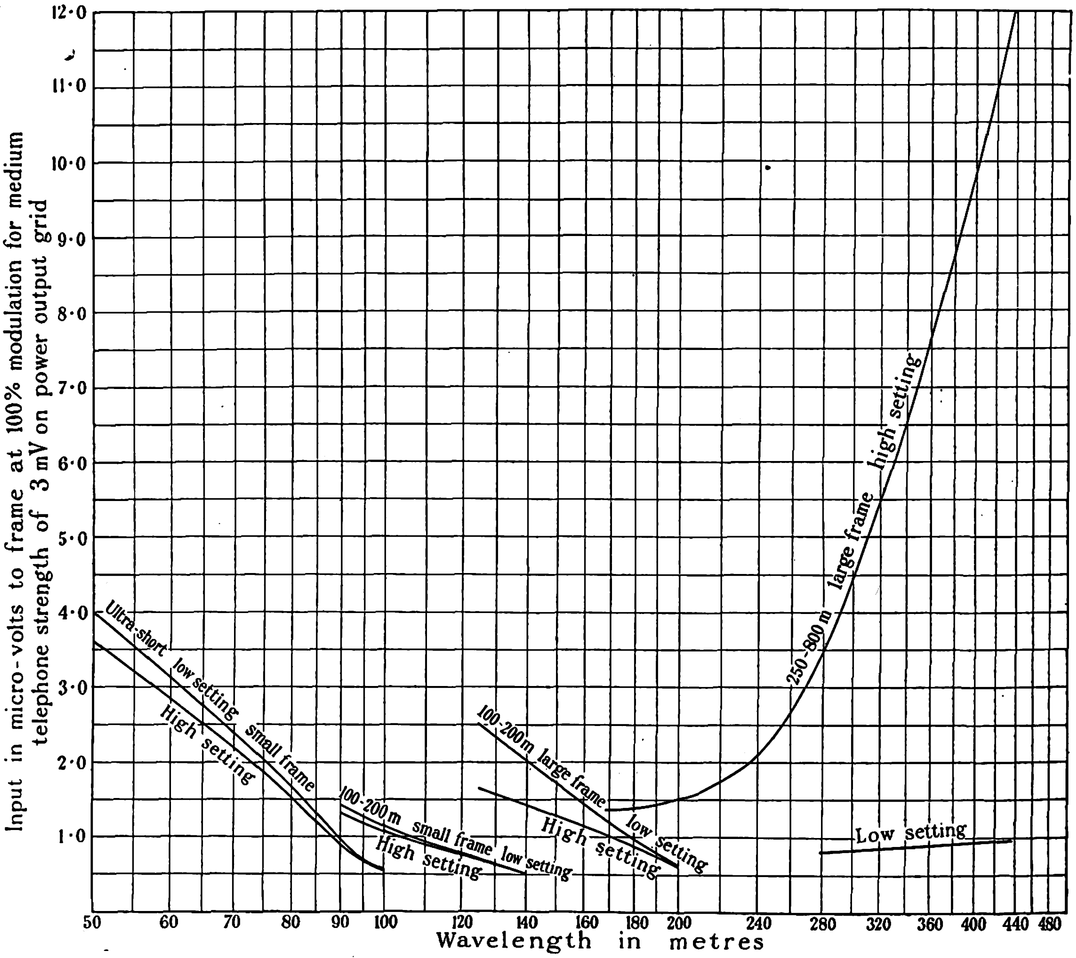

FIG. 27.

By means of the known dimensions of the frame aerials, the potential gradient required to give the standard signal of 3 mV can be readily calculated. This has been done in Fig. 28. By the use of this characteristic, the field intensity (μV/m) required to give the standard signal can be obtained for any wavelength, and this characteristic represents the complete performance of the receiver.

SECTION (3).—SUGGESTIONS FOR SPECIFYING THE PERFORMANCE OF RECEIVERS.

From a perusal of the foregoing examples of the properties of receivers, it is apparent that the overall properties of any receiver can be expressed in terms of three characteristics:—

(*a*) The input voltage required at a definite modulation percentage to produce a definite standard output signal at all wavelengths within the designed range.

(*b*) The sensitivity variation in the neighbourhood of certain fixed wavelengths—this gives the selectivity of the receiver.

(*c*) The output variation with constant input and modulation percentage but variable modulation frequency—this gives the frequency distorting properties of the audio-frequency stages.

The limiting range of any receiver is easily obtained by this means, and the range for medium loud-speaker reception can also be obtained in a similar manner. In the case of an open antenna this latter characteristic involves a knowledge of its effective height. In view of the accuracy with which field-intensity measurements can now be made, and the consequent knowledge of the field distribution from a transmitting station, the author feels that if similar field-intensity/output characteristics were forthcoming for receivers, a considerable step would be taken towards more scientific classification of types, and the immediate result of such a classification would be to improve the design of radio receivers.

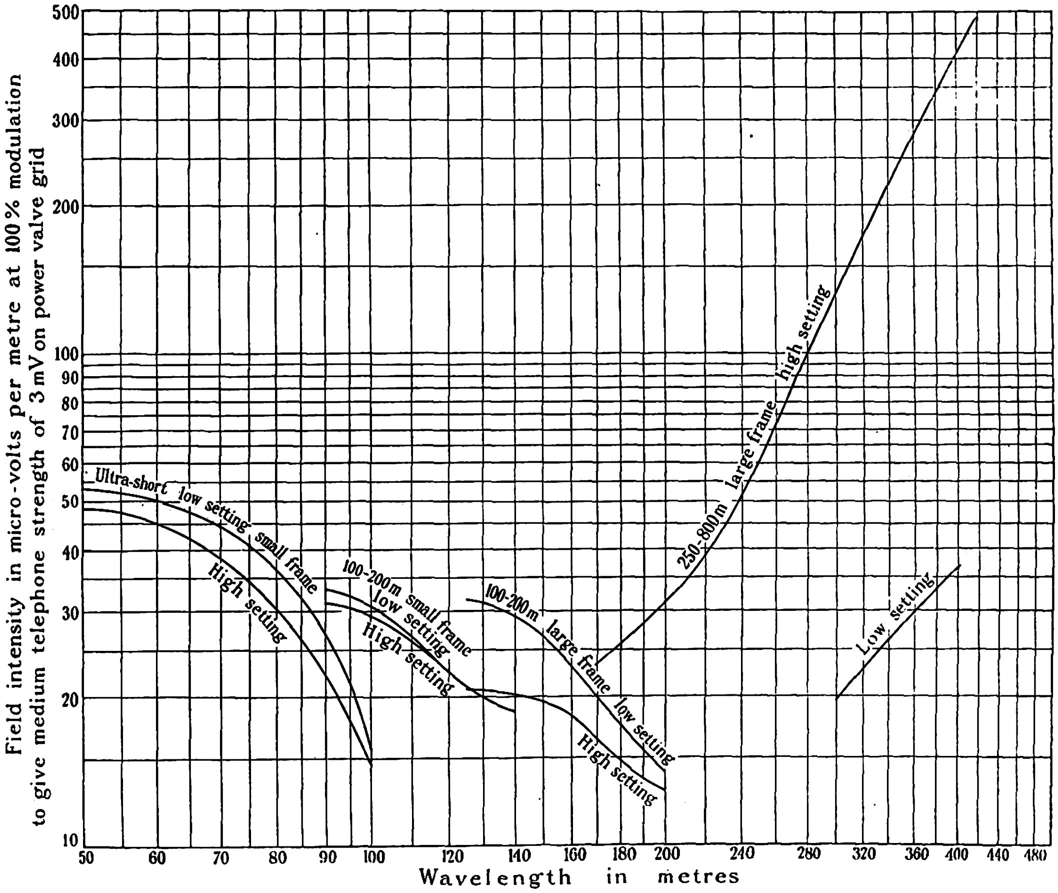

FIG. 28.

These three characteristics completely define the overall properties and, by means of them, the utility of a particular receiver can be obtained for any particular function. Oakley * has similarly concluded that these three properties are required to specify the overall performance of a receiver.

To determine the range of a receiver with respect to a particular transmitting station, two characteristics are required:

(i) The field-intensity characteristic of the transmitter expressed in the form of contour lines on a map.

(ii) The field-intensity/output characteristic of the receiver.

In a somewhat similar manner the classification of receivers into various selectivity categories would help towards the correct selection of a receiver for a particular purpose. The selective properties of a receiver could be expressed as a figure which could be appended to the previous characteristic at the different wavelengths covered by that characteristic. Such a simple system would simplify the final statement of performance and would, in fact, enable the radio-frequency properties to be expressed in the form of a single curve.

The audio-frequency properties of a receiver have received considerable attention, chiefly because such results are comparatively simple to obtain, and undoubtedly the progress in the design of audio-frequency amplifiers has followed measurements which have revealed the faults in the older types of amplifier. By means of an overall measurement, however, this characteristic would form a part of the tests and would take its place with the complete statement of the performance.

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* *Loc. cit.*

This work was carried out as part of the programme of the Radio Research Board and is communicated by permission of the Department of Scientific and Industrial Research. The author wishes to acknowledge the assistance given him by Dr. R. L. Smith-Rose and Mr. F. M. Colebrook, and also by his assistant, Mr. C. W. Spencer, in the latter portion of the work.

DISCUSSION BEFORE THE WIRELESS SECTION, 15TH JANUARY, 1930.

Dr. J. Hollingworth: In considering such a comprehensive piece of work as that described in this paper I think it is right that some recognition should be made of the special problems which have had to be dealt with. In a subject which is developing as rapidly as radio-telegraphy, one of the chief difficulties is that developments on the practical side tend to take place so rapidly that the scientific side has difficulty in keeping pace with them. In this particular case, when the research first started about six years ago bright-emitter valves with factors of 2 or 3 were still in general use and overall amplifications were comparatively small. With the development of valves of ever-increasing factors, however, continual re-design of the apparatus was needed to cope with the increasing sensitivity and accuracy needed. Another factor which invariably occurs in developing apparatus for a measurement which has not reached the stage of a routine technique is the difficulty of proving that the apparatus really measures the quantity it is designed to measure. It is, of course, impossible to determine this by a direct method and it can only be decided by a long and difficult process of cross-checking. The paper also emphasizes a most important point which, though generally accepted now, had a long fight for recognition, namely that a receiver-amplifier is fundamentally a single unit from aerial to loud-speaker, and except for pure theoretical study cannot be treated as an aggregate of parts. On the instrumental side two small points arise, both in connection with the screened resistances. The first is that the intervals of resistance given on page 477 seem to be rather irregular; one would have expected the interval given as 0·96 ohm to be nearer 2 ohms to give a regular series. The other is that these resistances, although absolutely suitable for their work, are rather elaborate to construct. In the light of experience gained with their use can the author say whether any form of simpler and less expensive construction could be used without sacrifice of accuracy? The remark on page 479 with regard to the loads placed on a circuit by a valve voltmeter may surprise many, but is not altogether unexpected by those of us who know from practical experience how extremely sensitive an amplifier may be to alterations in the output circuit. With regard to the statement on page 480, " It has been found that the output current given by the radio-frequency oscillator is sensibly proportional to $(V-K)$, where V is the high-tension d.c. voltage and K is an experimental constant," do not variations sometimes occur in the value of K? Some time ago, when valves were not so reliable, I used to find that K varied from day to day. With regard to the actual amplifiers themselves, the results completely confirm my experience that on short waves, retroaction is the vital factor. In a paper by myself and Mr. Naismith, read before this Section in 1929 * we described the application of this idea to the use of an untuned aerial. The hope which we then held, viz. that we were not losing a great deal, seems now to be justified. In my opinion it pays to sacrifice to a limited extent the amplification of the set in order to ensure optimum conditions for the retroaction. In the author's opinion, what is the probability, in the average set, of accurately repeating a reading? Although at one time such an achievement was regarded as impossible with an amplifier, this should not be the case provided that the retroaction is carefully designed.

Mr. P. K. Turner: I should like to know whether there is any means of communication between the two cabins A and B. The point is important, because if, for example, a telephone is connected between them the screening will probably be adversely affected. In the first paragraph the author states that the most important measurement which can be made in connection with a receiver consists of the characteristic relation between input and output, together with an analysis of the behaviour of the individual portions of the apparatus. Does not such a measurement embrace all the information which is obtainable in connection with the receiver? In connection with the statement that the whole of the screening was done with iron sheet, I should like to know whether this material was employed merely because it was found to be satisfactory, or whether it was considered to be definitely superior to copper in its screening effect. With regard to the point which Dr. Hollingworth has also mentioned, in connection with the heavy load imposed by a valve voltmeter, I have used a number of valve voltmeters under many varying conditions and have never encountered any serious trouble from the load at audio frequencies,. A valve voltmeter which produces an apparent saturation curve of the type shown in Fig. 4, is open to question, and I should like further information about it. In measuring up to 40 or 50 volts with such instruments I find the load imposed by the voltmeter to be that of a small condenser with a power factor of the order of 0·1 and a capacity of 12 to 20 μF. These values are quite definite, and, within the limits for which the voltmeter is designed, are independent of the voltage actually being measured. The type of receiver used for broadcast reception is of greatest interest to me. Most of the measurements made by the author are not of importance in connection with instruments of that type. For example, the measurements given on page 479, where the modulation percentage is never greater than 15, are not of much interest to me. In the general circuit diagram of Fig. 5 and elsewhere there are indications that the output is being measured across a 100-ohm resistance in series with the loud-speaker. Thus the reading of the output is a function of the loud-speaker impedance, and as in many cases the set has to be considered apart from the loud-speaker it may, in those cases, considerably falsify the results. Such would be the case in connection with Fig. 16, which shows the audio-frequency response characteristic. Unless the loud-speaker and set are designed to be invariably used in conjunction one with the other, it is not justifiable to measure their performance together. An alternative method is to put a pure resistance load on the last valve, usually of about twice the impedance of the latter, and to measure the amplification of the set under these conditions. By a simple calculation the change introduced by the loud-speaker can be found. In Fig. 6 the screened resistance is shown on the grid side of the tuned circuit; if the resistance, one side of which is earthed, were, in fact, to be inserted at that point, no measurements upon the receiver would have any meaning, because of the alteration to the input circuit of the set. Should not the resistance be connected on the earthed side of the input circuit? Critical retroaction is usually understood to be the condition which approximates most closely to oscillation. This definition is not, in my opinion, altogether satisfactory, and I would therefore ask the author how it is possible to ascertain whether or not a system is in a state of critical retroaction. In cases where the retroactive arrangements are bad, the voltage is fed back several degrees out of phase with the input voltage, and critical retroaction is easily obtained. The output rises to a maximum and then diminishes slightly just before oscillation occurs. If, however, the retroactive arrangements are well designed the voltage fed back is almost in phase with the input, the critical stage before oscillation is very indeterminate, and the degree of amplification is closely dependent upon the precise setting. On page 482 the relationship between the output and the modulation percentage is mentioned. This is of first-rate importance, and I am sorry that no curves are given for varying modulation percentage at constant carrier voltage, showing how nearly the rectification is linear. The author states on page 481 that "a typical modern 4-valve receiver" was examined, but I am doubtful whether this is an accurate description of the receiver in question.

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* " Portable Radio Intensity-Measuring Apparatus," *Journal I.E.E.*, 1929, vol. 67, p. 1033.

Mr. W. J. Brown: On page 479 the author states:—"the amplification must be expressed in terms of the voltage output delivered to the grid of the power stage with respect to some input voltage." Overall measurements on the receiver should definitely be made behind the output stage, as Mr. Turner has already suggested. His idea of including in the output circuit a resistance equal to twice the valve impedance seems to be a good one. Many of the author's measurements have been made under varying conditions of input and output, so that it is necessary in some cases to take input and output characteristics of the detector valve in order to interpret the measurements for constant input or constant output. I should like to suggest that, when specifying the performance of a receiver, all tests should be taken at a constant output power, and not necessarily with constant grid voltage on the power valve. The standards laid down by the Institute of Radio Engineers of America state that the measurements shall be made with a constant output of 50 milliwatts into an appropriate impedance. The sensitivity of the receiver is then expressed as the input signal which will give this constant output. A fixed percentage modulation of 400 cycles (40 per cent) is used for the purpose, while the input signal is usually expressed in terms of the field intensity in microvolts per metre, assuming a 4-metre aerial. In selectivity measurements the same principle of constant output might be employed in defining a standard test. The selectivity would then be measured by detuning the receiver by a certain amount and then increasing the input signal until the standard output had been obtained. The selectivity could then be expressed in terms of the detuning necessary when the input signal had been increased 10 or 100 times, for example. I am strongly in favour of the standardization of some form of test specification of the type suggested on page 489. I should like to ask the author how he has disposed of the difficulties to be met with in making measurements on a receiver which is close to oscillation. I suggest that it is almost impossible to measure, for instance, the selectivity of a receiver when the reaction is closely approaching its critical value. It may, therefore, be necessary to agree that such measurements should be made with the reaction adjusted to give, say, half the maximum attainable sensitivity.

Mr. T. H. Kinman: The measurements obtained on the higher frequencies are of particular interest to me and I should like to ask whether the inductive reactance of the input resistance, which is, of course, common to both filter circuit and input circuit of the receiver under test, was sufficient to cause interaction between these circuits when tuned to 10 megacycles and above. Such interaction would give rise to a variable reading on the input thermal meter "Q," Fig. 5. The author questions the value of the triode as a high-frequency amplifier for these higher frequencies. Has he made any measurements using a screen-grid valve for this purpose? My experience has been that with this type of valve not only is there a very useful high-frequency gain, but the tuning operation is, if anything, simpler, owing to the more uniform and less critical reaction adjustment required. No mention regarding the design of the thermo-couple is made in the paper, except that it was of the non-contact type. A thermo-couple designed for high-frequency measurements has been developed in America. It is assembled in such a way that the shunting capacity between its extremities is negligible. When dealing with very high frequencies, the usual construction is unsuitable owing to the shunting capacity across the pinch through which all the wires are usually brought out to base terminals.

Mr. A. G. Warren: I have encountered some difficulty in attempting to deduce Fig. 11 from Figs. 6, 7, 8, 9, and 10, arising from the fact that the conditions under which Fig. 9 was obtained are not given. The paper would be improved if these particulars were inserted.

In connection with the voltage measurement, can it be assumed that the voltage applied is equal to the product of the measured current and the resistance? Although this is usually the case, it may be incorrect when low-loss tuning coils are employed. I cannot agree that the three characteristics given on pages 488 and 489 for specifying the performance of receivers supply all the necessary information. The first deals with sensitivity which, in broadcast receivers, is not important as the signals received are usually strong. With regard to the third characteristic, which is of great importance, I would re-write the closing phrase in this way: "This gives the frequency-correcting possibilities of the audio-frequency stages." As has been already remarked, the set has to be designed with the loud-speaker, and even the best loud-speakers call for correction by adjustment of the audio-frequency characteristics of the set. A listener requires that his receiver shall be able to discriminate at all intensities between wood-wind and strings, and that the tone of a piano shall be correctly reproduced. These conditions are not, in my opinion, included in the three characteristics. The first condition may be put into a practical form as the measurement of the second harmonic at a standard modulation of, say, 50 per cent. With the parabolic rectification which the author shows, the second harmonic might be rather distressing. I cannot, without further consideration, suggest a test appropriate to my second condition, but doubtless a means of estimating the response of the set to transients could be devised.

Mr. M. G. Scroggie: The author describes in detail his screened cabin for the oscillator, and then goes on to state: "The amplifier, too, must be housed in a screened room to prevent induction from external sources." Surely the oscillator is an external source and therefore need not be screened, provided that the screening of the amplifier is satisfactory. It is common practice in America to have only one screened compartment in apparatus for measuring the overall performance of receivers. The oscillator is just outside the screened compartment containing the amplifier, and cannot affect the latter except through the chosen channel. In production tests it is found possible in a number of cases to dispense even with the screening of the amplifier. This can be effected by doubling the frequency of the oscillator so as to produce sufficient difference in tuning between the amplifier and the oscillator to prevent direct action between them. Although used only for comparatively inaccurate tests, the method should be valuable because, as Mr. Turner mentioned, the apparatus shown by the author is rather difficult to operate. It differs from accepted American practice in the method of measuring the high-frequency input to the amplifier. Rather than to measure directly the small current applied through the resistance might it not be more convenient to use a less delicate current-indicating instrument followed by a calibrated attenuator? The method of measuring the output, which necessitates a separate calibration of the power stage in each case, seems to me to be unsatisfactory. In my opinion a suitable type of valve voltmeter presents no difficulty when used in an audio-frequency circuit. The difficulty of defining critical retroaction seems to be the one outstanding problem in this class of measurement. In America the standard broadcast receiver uses no intentional reaction and is usually incapable of oscillation, so that the difficulty does not arise to the same extent. In broadcast practice, at any rate, the difficulty will probably disappear from this country also, owing to the tendency to abolish intentional reaction. It is unfortunate that some receivers of more modern design were not included as examples. The standard practice, at any rate in broadcast apparatus, is to use screen-grid valves. These would show a far closer approximation to the amplification one would expect and would give, with ordinary components, a stage amplification of the order of at least 30 to 40 on the usual broadcast wave-band. The effect shown in Fig. 11, where the amplification increases rapidly at the high-frequency end, which effect is clearly due to unintentional feed-back, would not occur to anything like the same extent under the conditions of standard broadcast practice. The curve in Fig. 8 does, however, show up in exaggerated form the effect which is obtained even with screened-valve amplifiers, owing to the use of tuning circuits in which the capacity is variable and the inductance is fixed. If a curve of amplification against frequency is drawn, either for the threshold of instability or for constant stability, it will fall towards the high-frequency end owing to the greater admittance of the anode-grid capacity of the valve, as indicated in Fig. 8. It is desirable for the tuning characteristics to be such that the actual amplification curve is one of constant stability and therefore parallel to the threshold curve and on the lower side of it. This is obtained if both capacity and inductance are varied in a definite relationship, but a very good approximation to this ideal is obtained if the capacity is fixed. The amplification curve in the case of a variable-capacity tuning circuit cuts across the ideal curve almost at right angles. The result is that the amplifier tends to be too unstable at the high-frequency end and too "dead" at low frequencies. One advantage of a screened-valve amplifier is that the constant-stability curve is far more horizontal than that, for example, of Fig. 8.

Mr. J. H. Reyner (*communicated*): It is clear from an examination of the paper that a great deal of time and trouble have been involved in the preparation of the apparatus described. The author dismisses in a few words difficulties which must have taken weeks to overcome, and those conversant with methods of testing receivers must feel some disappointment that these difficulties have not been dealt with more fully. Previous speakers have commented upon the fact that the apparatus is of a precise nature and unsuitable for commercial use, although much of the data will be of value in the preparation of simpler equipment. It will be interesting to have the author's views on the possibility of producing a less complicated apparatus. I have been experimenting for some time with the production of small modulated high-frequency voltages which can be introduced into a receiver for the purpose of checking the performance. The voltage has been introduced into a dummy aerial or directly induced in the frame aerial of the receiver, according to circumstances. This is the American practice and does not involve any alteration to the receiver itself. It has been found possible with a small apparatus some 2 ft. long, doubly screened, to produce and control voltages as small as 0·1 millivolt, which corresponds to a signal strength of 0·025 millivolt per metre, assuming a 4-metre aerial. This value of signal strength is distinctly smaller than that of the customary foreign stations which may be tuned in on any good modern set. It should be added that the experiments have been concerned mainly with frequencies below 1 500 kilocycles per sec., but some work has been done on much higher frequencies, with fair success. The most difficult part has been the production and calibration of a suitable method of coupling the receiver to the oscillator. The method which appears to be most satisfactory is an inductively coupled system which is calibrated by direct measurement, using a primary current many times larger than that employed in practice. This involves the assumption that the mutual inductance remains the same for small currents, which seems a reasonable supposition. The author condemns the inductively coupled method early in the paper, but it would appear to be the only practical method for a commercial testing equipment, since in order to obtain voltages as low as 0·1 millivolt by the voltage-drop system described in the paper the current would have to be too small to be measurable on any commercial instrument. An alternative method is the use of an attenuator, as mentioned by Mr. Scroggie. In this connection the Standardization Report for 1928 of the Institute of Radio Engineers is of considerable interest. Regarding the proposed specifications mentioned in Section (3), there can be no doubt that some such characteristic should be measured definitely on receiving equipment in order to obtain figures of merit. There is, however, a fourth characteristic about which we seem to know very little. This concerns the question of proportionality of input and output strengths. If the modulation of the incoming signal is increased by a certain amount, the low-frequency output should increase in strict proportionality, which it does not do in the majority of present-day receivers. The question is entirely separate from considerations of frequency distortion and is responsible for the poor behaviour of the average reproducing system on such instruments as the piano and similar instruments having a high percentage of transients. Mr. Warren has referred to this defect, but I believe that the root cause of the unsatisfactory reproduction is not well known. My experiments for some time past have all pointed to the lack of truly proportional amplification on differing strengths of signal as the fundamental defect. The greatest difficulty in the way of all such measurements arises from the use of reaction, which is still very popular in this country and is likely to remain so for many years. Not only does this affect the first of the proposed standard tests, but the second and third are also bound up with the amount of regeneration employed, while Mr. Turner has pointed out the extreme difficulty of defining the oscillation point. The attitude which I have continually encountered in discussions on receiver-testing is that while the performance of the receiver is dependent to such an extent upon the adjustment of the reaction control, any definite measurements are of academic interest only, and this point of view is difficult to combat. In America, simple modulated high-frequency oscillators are used as a matter of course by all concerns of any magnitude in the design, production and testing of their receivers. The technical public is, in consequence, educated to the idea and some real progress is being made in the matter. It would appear that the best method of procedure in this country is for the manufacturers themselves to commence forthwith to make receiver tests on the lines suggested in the paper. They will encounter difficulties peculiar to our own conditions and will doubtless devise their own methods of overcoming them. In due time, the industry as a whole will acquire the measurement habit which involves thinking and speaking in terms of definite data. If the present paper is responsible for development of this nature, the author will have rendered the industry a valuable service.

Mr. H. A. Thomas (*in reply*): With reference to Dr. Hollingworth's remarks, I would point out that many apparent defects in the final apparatus are due to the successive processes of rebuilding, modification and improvement which the equipment has undergone from time to time as points once considered essential have turned out to be of little account, whereas other details have been found to be all-important. All original apparatus is built in this way and, when in its final form, it is usually found that a great simplification can be made. If the apparatus were to be rebuilt it would take a quite different form as a result of the experience obtained with the original model. The input resistances have values which are not very accurately progressive, this being due to the difficulty of obtaining accurate lengths of the small-gauge resistance wire. The difficulties encountered in connection with the instruments were considerable and, since the range obtained by the first set of resistances was found to be sufficient for the purposes in hand, no modifications were made. Although it would be possible to simplify the design of these resistances, it must be remembered that accurate centring of the wire and adequate insulating and screening of the tapping lead involve rather a delicate construction. Comment is made regarding the effect of the valve voltmeter as a load on the output circuit, and I am glad that Dr. Hollingworth appreciates the effects which can be produced by such small loads when successively passed through the earlier stages of the amplifier. I have found that the value of K remains sensibly constant for the dull-emitter, low-amplification-factor, low-resistance valves that have been used. Undoubtedly the setting of the retroaction control to give critical reaction is delicate and the difficulty of reproducing conditions considerable, but with great care it was found that these critical reaction figures could be repeated to within 5 per cent in most cases.

In reply to Mr. Turner's remarks, I would point out that telephonic communication is maintained between the two cabins by means of screened leads which traverse a filter circuit of such design that no appreciable radio-frequency current passes along the line. Iron was used as the screening metal because of its superiority over copper. I would refer Mr. Turner to a paper by Dr. Smith-Rose * in which it is shown that the penetration of the eddy currents into the conductor is governed by the well-known "skin-effect" formula; the latter therefore determines the fraction of the original magnetic field which penetrates to any depth into the conductor. The decay factor governing the amplitude of the radio-frequency current at a depth x below the surface of the metal is $\epsilon^{-2\pi\sqrt{[(\mu f/\rho)x]}}$, where μ and ρ are respectively the permeability and resistivity of the metal, and f is the frequency of the alternations. Using this formula, the reduction in the field strength can be calculated for a screen of any given thickness and it can easily be shown that at medium radio-frequencies iron is 5·5 times more effective than copper if its thickness is the same. It is also clear that the screening effect is greatest at very high frequencies and that at audio frequencies effective screening becomes increasingly difficult. The load imposed by the valve voltmeter is not large if the last stage only is considered, but the effect of a small load may be serious when this load reacts back through the earlier stages of the amplifier. These were the conditions which were obtained in Fig. 4, and in view of the results it was considered expedient to use the voltmeter in the manner finally adopted. The figure for modulation (taken as 15 per cent) is an average value for good telephony transmission. Admittedly the figure is often greatly exceeded, but this fact does not invalidate the contention that 15 per cent is considered to be sound practice. In any case, the results with a greater percentage of modulation can be readily deduced from the curves given in the paper, since proportionality was found to exist up to a modulation percentage of 60. Mr. Turner criticizes my method of measuring the output and suggests that the properties of the amplifier should be determined with a resistance load, from which the actual properties with a loud-speaker can be estimated by "a simple calculation." I disagree with this—a view which is only too common. If the performance is determined with such a resistance load the input impedance of the last stage is greatly modified, and this impedance reacts back successively through each stage to the input. The effect on the early stages may be very considerable, especially if these stages have a high voltage-factor, and the calculation of the performance with an inductive load instead of a resistance load is far from simple. Again, the loud-speaker impedance is a very complex quantity involving a variable static and dynamic resistance and a static and dynamic reactance at different frequencies. In view of this fact it is essential that the receiver be measured under the actual conditions of use and I have laid great stress upon this point in the paper. Mr. Turner will see that I calibrate the last stage by applying to the grid an audio-frequency e.m.f. of the same frequency as the modulation, and obtain readings on the valve voltmeter. The 100-ohm shunt of the latter produces a negligible series modifying effect, and by this method the actual load is always in circuit. I agree that it would be an advantage to have a definite figure of amplification for the amplifier irrespective of the load, but this cannot be obtained, since every change in load affects the amplification characteristic. I must apologize for an error in drawing Fig. 6. The screened input-resistance is always used on the earthed side. My reply to Dr. Hollingworth covers the next portion of Mr. Turner's remarks on critical retroaction. A maximum figure was felt to be necessary and, as previously stated, it was found possible to obtain this with sufficient accuracy for most purposes.

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* R. L. Smith-Rose: "On the Electromagnetic Screening of a Triode Oscillator," *Proceedings of the Physical Society of London*, 1922, vol. 34, p. 127.

My reply to Mr. Turner covers the first part of Mr. Brown's comments. I cannot see that any advantage is to be gained by substituting a power relationship. It appears to me that an amplifier is essentially a voltage device and that, having obtained the voltage on the power-valve grid, it is easily possible to obtain the output power if the last stage is considered to be a power relay and the input is regarded as a controlling voltage. The American tests give selectivity characteristics in terms of the input signal at the various radio frequencies necessary to provide a constant output; these characteristics have the appearance of an inverted resonance-curve. Either method of expressing selectivity is permissible, but I do not see that much is to be gained by departing from well-established practice in this matter. The appearance of these characteristics is puzzling at first. The suggestion that the reaction should be so set that the amplification is one-half of the maximum attainable is interesting, but does this not involve a previous determination of the maximum value?

With reference to Mr. Kinman's remarks, the reactance of the input resistance was always so small that its effect was negligible up to a frequency of 10 000 kilocycles per sec., and at 20 000 kilocycles it only added about 5 per cent to the net impedance of the input resistance. The tests were performed before the screen-grid valve was manufactured commercially, and consequently the remarks made in the paper are not meant to apply to such valve circuits. The thermo-junction used was of a well-known standard commercial type. It is interesting to note that recent work by Mr. F. M. Colebrook at the National Physical Laboratory has confirmed the fact that this type of junction is suitable for current measurement up to frequencies of the order of 10 000 kilocycles per sec., with an error not exceeding a few per cent.

I must thank Mr. Warren for pointing out the absence of sufficient information in Fig. 9. I have inserted the necessary information for the *Journal*. The point raised regarding the value of the voltage inserted in the tuned circuit is important. I agree that if the tuned circuit has a very low resistance it will exert an appreciable shunting effect upon the input resistance. In the tests described, however, the magnitude of this effect was never in excess of 7 per cent. In the case of critical reaction the shunting effect may be serious, but difficulty arises as to the determination of the effective resistance of the input tuned-circuit. I agree with Mr. Warren that a test of the response of the audio-frequency portion of the amplifier to transients would be very valuable, but the technique of this problem is not at present available. The response to a sudden applied signal, such as a square wave-shape, would be an indication of the effects which would be produced if a transient were applied.

Mr. Scroggie refers to the use of two cabins: it would be possible to dispense with one of them in a reconstruction of the apparatus, but the remaining small cabin, which at present contains the permanent oscillators, would have to house the receiver—and the latter could not be erected in such a confined space without radical alterations in the construction of the cabin. It must be remembered that the apparatus described has been produced by repeated modifications and the final arrangement is, admittedly, not perfect. I do not agree that a larger current and an attenuator are preferable to the method described. In the first place, it is not true that the accuracy of measurement of a large radio-frequency current is superior to that of a small current. As has already been stated, recent work by Mr. Colebrook has shown that the small current measurements given by vacuum junctions are reliable to a few per cent up to very high frequencies of the order of 10^7 cycles per sec., and, even if attenuators were accurate, I see no necessity for using them if the ideally simple screened resistance can be employed. Again, the impedance of the secondary of the attenuator introduces an impedance into the input tuned circuit which must be allowed for, and the screening needs to be more elaborate in the case of the larger current.

In reply to Mr. Reyner, I fear that a detailed statement of all the difficulties encountered would make the paper unduly long and would make rather tedious reading. As I have already pointed out, the apparatus could undoubtedly be materially simplified if there were a demand for such a complete reconstruction. I do not think there is any great difficulty in obtaining an input of 0·1 mV by means of a screened resistance. H. D. Oakley * uses this method with satisfactory results. With reference to Mr. Reyner's concluding remarks, I hope that the manufacturers of this country will adopt statements of a more scientific nature regarding the performance of their receivers than they have done hitherto. The object of the paper is mainly to indicate the lines along which development in this direction should take place.

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* H. D. Oakley: "Quantitative Determination of Radio Receiver Performance," *Transactions of the American I.E.E.*, 1927, vol. 46, p. 498.

ADDRESS TO THE SHEFFIELD SUB-CENTRE

By Colonel Sir Thomas F. Purves, O.B.E., President.

(*Address delivered at* Sheffield *19th February*, 1930.)

In seeking for a suitable subject on which I might address you, I experienced a kind of *embarras de richesses*. The field of interest of our Institution is a very wide one, for within its ranks the Institution includes engineers dealing with practically all the multifarious uses to which electricity is applied in the service of man. Since, however, I am to some extent a representative of communications engineering, whilst many in this audience are representative of the heavy-current engineering activities of the great industrial areas of the Midlands, I have thought it well to address myself to what we may call the meeting point of these two branches of electrical engineering and to the problems which arise from their co-existence side by side.

It can be said that practically every application of electricity to a special purpose derives some of its success from the work of all the other branches of the art. On the other hand, there are characteristics associated with some applications of electricity to the purposes of industry which can, or may, be harmful to work in other branches providing equally important public services.

The first successful applications of electricity to the every-day practical needs of the community were concerned with communications, and as the use of stronger currents for lighting, power and traction purposes developed, it speedily became evident that difficulty would be experienced in preventing the latter from paralysing the activities of its elder, but weaker, brother.

Efforts to devise means of safeguarding the existing and essential art of electrical communication have been reflected in various Acts of Parliament, and much has been written of the so-called conflict between the "weak current" and "strong current" interests in the past. Solutions have now been found of many difficulties which appeared to be almost insurmountable in the early days, but the urgent public need for the increase of both power and communications services continuously presents new difficulties in more and more acute forms, and the subject is still of great interest and importance. I propose therefore to devote a little time this evening to dealing with recent developments, and more particularly with the efforts now being made to solve the outstanding problems by the co-operation of all the parties concerned.

Many of you know that there has now existed for some years an international organization called the "Comité Consultatif International des Communications Téléphoniques à Grande Distance," fortunately capable of being referred to in brief as the "C.C.I." This organization was inaugurated for the purpose of solving technical problems in connection with long-distance telephonic transmission and for the standardization, as far as possible, of line transmission plant, apparatus, and methods of exploitation. The C.C.I. consisted at first of representatives of the various telephone administrations of Europe, but more recently the field of membership has been extended and made practically world-wide.

An important special matter which has been the subject of continuous study by the International Committee is the protection of communication lines against interference set up by power circuits in their vicinity. Such interference may take the shape of electrolytic damage to the lead sheathings of cables by leakage currents from traction systems, of inductive interference with communications, or of direct injury to plant or personnel by contact with high-voltage lines. The questions of electrolytic damage and inductive interference have hitherto been given most consideration, and in arriving at its conclusions the C.C.I. has had the advantage of co-operation with representatives of the power side of the industry through certain international bodies, including the Union Internationale des Chemins de Fer (International Union of Railways), the Conference Internationale des Grands Reseaux Electriques à Haute Tension (International Conference on High-Tension Electrical Lines), the Union Internationale des Producteurs et Distributeurs d'Energie Electrique (International Union of Producers and Distributors of Electricity), and the Union Internationale de Tramways et Chemins de Fer d'Interet Local (International Union of Tramways and Local Railways).

The " Recommendations " issued by the C.C.I. in connection with the protection of cables against corrosion due to electrolytic action follow Continental practice in that the " isolation " system is favoured, in preference to the system of " electrical drainage " or the connection of cable sheaths and pipes with the negative return or busbar. At the moment there is a decided difference of opinion among engineers as to the best way of tackling the universal problem of protection against electrolysis set up by stray currents from tramway systems.

One school advocates the " isolation " system and the other " drainage." In Switzerland, Germany and other Continental countries the connection of cable sheaths or pipes to the uninsulated rails or negative busbar of a tramway system is forbidden, whilst in America such connections are common practice.

In this country the position is somewhat peculiar. Although the Regulations of the Ministry of Transport appear to aim at an isolated system—except that the negative busbar or the points of connection of negative feeders to the rails have to be earthed—the practice of connecting the sheathings of their cables to the rails and/or to the negative busbar has grown up amongst tramway undertakers.

The " drainage " school claim that their method tends to ensure immunity from electrolytic action by stray currents, whilst the advocates of " isolation " say that drainage systems extend the danger area and thus jeopardize, or increase the danger to, the cables and pipes of other users of the soil. It should be observed that the Advisory Committee on Railway Electrification appointed by the Ministry of Transport, advised isolation for electric railways in this country.

So far as a telephone administration is concerned, the isolation system has much to commend it. At all events it is clear that the connection of cable sheathings to rails and negative returns should only be made after careful electrolytic surveys have been carried out in order to determine the proper positions for the connections, and that, when the connections have been installed, there should be continuous control and supervision to ascertain whether plant extensions and developments may have made it essential to alter the positions of the drainage connections.

Apart from the question as to which method of providing protection is the more effective, it is clear that the " isolation " system places the responsibility for maintaining satisfactory stray-current conditions upon the traction authority, whilst the " drainage " system shifts the responsibility to the shoulders of the cable or pipe owner, who is burdened with additional and recurring expenditure for maintenance and supervision of drainage connections.

In connection with the inductive interference problem the C.C.I. has issued *Directives* (guiding principles) which indicate the best practice to be followed by the electric power industry and by the telephone administrations in order to minimize trouble. Current and voltage waveshape, tooth ripples, harmonics and methods of protectively balancing the telephone lines, are all dealt with. Tolerable limits of induced voltages, etc., are defined and methods are specified for the predetermination of the induced voltages which will be set up under given conditions by all the usual types of power installations.

Whilst the *Directives* cover the subject so far as up-to-date experience and research have taken us, there are many outstanding questions which require further investigation, and arising out of this an international body has been set up to carry out research into problems that jointly concern the power and communication interests. This offshoot of the C.C.I. is called the " Commission Mixte International " (C.M.I.). It is composed of representatives of the C.C.I. and of the international bodies I have already referred to.

Responsibility for necessary investigations has been distributed between the various European telephone administrations and the power interests, and a programme of work has been drawn up. At the last meeting of the C.M.I. it was decided to extend the programme to include the protection of pipes and cables against electrolytic and chemical action, and to enlarge the membership to embrace the gas and water industries, who are equally concerned with this problem. Further, it was decided to include a class of " associate members " in the organization, as it was evident that a very large proportion of the electrical industry is not represented by the international bodies now acting.

The problem of adequate representation of the electric light and power industry of Great Britain, both in connection with the work of the C.C.I. and the C.M.I., has been a matter of considerable concern to me, since the international associations mentioned do not appear to receive any considerable degree of support from this country. The formation of the associate membership class of the C.M.I. appears to afford a way out of the difficulty. The Institution of Electrical Engineers has itself joined as an associate member.

The outstanding problem at the moment in connection with inductive interference is concerned not with "disturbance," but with "dangerous" induced effects. The great increase in the use of electrical energy for power and traction purposes, and the transmission of such power by means of overhead lines working at very high voltages, has brought about conditions which may endanger not only telegraph and telephone plant and apparatus but also the engineering and operating staff, and the members of the public using the communications circuits, even when there is no direct contact between the two sets of plant.

These dangerous effects are produced inductively and, ignoring traction systems, take place only on the occurrence of faults or in some cases during switching operations on the power systems. The telephone plant may be damaged by the breaking down of insulation of apparatus or lines, and in severe cases by the outbreak of fire.

In the matter of danger to staff, the lives of personnel may be jeopardized by shock; for example, a man may be caused to lose his hold when in a hazardous position on a pole, or, if very severe, death or permanent injury may be caused by the passage of the induced current through his body.

Further, and this is much the more common, operators and telephone users may be adversely affected by "acoustic shock." Serious acoustic shock is caused when voltages sufficient to operate the lightning protectors (about 350 V) are induced in the two wires of the telephone circuit. When this occurs it is certain that the lightning protectors, one of which is in each leg of the circuit, will not act simultaneously, and the consequence is that the charge passes through the operator's set, and the diaphragm of the telephone receiver is brought into violent contact with the pole-pieces. The ear may be damaged and, even if it is not, frequent disturbance of this kind adversely affects the nerves of the person listening, and in the case of telephone operators may cause such loss of *moral* that continued work is impossible. In such countries as Germany and America where power systems are highly developed, the amount of trouble caused in this way has been very serious.

It should be observed that "acoustic shock" appears to be chiefly associated with the operations of 3-phase systems employing an unearthed neutral point, as with this type of system "arcing earths" may be set up by the failure of an insulator, and these may persist without the circuit breakers coming into action. The unearthed neutral system has, however, an advantage over the earthed neutral in that it is not necessary with the former to arrange for such great separating distances in cases where the power lines run parallel with communication circuits.

With the earthed neutral system, which is the common practice in this country, the occurrence of a fault to earth, on any phase, results in the passage of a considerable current between the fault and the earthed neutral point. This current, passing through the faulty phase and earth, acts by electromagnetic induction on neighbouring communications circuits and may produce very dangerous effects. The intensity depends upon the strength of the fault current to earth, the separating distance between the power line and the communication circuit, and the length of parallelism.

This problem is of first-rate importance at the moment in connection with the installation of the "grid" by the Central Electricity Board, which, as you are aware, is to be operated at 132 kV with the neutral point directly connected to earth at all feeding points.

The Post Office has adopted the figure of 300 volts, given by the *Directives* as the maximum longitudinal voltage that can be allowed in a communication circuit on the occurrence of a fault to earth. The calculation to determine whether under any given condition this voltage will be exceeded is a matter of great difficulty. Formulæ for the calculation of the coefficient of mutual induction have been developed by Breisig, Rüdenberg, Pollaczek and Carson. These formulæ agree with experimental results in certain circumstances, but none of them can be said fully to meet the general case. Further, in applying the formulæ one of the principal factors, the specific resistance of the earth, is difficult to determine, since the earth is not homogeneous and in any case the measurement is a difficult one. In the first instance the C.C.I. recommended that the Rüdenberg formulæ should be used, with an assumed value of 20 000 ohms per cm^3 as the resistivity of the earth.

Subsequent to this recommendation a number of investigations were carried out in Germany, and also in this country, which go to show that the formula of Pollaczek gives results more in agreement with those obtained by actual tests, and, further, that 20 000 ohms per cm^3 is too high a figure for general use. On the other hand, investigations in Sweden show that the earth resistivity of 20 000 ohms is exceeded in some parts of that country. It should be observed that the higher the specific resistance of the soil the greater will be the induced voltage.

The investigations in this country were carried out in co-operation with the Central Electricity Board, utilizing for the purpose the British Electrical and Allied Industries Research Association, and as a result it has been agreed that Pollaczek's formula shall be employed when calculating the probable inductive effects on the occurrence of earth faults on the Board's 132 000-V overhead lines. The resistivity of the earth will, in general, be assumed to be 4 700 ohms, in accordance with a modification of the *Directives* adapted at the plenary meeting of the C.C.I. held in Berlin in June last.

It is stipulated, however, that where power lines are projected in neighbourhoods where it is known that the geological conditions point to higher resistances of the soil, tests will be made beforehand to ascertain whether a higher figure than 4 700 ohms should be taken.

The calculation of the values of earth fault currents to be expected where an extensive and complicated network is concerned appears to be a matter of some difficulty. Although fault currents to earth as great as 5 000 amperes have been suggested as possible, the engineers of the Central Electricity Board are at the moment somewhat non-committal. To ensure safe conditions for such large currents the power lines and communication circuits would have to be separated by great distances if the routes ran parallel for any considerable distance.

With the existing extensive system of Post Office overhead and underground lines it is a difficult matter to find routes for the " grid " which will avoid parallels with relatively close separation. The design of the Central Electricity Board's " grid system " includes a high-conductivity steel-cored aluminium earth-wire connected to every tower and thereby to earth. It has been proved, both theoretically and by experiment, that a reduction of about 33 per cent in the induced voltage is brought about by this arrangement. Making due allowance for this, however, the position is not free from anxiety, which only satisfactory working experience can remove.

Although this Address is already larger than I had intended, I should like to add a few words about " Crossings of Post Office Lines by the ' Grid ' Transmission Lines."

The construction of the " grid " has confronted the Post Office with a difficult problem as regards the course to be followed in providing satisfactory protection to Post Office lines where they are crossed by the transmission lines.

It has been urged that the factors of safety used in the construction of the " grid " are so liberal that risk of a breakdown which would result in direct contact with Post Office circuits is so small that it might be ignored. The breakage of conductors from various causes which are not covered by factors of safety cannot, however, be ruled out of the range of possibilities, and in view of the consequences of an accidental contact, especially as regards risk to life of Post Office personnel and to users of the telephone system, it is felt that the attitude of the Courts and of the public would be such that the absence of any specific precautions would be condemned in the event of a serious accident.

In the case of subscribers' circuits there is no particular difficulty in following the normal procedure of putting the Post Office circuits underground at the crossing points, but the position as affecting trunk lines gave rise to some concern.

In the past every effort has been made to avoid the degradation of the transmission efficiency of important aerial trunk lines produced by the insertion of short intermediate lengths of underground, and protection has been provided at high-tension crossings either by placing the power line underground or, where this course was not feasible, by the erection of a cradle guard beneath the power line. Neither of these measures is practicable in the case of the " grid," and the alternative of placing the trunk circuits underground at the danger points has had to be accepted.

In deciding on this procedure we were also influenced by apprehension of the disturbance likely to be produced by electrostatic induction where an aerial telephone line is crossed by a 132-kV overhead line. German experience and calculations have indicated that where voltages exceed 100 kV, and there is more than one crossing, excessive noise will be produced in the telephone circuits during normal operation of the power line, with the possibility of acoustic shocks on the occurrence of faults.

It can be taken that an induced difference of potential of 5 mV between the two sides of a telephone circuit will result in excessive noise when the frequency of the induced current is of the order usually produced by power-circuit harmonics.

Unfortunately, the main roads in this country along which telephone trunk lines have been built are on the whole rather tortuous, and consideration of the routing proposed by the Central Electricity Board showed that many important telephone trunk circuits would be crossed several times. The effect on telephone transmission of a number of short underground lengths is serious, but in view of the considerations which I have mentioned it was reluctantly decided that there was no reasonable alternative to burying the Post Office lines at the crossing points.

The placing of trunk telephone circuits underground at crossings is, in practice, being effected by the use of a number of 8-pair, 70 lb. star quad cables appropriate to the size of the overhead route. This cable has a specially low wire-to-wire capacity designed to alleviate somewhat the prejudicial effect of the underground section. The use of a number of small cables, in place of a single cable large enough to carry all the circuits, should tend to limit the possible effect of damage to the underground section in the event of the overhead line suffering from the effects of lightning.

I think it will be obvious to all that the difficulties to which I have briefly referred to-night will necessarily be accentuated as the use of electricity expands and greater and greater amounts of power have to be generated and transmitted over long distances.

No doubt new problems will also arise and, if they do, I trust that they will all be tackled on the lines which I have described, that is, by co-operation between the interested parties. The " Commission Mixte International " is an attempt to provide the machinery for such co-operation. It is perhaps necessary to point out that the C.M.I. is solely concerned with the solving of technical problems and has nothing to do with any legal questions that sometimes, unfortunately, arise out of these matters.

MEASUREMENTS ON LONG TELEPHONE LINES BY THE "OPEN AND CLOSED" METHOD.[*]

By A. Rosen, B.Sc.(Eng.), Ph.D., Associate Member.

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SUMMARY.

Simplified approximate formulæ are given for calculating the attenuation, wavelength constant and characteristic impedance from the "open" and "closed" impedances. The limits of error of these expressions are ascertained, and the formulæ are developed directly in terms of the bridge readings. The limitations of the "open and closed" method on long lines are discussed, and the sensitivity of the bridge necessary to obtain a given accuracy in the measurement of attenuation is found.

INTRODUCTION.

The "open and closed" method of determining the attenuation of telephone lines consists of measuring the impedance from one end with the distant end of the line successively open and closed. Generally an alternating-current bridge is employed.

This method is the one commonly used where accuracy is desired, and it has the advantage that the characteristic impedance and wavelength constant (and thus the primary constants of the line) can be determined from the same readings. It has, however, hitherto suffered from the disadvantage that, owing to the system of the calculation adopted, the work became more laborious and the accuracy decreased as the attenuation became greater, and for long lines with an attenuation of 2·0 népers or more it was desirable to use another method, such as the potentiometer arrangement described by Mayer.[†]

It is shown below that the "open and closed" method can be employed for long lines with considerable accuracy and without undue labour in the calculations, by making use of the sum and difference of the "open" and "closed" impedances instead of their ratio, and formulæ are given for obtaining the attenuation and wavelength constants directly from the bridge readings. The corresponding expressions for the characteristic impedance are also given; in this case, as the calculations by the usual method are comparatively short, there is not such a great saving in labour.

Where it is necessary to distinguish between a complex vector and its modulus, a capital letter is employed to denote the complex quantity, and the corresponding small letter is used for the modulus.

FORMULÆ USING RATIO OF IMPEDANCES.

Let Z_f and Z_c be the impedances measured at one end with the distant end respectively open and closed. Then

$$Z_f = Z_0 \coth \gamma l \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$Z_c = Z_0 \tanh \gamma l \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where Z_0 = characteristic impedance,
γ = propagation constant = $\beta + ja$,
β = attenuation constant,
a = wavelength constant, and
l = length.

The usual method of solving these equations to obtain β and a is to divide (2) by (1), in which case

$$\gamma l = \text{arc tanh}\,(\sqrt{Z_c/Z}\,) \quad . \quad . \quad . \quad (3a)$$

If we write $\sqrt{(Z_c/Z_f)} \equiv H \equiv h\underline{/\phi}$

we obtain $\gamma l = \text{arc tanh}\, H = \frac{1}{2}\log_e \dfrac{1+H}{1-H} \quad . \quad . \quad (3b)$

$$\beta l = \tfrac{1}{2}\,\text{arc tanh}\left(\frac{2h\cos\phi}{1+h^2}\right) \quad . \quad . \quad . \quad (4a)$$

$$= \tfrac{1}{4}\log_e \frac{h + (1/h) + 2\cos\phi}{h + (1/h) - 2\cos\phi} \quad . \quad . \quad (4b)$$

$$al = n\pi + \tfrac{1}{2}\,\text{arc tan}\left(\frac{2h\sin\phi}{1-h^2}\right) \quad . \quad . \quad (5)$$

where n is an integer.

Multiplying (1) by (2) we have

$$Z_0 = \sqrt{(Z_f Z_c)} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

It will be seen that as γl becomes large and Z_f approaches Z_c in value, it is necessary to determine H to several significant figures in order to evaluate β and a.

FORMULÆ USING SUM AND DIFFERENCE OF IMPEDANCES.

From equation (3b) we have

$$\gamma l = \tfrac{1}{2}\log_e \frac{\sqrt{Z_f} + \sqrt{Z_c}}{\sqrt{Z_f} - \sqrt{Z_c}}$$

$$= \tfrac{1}{2}\log_e \frac{Z_f + Z_c + 2\sqrt{(Z_f Z_c)}}{Z_f - Z_c}$$

$$= \tfrac{1}{2}\log_e \frac{Z_f + Z_c + 2Z_0}{Z_f - Z_c} \quad . \quad . \quad . \quad . \quad (7)$$

Now as γl becomes large,

$$2Z_0 \rightarrow Z_f + Z_c$$

$$\therefore \gamma l \doteqdot \tfrac{1}{2}\log_e \frac{2(Z_f + Z_c)}{Z_f - Z_c} \text{ very nearly} \quad . \quad (8)$$

Writing $(Z_f + Z_c)/(Z_f - Z_c) \equiv U \equiv u\underline{/\psi}$

we obtain $\beta l \doteqdot \frac{1}{2}\log_e 2u$ very nearly . . . (9)

and $al \doteqdot n\pi + \frac{1}{2}\psi$ very nearly . . . (10)

where n is an integer.

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (excepting those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] *Elektrische Nachrichten-Technik*, 1926, vol. 3, p. 141; see also W. T. Palmer: *Post Office Electrical Engineers' Journal*, 1926, vol. 19, p. 359.

LIMITATIONS OF SUM AND DIFFERENCE FORMULÆ.

The error involved in the approximation in equations (8), (9) and (10) can be evaluated by deriving equation (8) in another way.

From (1) and (2)

$$\frac{Z_f + Z_c}{Z_f - Z_c} = \frac{\coth \gamma l + \tanh \gamma l}{\coth \gamma l - \tanh \gamma l}$$
$$= \frac{\cosh^2 \gamma l + \sinh^2 \gamma l}{\cosh^2 \gamma l - \sinh^2 \gamma l}$$
$$= \cosh 2\,\gamma l$$

$$\therefore \quad \gamma l = \tfrac{1}{2} \operatorname{arc\,cosh} \frac{Z_f + Z_c}{Z_f - Z_c} = \tfrac{1}{2} \operatorname{arc\,cosh} U \quad . \quad (11)$$

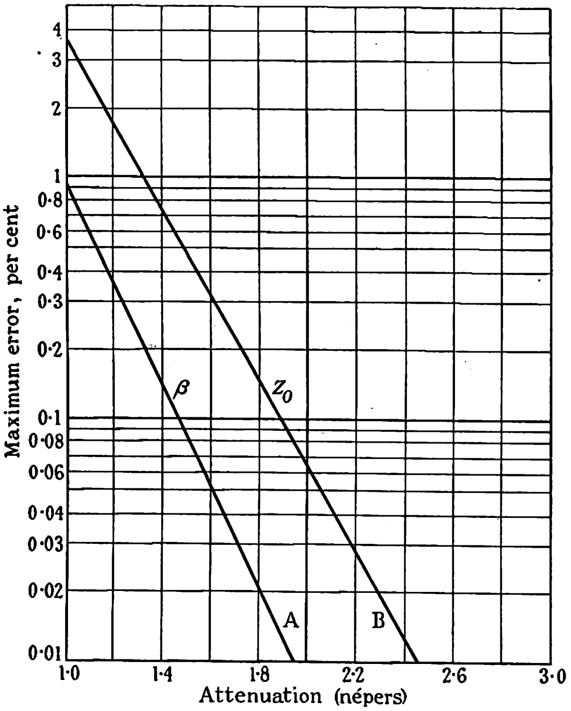

FIG. 1.

Since $U > 1$, we can expand it in the series

$$\operatorname{arc\,cosh} U = \log_e 2U - \tfrac{1}{2} \cdot \tfrac{1}{2}(1/U)^2$$
$$- \tfrac{1}{2} \cdot \tfrac{3}{4} \cdot \tfrac{1}{4}(1/U)^4 - \tfrac{1}{2} \cdot \tfrac{3}{4} \cdot \tfrac{5}{6} \cdot \tfrac{1}{6}(1/U)^6 - \ldots$$

whence

$$\beta l = \tfrac{1}{2}\left(\log_e 2u - \frac{\cos 2\psi}{4u^2} - \frac{3 \cos 4\psi}{32u^4} - \ldots\right) \quad (12)$$

and

$$\alpha l = \tfrac{1}{2}\left(2n\pi + \psi + \frac{\sin 2\psi}{4u^2} + \frac{3 \sin 4\psi}{32u^4} + \ldots\right) \quad (13)$$

When βl is large, the third and subsequent terms in (12) are negligibly small. The magnitude of the second term, $\cos 2\psi/(4u^2)$, varies with the angle ψ, but in any case it can never be greater than $1/(4u^2)$, i.e. the maximum error in equation (9) cannot be greater than $1/(8u^2)$.

Curve A in Fig. 1 shows the maximum error calculated as a percentage of βl for different values of βl. It will be seen that for lines of 1·5 népers equation (9) is correct to 0·1 per cent, and that when βl is 2·0 népers the error is less than 0·01 per cent.

Similarly the error in αl as calculated by equation (10) cannot be greater than $1/(8u^2)$, and as αl is greater than βl the percentage error is even less than that shown in curve A, Fig. 1.

The approximate formula for Z_0 is

$$Z_0 \doteqdot \tfrac{1}{2}(Z_f + Z_c) \text{ very nearly} \quad . \quad . \quad (14)$$

The degree of approximation in this equation may be ascertained as follows:—

From equations (1) and (2)

$$Z_f + Z_c = Z_0(\coth \gamma l + \tanh \gamma l)$$
$$= 2Z_0\left(\frac{e^{2\gamma l} + e^{-2\gamma l}}{e^{2\gamma l} - e^{-2\gamma l}}\right)$$
$$= 2Z_0(1 + e^{-4\gamma l})\,(1 - e^{-4\gamma l})^{-1}$$
$$= 2Z_0(1 + 2e^{-4\gamma l} + 4e^{-8\gamma l} + \ldots) \quad . \quad (15)$$

When γl is large this becomes

$$Z_f + Z_c \doteqdot 2Z_0(1 + 2e^{-4\gamma l})$$

and the error in equation (14), expressed as a ratio, is $2e^{-4\gamma l}$.

The maximum percentage error in Z_0 as given by equation (14) has been calculated for various values of βl, and is shown as curve B in Fig. 1.

FORMULÆ IN TERMS OF BRIDGE READINGS.

Two bridges are in general use for measuring the impedance of telephone lines. In the inductance bridge (Fig. 2*a*), a variable inductometer and resistance in series are employed * and the impedance is obtained in the form $Z = R \pm j\omega L$, where R and L are the readings in ohms and henrys respectively, and $\omega = 2\pi \times$ frequency. Means are provided for reversing the sign of L when the angle is negative.

In the capacity bridge (Fig. 2*b*) a variable condenser and resistance in parallel are used, and the impedance is $Z = R(1 \pm j\omega CR)/(1 + \omega^2 C^2 R^2)$, C and R being the readings in farads and ohms respectively. The corresponding expression in terms of the admittance Y is $Y = G \mp j\omega C$, where $G = 1/R$. When the impedance angle is positive the condenser is connected across the line and C is given a positive sign; when the angle is negative the condenser is placed across the variable resistance and C is given a negative sign. The signs are reversed when dealing with admittances.

(*a*) *Inductance Bridge.*

Let R_f, L_f = readings with the distant end open,
R_c, L_c = readings with the distant end closed

Further, let $R_s \equiv R_f + R_c$
$R_d \equiv R_f - R_c$
$X_s \equiv \omega(L_f + L_c)$
$X_d \equiv \omega(L_f - L_c)$

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* P. E. ERIKSON and R. A. MACK: *Journal I.E.E.*, 1924, vol. 62, p. 676.

Then $$u\underline{/\psi} = \frac{Z_f + Z_c}{Z_f - Z_c}$$
$$= \frac{R_f + R_c + j\omega(L_f + L_c)}{R_f - R_c + j\omega(L_f - L_c)}$$
$$= \frac{R_s + jX_s}{R_d + jX_d}$$

(i) *Attenuation Constant.*

$$u^2 = \frac{R_s^2 + X_s^2}{R_d^2 + X_d^2}$$

∴ from equation (9),

$$\beta \doteqdot \frac{1}{4l}\log_e 4\left(\frac{R_s^2 + X_s^2}{R_d^2 + X_d^2}\right) \text{ népers} \quad . \quad . \quad . \quad (16a)$$

$$\doteqdot \frac{0\cdot57564}{l}\log_{10} 4\left(\frac{R_s^2 + X_s^2}{R_d^2 + X_d^2}\right) \text{ népers} \quad . \quad (16b)$$

$$\doteqdot \frac{5}{l}\log_{10} 4\left(\frac{R_s^2 + X_s^2}{R_d^2 + X_d^2}\right) \text{ decibels} \quad . \quad . \quad (16c)$$

(*b*) *Capacity Bridge.*

Let $R_f(= 1/G_f)$, C_f be the readings with the distant end open
$R_c(= 1/G_c)$, C_c be the readings with the distant end closed

Further, let
$$R_s \equiv R_f + R_c$$
$$R_d \equiv R_f - R_c$$
$$X_s \equiv \omega R_f R_c(C_f + C_c)$$
$$X_d \equiv \omega R_f R_c(C_f - C_c)$$

Then $$u\underline{/\psi} \equiv (Z_f + Z_c)/(Z_f - Z_c)$$
$$= (Y_c + Y_f)/(Y_c - Y_f)$$
$$= \frac{G_c + G_f - j\omega(C_c + C_f)}{G_c - G_f - j\omega(C_c - C_f)}$$
$$= \frac{R_s - jX_s}{R_d + jX_d}$$

(i) *Attenuation Constant.*

$$u^2 = (R_s^2 + X_s^2)/(R_d^2 + X_d^2)$$

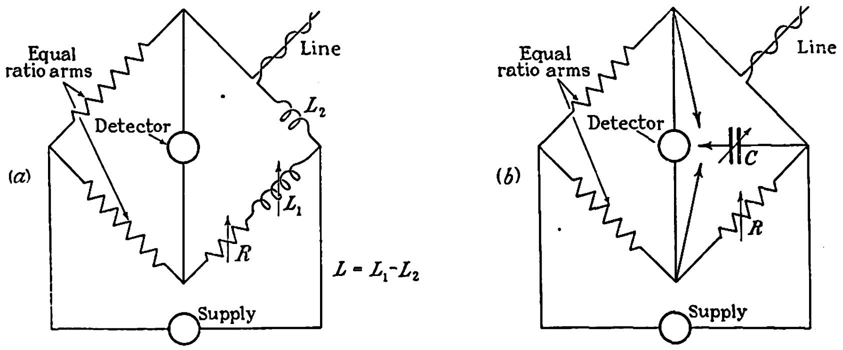

FIG. 2.

(*a*) Inductance bridge; (*b*) Capacity bridge.

(ii) *Wavelength Constant.*

$$\psi = \arctan\frac{X_s}{R_s} - \arctan\frac{X_d}{R_d}$$

Let $\theta_s \equiv \arctan\frac{X_s}{R_s}$ and $\theta_d \equiv \arctan\frac{X_d}{R_d}$

Then from equation (10),

$$a \doteqdot \frac{1}{l}\left\{n\pi + \tfrac{1}{2}(\theta_s - 0_d)\right\} \text{ radians} \quad . \quad . \quad (17)$$

where n is a suitable integer.

(NOTE.—In determining the values of θ_s and θ_d, regard must be paid to the signs of X_s, R_s, X_d and R_d. The quadrant in which the angle lies may be found by considering R_s, R_d as "real" quantities, and X_s, X_d as "imaginary" quantities at right angles to R_s, R_d respectively.)

(iii) *Characteristic Impedance.*

$$Z_0 \doteqdot \tfrac{1}{2}(Z_f + Z_c)$$
$$\doteqdot \tfrac{1}{2}\sqrt{(R_s^2 + X_s^2)}\underline{/\theta_s} \text{ vector ohms} \quad . \quad (18)$$

∴ from equation (9),

$$\beta \doteqdot \frac{1}{4l}\log_e 4\left(\frac{R_s^2 + X_s^2}{R_d^2 + X_d^2}\right) \text{ népers} \quad . \quad . \quad (19a)$$

$$\doteqdot \frac{0\cdot57564}{l}\log_{10} 4\left(\frac{R_s^2 + X_s^2}{R_d^2 + X_d^2}\right) \text{ népers} \quad (19b)$$

$$\doteqdot \frac{5}{l}\log_{10} 4\left(\frac{R_s^2 + X_s^2}{R_d^2 + X_d^2}\right) \text{ decibels} \quad . \quad . \quad (19c)$$

(ii) *Wavelength Constant.*

$$\psi = -\theta_s - \theta_d$$

where $$\theta_s \equiv \arctan\frac{X_s}{R_s}$$
$$\theta_d \equiv \arctan\frac{X_d}{R_d}$$

Therefore from equation (10),

$$a \doteqdot \frac{1}{l}\left\{n\pi - \tfrac{1}{2}(\theta_s + \theta_d)\right\} \text{ radians} \quad . \quad . \quad (20)$$

where n is a suitable integer.

[NOTE.—The remarks concerning the values of θ_s and θ_d in equation (17) apply also to equation (20).]

(iii) *Characteristic Impedance.*

$$Z_0 = 1/Y_0$$

Now $$Y_f + Y_c = Y_0(\coth \gamma l + \tanh \gamma l)$$

$$\therefore Y_0 \doteqdot \tfrac{1}{2}(Y_f + Y_c)$$

to the same degree of approximation as equation (14), which deals with the corresponding impedances,

i.e. $$Y_0 \doteqdot \tfrac{1}{2}\left\{G_f + C_c - j\omega(C_f + C_c)\right\}$$

$$\doteqdot \frac{R_f + R_c - j\omega R_f R_c (C_f + C_c)}{2R_f R_c}$$

$$\doteqdot (R_s - jX_s)/(2R_f R_c)$$

$$\therefore \quad Z_0 \doteqdot \frac{2R_f R_c}{\sqrt{(R_s^2 + X_s^2)}}\underline{/\theta_s} \text{ vector ohms} \quad . \quad (21)$$

SUMMARY OF FORMULÆ.

For convenience, the formulæ relating to the inductance and capacity bridges are summarized in the following table, which shows the points of resemblance.

<table>
<tr><th></th><th>Inductance bridge</th><th>Capacity bridge</th></tr>
<tr><td>Resistance reading, end free</td><td colspan="2">R_f</td></tr>
<tr><td>Resistance reading, end closed</td><td colspan="2">R_c</td></tr>
<tr><td>Reactance reading, end free</td><td>L_f</td><td>C_f</td></tr>
<tr><td>Reactance reading, end closed</td><td>L_c</td><td>C_c</td></tr>
<tr><td>Derived values R_s</td><td colspan="2">$R_f + R_c$</td></tr>
<tr><td>Derived values R_d</td><td colspan="2">$R_f - R_c$</td></tr>
<tr><td>Derived values X_s</td><td>$\omega(L_f + L_c)$</td><td>$\omega R_f R_c (C_f + C_c)$</td></tr>
<tr><td>Derived values X_d</td><td>$\omega(L_f - L_c)$</td><td>$\omega R_f R_c (C_f - C_c)$</td></tr>
<tr><td>θ_s*</td><td colspan="2">$\text{arc tan}\,\frac{X_s}{R_s}$</td></tr>
<tr><td>θ_d*</td><td colspan="2">$\text{arc tan}\,\frac{X_d}{R_d}$</td></tr>
<tr><td>Attenuation constant, népers</td><td colspan="2">$\frac{1}{4l}\log_e 4\left(\frac{R_s^2 + X_s^2}{R_d^2 + X_d^2}\right)$</td></tr>
<tr><td>Attenuation constant, népers</td><td colspan="2">$\frac{0\cdot 57564}{l}\log_{10} 4\left(\frac{R_s^2 + X_s^2}{R_d^2 + X_d^2}\right)$</td></tr>
<tr><td>Attenuation constant, decibels</td><td colspan="2">$\frac{5}{l}\log_{10} 4\left(\frac{R_s^2 + X_s^2}{R_d^2 + X_d^2}\right)$</td></tr>
<tr><td>Wavelength constant,* radians</td><td>$\frac{1}{l}\left\{n\pi + \tfrac{1}{2}(\theta_s - \theta_d)\right\}$</td><td>$\frac{1}{l}\left\{n\pi - \tfrac{1}{2}(\theta_s + \theta_d)\right\}$</td></tr>
<tr><td>Characteristic impedance modulus, z_0</td><td>$\tfrac{1}{2}\sqrt{(R_s^2 + X_s^2)}$</td><td>$2R_f R_c/\sqrt{(R_s^2 + X_s^2)}$</td></tr>
<tr><td>Characteristic impedance angle, ϕ_0</td><td colspan="2">θ_s</td></tr>
</table>

* See note on page 501 following equation (17).

Example.—Using the capacity bridge at a frequency of 800 cycles per sec., i.e. $\omega = 5\,024$ radians per sec., the readings obtained were:—

$$R_f = 238\cdot 0 \text{ ohms}, \quad C_f = -\,0\cdot 1537\ \mu\text{F},$$
$$R_c = 258\cdot 3 \text{ ohms}, \quad C_c = -\,0\cdot 0765\ \mu\text{F}.$$

Whence $$R_s = 496\cdot 3, \quad R_d = -\,20\cdot 3$$
$$X_s = -\,71\cdot 1, \quad X_d = -\,23\cdot 84$$
$$\theta_s = \overline{\backslash 8^\circ\, 9'}, \quad \theta_d = \underline{/180^\circ + 49^\circ\, 37'}$$
$$\beta l \doteqdot 1\cdot 733_2 \text{ népers}$$
$$al \doteqdot n\pi - 1\cdot 933 \text{ radians}$$

From a knowledge of the approximate values of the capacity C per mile, and the inductance L per mile, and using the well-known formula $a \doteqdot \omega\sqrt{(CL)}$, n was deduced to be 4. We therefore have

$$al \doteqdot 10\cdot 634 \text{ radians.}$$
$$Z_0 \doteqdot 245\cdot 2_6 \overline{\backslash 8^\circ 9'} \text{ vector ohms.}$$

Calculated by the full formulæ, using 7-figure logarithms, the following results were obtained:—

$$\beta l = 1\cdot 733_1 \text{ népers.}$$
$$al = 10\cdot 634 \text{ radians.}$$
$$Z_0 = 245\cdot 2_9 \overline{\backslash 8^\circ\, 2'} \text{ vector ohms.}$$

LIMITATIONS OF THE "OPEN AND CLOSED" METHOD ON LONG LINES.

In any process of measurement it is desirable to know the effect of a given deviation in the readings or in the calculations on the final result. In the case of attenuation of a long line, the simplicity of the formulæ given in terms of the bridge readings makes it easy to calculate the effect of such a deviation.

Let δu be a small change in u, and $\delta(\beta l)$ the corresponding small change in βl.

Then, differentiating equation (9), we have

$$\frac{\delta(\beta l)}{\delta u} \doteqdot \frac{1}{2u}$$

i.e. $$\frac{\delta(\beta l)}{\beta l} \doteqdot \frac{1}{2\beta l}\cdot\frac{\delta u}{u} \quad . \quad . \quad . \quad . \quad (22)$$

Here $\delta u/u$ is a small proportional change in u and $\delta(\beta l)/\beta l$ the resultant proportional change in βl.

Calculation by Slide Rule.—In using a 20-inch slide rule for calculating u, the possible error is, say, 0·1 per cent. Putting $\delta u/u$ in equation (22) equal to 0·1 per cent, we find that when βl is 1·5 the resultant error is 0·033 per cent, and when βl is 2·0 the error is 0·025 per cent. Hence the 20-inch slide rule will give a precision which is probably greater than the exactness of measurement. For the same order of accuracy using the "ratio" formula, computation by 7-figure logarithms would be necessary.

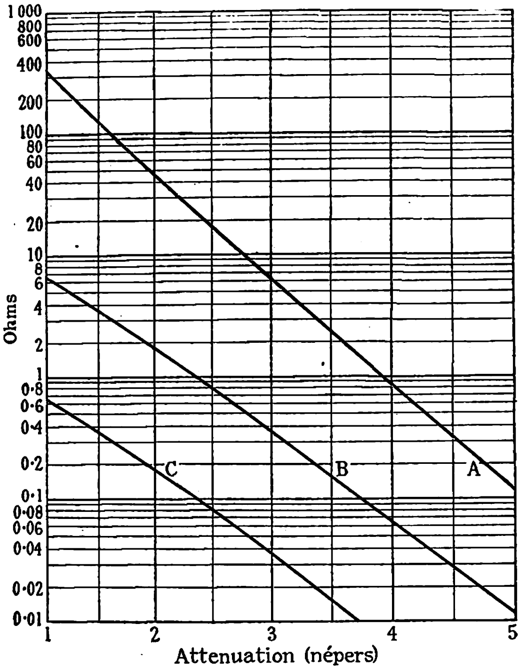

FIG. 3.

A = Difference between "open" and "closed" impedances on 600-ohm line.
B = Bridge sensitivity for 1 per cent accuracy in attenuation on 600-ohm line.
C = Bridge sensitivity for 0·1 per cent accuracy in attenuation on 600-ohm line.

Required Sensitivity of Bridge.—Equation (9) can be written

$$\beta l \doteqdot \tfrac{1}{2}\log_e \frac{4z_0}{z_d} \quad . \quad . \quad . \quad . \quad (23)$$

where z_d is the modulus of the difference between the "open" and the "closed" impedances. It is evident that as the attenuation increases, z_d decreases, and the limit of this method of measurement will be reached when z_d is so small that it cannot be measured with sufficient accuracy. Equation (23) is plotted in Fig. 3, which shows how z_d varies with increase of βl for a line having a characteristic impedance of 600 ohms.

It will also be seen from equation (23) that small errors in the readings will affect z_d much more than z_0. Thus the sensitivity of the bridge necessary to obtain a given accuracy in βl will be determined by the error permissible in measuring z_d. Let this error be δz_d. Then from equation (23) we obtain

$$\delta z_d \doteqdot -8\beta l z_0 e^{-2\beta l}\frac{\delta(\beta l)}{\beta l} \quad . \quad . \quad . \quad (24)$$

In this equation the sensitivity δz_d is expressed in terms of the attenuation, characteristic impedance and accuracy of the final result. Fig. 3 shows the precision required for a 600-ohm line for the two cases in which the limits for the error in βl are 1 per cent and 0·1 per cent respectively.

Effect of Bridge Errors.—For a given value of attenuation, the accuracy with which β can be determined is directly proportional to the exactness with which u can be measured.

The numerator of u is proportional to the characteristic impedance, and in it will appear all the errors due to departures from absolute accuracy of the bridge, such as incorrect calibration and effects of interference and of impedance to earth of bridge components.

The denominator of u is proportional to the difference between the "open" and "closed" readings, and in it the errors due to earth impedance and interference will practically cancel out, as will also those due to incorrect calibration of the coarse adjustments which are not altered between the two sets of readings. Thus the denominator will contain only the errors due to incorrect calibration of the fine adjustments, which are generally small, and those due to insufficient sensitivity of the detector.

The sensitivity can be increased by the use of an amplifier in the detector circuit. As a rule, unless elaborate precautions are taken, an amplifier introduces errors which decrease the absolute accuracy of the bridge. Fortunately, when the attenuation is high and an amplifier is desirable, a lower absolute accuracy is permissible. For example, on a 600-ohm line with an attenuation of 4 népers, to secure a precision of 1 per cent it is necessary to be able to detect an impedance change of the order of 0·1 ohm (see curve B, Fig. 3); the absolute accuracy of the bridge, however, which is given by $\delta u/u$ in equation (22), need not be greater than 8 per cent. Thus the "open and closed" method could be used at carrier frequencies where large attenuations are frequently encountered, although bridge measurements at these frequencies are not of such a high order of absolute accuracy as can be obtained over the audio range.

The author wishes to express his thanks to the management of Messrs. Siemens Brothers and Co., Ltd., for permission to present this paper, and also to Messrs. M. Reed, M.Sc., and E. S. Ritter, Member, for suggesting simpler proofs of some of the equations than those given in the original draft.

DISCUSSION ON

"THE DIESEL ENGINE APPLIED TO RAILWAY TRACTION."

ARGENTINA LOCAL CENTRE, AT BUENOS AYRES, 20TH JUNE AND 15TH JULY, 1929.

Mr. A. C. Kelly: The conditions of suburban passenger service are, as far as the Diesel engine is concerned, much more severe than those of long-distance main-line service, because in the former case high acceleration is necessary, and during starting this involves a very large output in proportion to the output required when the train has reached full speed. In suburban service this large output is required for only a small portion of the time, and the engine is therefore giving alternately maximum output and zero output every few minutes. In main-line working with low rates of acceleration the loading is much more uniform and therefore the conditions for the engine are more favourable. Apart from the fuel economy of the Diesel engine, there is the advantage (of particular importance in the Argentine) that such an engine can work through bad water areas for a long time without requiring a fresh supply of water.

Mr. J. Wilson: Various tests with Diesel-electric motor trains have been made on the Canadian National Railway, and as a consequence that railway has ordered the largest Diesel-electric locomotive in the world, consisting of two units of about 1 300 h.p. each.

Mr. P. C. Saccaggio: Investigations which I made into the subject led me to recommend my company to purchase four different units for trial purposes. These are now being erected in this country, and I shall have more to say about them after the trials have been completed. Whilst I have great faith in the future of the Diesel engine in traction work, I think that much still remains to be done to avoid complication in the engine and in making it so thoroughly reliable that it will be able to run for considerable periods without requiring skilled attention. I consider this feature to be of much more importance than the attainment of the highest fuel economy. I should be content with a moderate fuel economy, provided I could obtain a machine which would give reliable and satisfactory service in the hands of an ordinary driver. I consider that it is not essential to cut down weight to the lowest limit, and I should prefer the speed of the engine not to be excessive; between 700 and 800 r.p.m. is quite sufficient for a 1 000-b.h.p. engine. The cost of such engines is at present excessive, but when the industry is more fully developed and orders for 20 or 30 similar machines can be placed, there will probably be a very substantial reduction in the price. On the question of transmission, I am of the opinion that at the present time electric transmission is the most satisfactory, but that an increase in the dead load or un-springborne load on driving axles is very undesirable. I advocate an arrangement of motor drive without side rods or jack shafts in which the motor load can be entirely spring-borne. Although hydraulic transmission, using oil as the medium, has not hitherto been satisfactory, I believe that difficulties with this type can be surmounted and that possibly water may be used as the medium instead of oil. In conclusion, there would appear to be urgent need for the fullest co-operation between Diesel-engine designers and railway engineers, in order that the many interesting and important problems involved may be solved in the shortest time. When the work which I am now carrying out has been completed I shall be pleased to welcome any members who may wish to visit the works.

[At this point the discussion was adjourned until the 15th July.]

Mr. J. Brunner: For Diesel locomotives the airless injection type of engine is the only one to be considered. Mechanical means must therefore be employed to atomize the fuel and admit it to the working cylinder. That early Diesel locomotives were not fully satisfactory can to a large extent be traced to the use of air compressors with all necessary regulating devices for traction conditions. The water radiators on Diesel locomotives must necessarily be compact. This involves higher cooling-water temperatures than are used on stationary Diesel engines. Air compressors working to as high a pressure as 70 atmospheres will not stand this higher cooling temperature. By omitting air compressors the engine is simplified, which is important on a locomotive. It can be said generally that the speed limit is determined not by the combustion or chemical process, but by the physical and dynamic actions and their results, chiefly frictional losses and the quality of materials. The usual basis for comparison is the mean piston speed. My firm have carried out very detailed experiments to determine the permissible mean piston speed for locomotive work up to 12 metres per sec. As a result of these experiments they have decided that the mean piston speed should not exceed 8 metres per sec. It seems unreasonable to the designer that the Diesel engine, the primary part of the locomotive, should be pressed so much to its maximum revolutions and specific output that safety of working suffers, whilst it is not uncommon in railway work to strengthen the rolling stock so as to increase safety. Diesel engines for land and marine work are generally limited to a mean piston speed of about 5 metres per sec., and nobody believes that less reliability is required on a locomotive than on stationary plant. In addition, railway companies, owing to their experience with steam locomotives, expect a high standard of durability. In no other application of the Diesel engine is absolute reliability of starting so important. Economy of fuel and lubricating oil and reduction of noise at stations, particularly covered stations, makes it necessary frequently to shut down the engine. This involves the necessity for making quick, reliable and repeated starts from the driver's cab. Starting by compressed air involves storage of air at high pressure and air compressors working under conditions already described as undesirable. For this and other reasons, which have less importance in Argentina than in cold countries, my firm decided over 10 years ago to adopt electric starting. The current is taken from the storage batteries which supply the auxiliary services. Starting, therefore, is not influenced by high or low temperatures and is easily carried out from the driver's compartment. Further, in the case of electrical transmission the generator is already coupled to the engine and an insignificant change is necessary to convert this to a motor. There should therefore be no hesitation in adopting electrical starting. The Diesel engine, which must be considered as the most economical heat engine to-day, is, from its nature, not without difficulties when applied to locomotive work. The combination of chemical and physical processes in one machine provides great advantages as well as disadvantages. For instance, a unit of a given size is able to burn only a definite amount of fuel, independent of the engine revolutions. From this it follows that for a given size of engine and load the torque and revolutions are constant—an overload cannot generally be carried by an internal-combustion engine. If it were a technical possibility to separate the physical and chemical actions without affecting the high thermal efficiency, it would be possible to vary the torque and the number of revolutions independently, and the ideal Diesel engine for traction work would be obtained. Unfortunately this cannot be expected at present. The Diesel locomotive designer must therefore find a way of transmitting the power of the engine to the driving wheel which takes into account the interdependent values, tractive effort and velocity. The algebraic product of these must equal the normal power of the engine. Up to the present, the following transmission systems are known: (*a*) Direct drive to locomotive axle; (*b*) electrical transmission; (*c*) hydraulic transmission; (*d*) toothed variable-speed gear; (*e*) pneumatic transmission; and (*f*) combined internal-combustion and steam engine.

(*a*) *Direct Drive to Locomotive Axle.*—My firm began more than 20 years ago the study of Diesel locomotives, and built in 1910–1913 the first locomotive of 1 000 h.p. for the Prussian State Railways. Thorough tests on both the Swiss and Prussian Railways were carried out during 1913 and 1914 until stopped by the War. In spite of applying to the Diesel engine a system allowing a considerable increase of the torque, its adoption for traction service was not satisfactory, in particular the starting acceleration being insufficient. It is clear from the above that with this transmission the starting of the Diesel engine, and therefore also the train, has to be performed by means of compressed air, which is very disadvantageous. The trials, however, gave valuable indications of the course of future development.

(*b*) *Electrical Transmission.*—As a result of the experience gained with the first locomotive, the Prussian State Railways ordered from my firm in 1913 three 200-h.p. Diesel-electric motor-cars; these were delivered in 1914. The control and flexibility of operation of the electrical transmission was satisfactory in every way. In spite of this, the designers still looked for other means of transmission to avoid the high first cost, which weakened the chances for the development of the Diesel locomotive. In addition, designers were not sufficiently experienced in locomotive requirements to be able to provide against all the difficulties involved. Moreover, steam locomotive engineers were obstinate in their ideas and did not as a rule appreciate the Diesel engine. Under these conditions, new proposals were worked out during 1915–1925.

(*c*) *Hydraulic Transmission.*—My firm were the first to try out hydraulic transmission for Diesel locomotives. In 1920 they constructed, with the aid of the inventor, a special "Lenz" fluid driving gear of 400 h.p. for traction purposes. The trials failed, chiefly through poor regulation, low efficiency and noisy working, so that my firm declined to develop this type, and did not give it further consideration. In the following years, several European makers developed different types of fluid drive for traction purpose. Without exception these all failed for different reasons, so that now neither Diesel engine builders nor railway companies believe in the possibility of using hydraulic transmission. The difference in price between hydraulic and electric transmission is small. Hydraulic transmission has a lower efficiency, and the construction of the locomotive, arrangement of the axles, etc., and the starting of the Diesel engine, cannot be solved in such a simple and reliable way as with Diesel-electric drive.

(*d*) *Toothed Variable-Speed Gear.*—Considering the further development of manufacturing methods for variable-speed gears, the gear manufacturers believed that they could be applied to power transmission in the same way as for motor-cars. This view was strongly supported at first as it seemed to offer higher transmission efficiency. It was soon found, however, that, in comparison with a Diesel-electric locomotive of the same motor output, the geared locomotive was not able to deal as well with the normal motor capacity; in other words the efficiency of transmission was lower. Further, it had not been sufficiently considered that working conditions on a main-line locomotive are very different from those on a motor-car. Toothed gear transmissions can only be considered for small powers up to a maximum of 200 h.p., while to-day locomotives of 2 000 h.p. and over are required. Another objection is that starting with toothed gear transmission is just as unfavourable as with direct drive.

(*e*) *Pneumatic Transmission.*—To this class belong all kinds of transmission effected by means of air, gas or steam. As in hydraulic transmission, the Diesel engine is directly connected to the primary part, the air, gas or steam compressor. The transmitting medium expands in the secondary part, which is constructed like a piston engine in a steam locomotive, and circulates back to the compressor. The character of the tractive effort in this type is similar to that of a common steam locomotive. In Diesel locomotives the power of the engine is constant, and in steam locomotives the boiler output is approximately constant. The different trials of this type of locomotive have so far not given much practical result as the efficiency of this transmission is very low and the price and weight but little less than for electric drive.

(*f*) *Combined Internal-Combustion and Steam Engine.*—Direct drive gives the highest transmission efficiency. It is natural, therefore, that schemes have been worked out to use this advantage, whilst the disadvantage of poor starting torque is compensated by combination with the steam locomotive. In such a case the steam engine would be mainly used for starting the train and on gradients for compensating the reduction of Diesel engine output, owing to the lower number of revolutions. Even when the Diesel engine takes over the whole tractive work, the boiler must be in operative condition, and it would be convenient or even necessary that the steam engine should work with reduced output during that time. For this reason the thermal efficiency of this combination will be low, and for certain districts a very important advantage of the Diesel engine, i.e. that it requires practically no water, will be lost. Both price and weight are higher than for electric drive.

The various auxiliary services on a Diesel locomotive are not without influence on the decision as to the kind of transmission to be employed. For large Diesel locomotives with other than electric drive, the arrangement of the radiators and the drive of their fans would occasion some difficulties to the constructor. The same can be said regarding the air-brake compressor and, to a greater extent, regarding the vacuum pump. Drives other than electric can scarcely be applied to the vacuum pump, as the latter has to work with maximum speed, mainly in the stations for releasing the brakes. For well-known reasons the Diesel engine ought to be shut down whilst the locomotive is at rest in a station. The best arrangement is to connect the vacuum-pump motor to the battery in such a way that the motor can be fed by the exciter as soon as the latter has reached the corresponding voltage. Train heating by means of electrical resistances directly connected to the generator terminals is advantageous and very simple, does not need any attendance, and the efficiency is better than for any other system. With an adequate system of connection the heating current taken from the generator is automatically adjusted to the profile of the line, i.e. with increasing gradient the train speed and consequently the generator voltage have to be reduced, thereby lowering the heating effect proportionally to the square of the voltage variation, and thus the tractive power is increased. It is advantageous to connect the complete lighting of the locomotive, including the headlights, to the starting battery. In order to satisfy the usual condition for low-voltage lamps, the battery is divided accordingly, and it is periodically switched from one section to another. I hope that these remarks have given the members some idea of the development of the Diesel locomotive, together with an idea as to the lines along which designers should work in the future. There is no doubt that the Diesel-electric locomotive with mechanical injection and electrical starting is the most probable type for future requirements. The relatively small increase of price, compared with other systems, should not prejudice the chance of such a locomotive, the main points to be considered being the financial and operation results obtained over a lengthy period. A railway company would agree to a higher first cost for the locomotive material if equivalent advantages could be obtained in traction service. On the other hand, it is the duty of the designer to deliver what is, in his opinion and according to his experience, the most serviceable article. Experiments can so much affect a cause that years of hard work are required to eliminate certain prejudices. It can be said that the Diesel-electric locomotive has passed through its infancy and has proved its vitality. It has also proved, in service over several years, that with a high standard of manufacture and correct treatment its maintenance charges are less than those of the steam locomotive. Closer study of the electrical equipment as regards its rating and co-ordination with the Diesel engine has led to important progress with regard to prices and weights. To-day electrical transmission has an average efficiency of over 80 per cent, with a maximum peak value of 84 per cent. The lubricating-oil consumption of a Diesel-electric locomotive is about equal to that of a steam locomotive, but the fuel consumption in the former case is only about one-fourth to one-fifth of that in the latter.

Mr. Val Stewart: In my view too much publicity has been given to this subject up to the last year or two. It is quite a good thing to record in due course the difficulties in connection with any new development in engineering, but to do so too soon when the way out is not so apparent often results in wrong conclusions being drawn. The difficulties get an exaggerated status and when the solution by research is proved to be simple there is quite frequently an inclination to be sceptical about its achievement which is quite difficult to overcome. However, the best method of overcoming that difficulty is to give actual operating experience and what I have to say bears the seal of main-line operation, amounting in Canada alone to 3 200 000 km. This is particularly gratifying as it is *inter alia* an assurance that Britain has again taken a lead in an important development in railway engineering. I shall now endeavour to give briefly the history of the development of the Beardmore high-speed Diesel engine, my object in going into this particular detail being to show that the parentage of this engine is quite removed from that of other engines in course of development. In 1923 the British Government asked the Beardmore Co. to start the development of a Diesel-type engine for air service, more particularly to assist in the solution of the difficulties of the development of the airship. Of course there were many difficulties to face in arriving at a suitable design where permissible weight was so extremely small for the power necessary, but the development stage was retarded by an almost unlooked-for difficulty. This was the impossibility for many months of obtaining a crankcase casting, which had, of course to be made of an aluminium alloy. The difficulty was a foundry one. Owing to its area and necessarily light scantlings a portion of the case always contained metal that had reverted. This difficulty became so acute and so effectively prevented the proving-out of the remainder of the engine, that I took the patterns into our steel foundry and at the third attempt made a satisfactory case. When the engine was assembled with this case and operated on the test-bed, it soon became apparent that, while much remained to be done to put it in the air, we had something which could be made to apply to commercial work. The speed was reduced, the weight was increased where to do so meant adding to the engine's life, and the mean effective pressure was reduced. This is the essential difference between the Beardmore and all other engines, because while with the Beardmore engine the speed has been reduced, the weight increased and the mean effective pressure brought down, others have been developed from low-speed engines where the reverse has been the case, leading to compromise to obtain results. Now just at the time the developments referred to were in progress, the Canadian National Railways were in much difficulty on account of their finding various branch lines quite uneconomic to operate. Sir Henry Thornton sent to Europe a mission, headed by Mr. Brookes, the chief mechanical engineer of the line, to look into any alternative methods of operating that would solve their problem. They spent their time largely on the Continent and finished in Britain in the autumn of the year, having found nothing. Almost by chance Brookes was told in London of what was going on in Glasgow for the air service and that it was rumoured that we had something that was going to be applied to railways. He took the next train to Glasgow, saw a single-cylinder engine operating on the test-bed, the experimental air engines going through the shops, and our drawings and data on the application to rail traction. In three weeks he sailed to Canada followed by plans of 4- and 8-cylinder engines, and in a couple of months orders came through for seven 4-cylinder and two 8-cylinder engines on the understanding that we should see them through jointly. I think that too much prominence cannot be given to Brookes for the part he has played in the development of the Diesel-electric locomotive. His perception, courage and technical attainments made the practical application of the system possible very much more quickly than could have been the case had it been left in the hands of a manufacturing company to develop. The 4-cylinder engines were fitted into cars with an overall length of 60 ft. and seating capacity for 57 passengers. The cars weighed 45 tons and the engine, which developed 200 h.p. at 750 r.p.m., was quite equal to giving the required operating speed with trailer loads of 30 tons attached. The 8-cylinder engines were fitted to a double articulated coach with an overall length of 102 ft. and seating capacity for 126 passengers. The cars weighed 85 tons and the engine developed 350 h.p. at 750 r.p.m., giving the required train speed when also hauling a trailer of 30 tons weight. The average speed at which these cars were designed to run was 30 m.p.h. On the track both cars were operated comfortably at 60 m.p.h. Started in 1925, they were responsible for the bulk of the 3 200 000 km of operating experience to which I have already referred. By the courtesy of the Canadian Railway organization it is possible for me to give operating results that speak more eloquently than any calculation. The gross excess of income over expenditure on the portion of the line now operated by Diesel-electric locomotives amounted in 1923 to 1·3 cents per mile and in 1924 to 2·1 cents per mile. The Diesels were introduced in the following year but only a small proportion of the total mileage was operated by them. However, the excess of income over expenditure rose to 5·5 cents per mile, in 1926 it rose to 13·4 cents per mile, and in 1927 when over 50 per cent of the total mileage was operated by Diesels the figure had risen to 17·7 cents per mile. The 1928 figures were not to hand before I left England. On these results the Canadian authorities have equipped 10 more trains for their service, but the most important development arising from the success of these relatively small units was their decision to build a main-line locomotive for the express freight traffic. The locomotive was built in Canada and the engines were ordered from Messrs. Beardmore. The total power installed was 2 500 h.p. in two units of 1 250 h.p. each. The engines are of the 12-cylinder V type, the cylinders having a bore of 12 in. and a 12-in. stroke. Their power is developed at a designed speed of 750 r.p.m. On the test-bed both these engines were run for long periods at 900 r.p.m., at which speed they developed 1 500 h.p. with a clear exhaust and almost equal oil consumption. Later, as an experiment, one of them was fitted with a supercharger and developed 1 800 h.p. very satisfactorily. I cannot give you the results of operating the double unit, as they have not reached me, but the trials of the single unit gave the following leading result. Operating a load of 1 950 tons a distance of 400 km, the fuel consumption was 2·94 litres per 1 000 ton-kilometres excluding the weight of the locomotive, and 2·73 litres per 1 000 ton-kilometres including the weight of the locomotive. Speeds were attained up to 60 m.p.h. and the operation of the engine is reported as being most impressive. The engine was governed perfectly at speeds varying between 300 and 900 r.p.m. The fuel oil consumption is about 1/15th by weight of what a good steam locomotive would require. The complete locomotive when loaded weighs 290 tons, of which the Beardmore engine with its under-bed but excluding the electric generator accounts for just over 30 tons. At this point I should like to touch on one or two points that have been raised elsewhere. It is rather strange that when one is pioneering a development in engineering, the majority of one's fellow-craftsmen endeavour to prove that it cannot be done. Only a few years ago people rejected the possibility of the Diesel engine for traction work on the ground that it involved weights that could not be supported by the tracks. Now, having evolved an engine that removes that difficulty, I often hear the objection that the engine is too light. After 4 years' running experience I feel I am entitled to say that the theory that the engine is too light for railway work is disproved. Of all the amendments that have had to be made since the first unit was placed in service, not one of them has been caused by the necessity of increasing scantlings, and each one of them would have had to be made if the engine had been twice the weight. In an engine of this type, that must of necessity be high-speed, there is a positive danger in the inclination, that is perhaps quite natural with the majority of railway engineers, to make what is called a more robust job because they fear that their personnel cannot handle the light proposition. Then there are some who question the wisdom of having the cylinder liner made out of a solid-drawn steel tube. It is held that a cast-iron liner would give greater immunity from mishap in the hands of the operator. I must again refer to experience. There is no record of a mishap due to this cause in all the running that has been done. Six liners had to be replaced on the second 8-cylinder engine sent to Canada owing to these distorting, but on the matter being investigated the liners were found not to be at fault. At the time we had not fully appreciated the necessity of dead-annealing the crank-case casting and sufficient care had not been taken with the annealing of the second case. After it was put into operation it started to creep and this creeping continued until the cylinder centres became altered to such an extent that either a bad break had to occur or the liners had to distort, and fortunately the latter occurred. The incident has given rise to a statement that there has been trouble with these somewhat unorthodox liners. The reason for their adoption is twofold. Firstly, cast iron, even when very specially treated, is not a good material for withstanding shock, while steel in a refined state is the best. Secondly, to get the required strength in iron it is essential to have a relatively thick liner and that is bad from the point of view of getting rid of the heat passing into the cylinder walls. It is the careful arrangement in the Beardmore engine that has been made for heat exchange that, in my opinion, is mainly responsible for the relatively small upkeep charges that are incurred. Any marine superintendent, if asked, will say that what causes him most trouble in Diesel engines is cast-iron liners. Coming to other interesting applications of this system which are operating, pride of place should perhaps be given to the converted electric train on the London, Midland and Scottish Railway. This work is not altogether satisfactory to the Diesel engine, as compromises had to be made where compromises are not advisable. The train consists of a 4-coach unit, the power unit being carried in a new motor bogie. The train is running what is known as a shuttle service between Blackpool and Lytham, a distance of 7½ miles with five stops. Operating costs, while not yet official before I left England, were showing that the service was being run at less than half the cost of steam. The engine of this train fractured its crankshaft at the end of last year, and my company called in Dr. Lancaster to investigate the matter. To show how unsatisfactory it is to work on compromises on a new departure of this kind, I may say that the cause of fracture was traced back to the instability of the under-frame of the power coach. The equipment of the Spanish Pyrenees service from San Sebastian to Pamploma is interesting from the point of view that this line approximates to some of the difficulties to be met with in the hill districts of South America and more particularly on the other side of the Andes. The line is 56½ miles long and, starting at sea-level, rises to an altitude of 2 200 ft. at about 35 miles. The maximum gradient is 3 per cent. The power unit is a 200-h.p. engine and draws the coach in which it is mounted and two trailers, weighing, in all, 67 tons. Three other similar engines have been fitted into rail-cars manufactured by the English Electric Co. for the Venezuelan Railway, and these units are by now starting operation. Two 6-cylinder engines are in course of manufacture for the General Electric Co. and are destined for the Indian State Railways. These engines will be fitted to work as locomotives. An interesting proposition which has been settled subsequent to my departure is a 1 000-h.p. goods locomotive for the London and North Eastern Railway. This was also a job of conversion, the locomotive having first been built for all-electric service. The engine which will be installed in this unit will be an 8-cylinder straight 12-in. bore by 12-in. stroke. The locomotive will weigh 88 tons and is designed to haul 1 100 tons at 25 m.p.h. Although I am a strong advocate of the adoption of the Diesel engine for railway work, I do not wish it to be thought that I hold the opinion that under all circumstances it has advantages over the all-electric system. Where there is a very dense population that has to be moved from the city to a limited radius, and where, at the same time, current can be purchased at a cheap rate, there will always be a case for the all-electric locomotive. It is very often stated that the Diesel-driven locomotive is unsatisfactory as regards acceleration, but this all depends upon what power it is decided to employ. It must not be forgotten, also, that the fuel consumption of the Diesel engine is very good down to about half full load. Even where the all-electric drive might be desirable it is possible, by using a Diesel engine in addition, to cut down the initial outlay very greatly on account of the fact that the sidings, etc., will not have to be equipped, and one can contrive without difficulty to run the express long-distance service all-electrically to the point where it no longer pays and then without loss of time change over to the Diesel-electric set. Largely on account of the initial cost, however, there are relatively few cases to be made for complete electrification, and even then only for quite a small portion of the track mileage. In comparison with the steam engine the Diesel engine will reduce the operation bill by anything from a quarter to a half, depending upon the cost of fuel. These figures are not calculated from test results but are obtained over long periods of operation. I have been privileged to see the calculation of saving to be effected, made by a highly experienced railway engineer; this showed a clear reduction in his fuel bill to one-fifth of the present cost, but in that case fuel was obtainable only at a very high figure. Apart from the saving arising from fuel economy the use of the Diesel engine will result in very large savings due to the abolition of round-houses with their attendant staffs, and much less in the form of spares will have to be carried, all parts being interchangeable and concentrated at one centre. Water troubles, with their attendant cost, will be non-existent, and there will be no necessity to maintain fuel depots or to incur the heavy cost of fuel transport. Fire risks from cinders at large goods termini and docks will be eliminated, and a smaller number of locomotives will be required to operate the line for a given service. In Canada they find that one Diesel-electric car replaces two locomotives.

Mr. D. B. Parsons : During my visit to Europe in

1928, I found that some prominent engineers in Germany were convinced that mechanical transmission with toothed gears was entirely feasible, and more economical than electric transmission. I therefore think that, in spite of the view held by the majority that electrical transmission is the best method available, the possibilities of mechanical transmission should not be lightly dismissed but should be taken into further consideration.

Mr. P. C. Saccaggio : Since the last discussion I have been able to make a trial run with one of the Diesel-electric locomotives under construction for the Buenos Ayres Southern Railway. The unit was a Diesel engine giving 450 h.p. at 900 r.p.m. and 375 h.p. at 700 r.p.m., the speed which was used in the trial, and the total weight of locomotive and train was 160 tons. The outward run of 1 240 km to Cipolletti was made without a stop. Shortly after beginning the return journey, a defect which developed in the exciter made it necessary to run on the battery for some 345 km until Bahia Blanca was reached. With the help of a recharged battery the return journey was completed without assistance. During the outward run of 1 240 km a speed of about 60 km per hour was maintained on the average, a distance of about 105 km being covered at 75 km per hour. The consumption of current was 2 980 kWh, or 2·4 kWh per train-kilometre. The consumption of Diesel fuel of 0·88 specific gravity was 1 114 litres (980 kg). This corresponds to 329 grammes per kWh, 4·94 grammes per ton-kilometre, and 791 grammes per train-kilometre. I consider that a steam locomotive under the same conditions would have consumed at least 6 kg of fuel oil per train-kilometre. In commenting on the mean piston speed for Diesel engines, which, according to Mr. Brunner, should not exceed 8 metres per sec. (1 575 ft. per min.) I should like to point out that it is not uncommon to find steam locomotives working with a piston speed of 1 600 ft. per min. Personally, I think that for Diesel engines in traction work a mean piston speed of 1 300 ft. per min. is the maximum advisable. As I have already stated, I have a strong belief in the ultimate success of hydraulic transmission, and I wish to urge that all concerned should concentrate on making the whole of the mechanism robust, simple and reliable, basing their efforts on a machine of about 2 000 h.p. output, which output I consider to be now required to meet conditions on the Argentine broad-gauge railways. I am strongly of the opinion that in a short time really reliable machines of this type will be developed which can be counted on to run at least 15 000 km per month in regular service, with overhauls at infrequent intervals. At the present time, and under all the difficulties caused by labour conditions in Argentina, it is not possible to get a steam locomotive to run more than 7 000–8 000 km per month on the most reliable services. Bearing in mind the growth of road transport and the very high cost of wages and fuel for steam locomotive traction, I believe that the Diesel engine offers the one means open for reducing operating cost and enabling the railways to hold their own. Taking into account all the items which make up the cost of steam traction, I think it may ultimately be possible by employing Diesel locomotives to reduce the total costs to about one-fifth of present-day costs.

Mr. J. M. Eddy : I should like to add a few words from the administrative point of view. The railways in Argentina are faced with growing competition from road transport, which they have to meet with the additional disadvantage of ever-growing demands from labour which increase the cost of operation. I look to engineers as a whole to do their utmost to produce more economical methods of transportation. I believe that the railway companies must aim at giving the same sort of service that road transport companies are able to give, that is, collection of goods at the producers' doors and delivery at the final destination with rapidity and efficiency. The railways would have this one advantage over their competitors that the greater part of such transport could be carried over their own right-of-way at higher speeds and lower costs than by motor vehicles running on ordinary roadways. I wish to appeal for wholehearted co-operation between the railway companies, their engineers, and the manufacturers and their staffs to solve this problem as early as possible and on sound economic lines. It will require a considerable expenditure, but I believe that by joint action and enterprise the individual burden will not be heavy, and the ultimate gain to the railway companies will be very well worth the initial expense. In conclusion, I should like to suggest that as this discussion has already produced excellent results, and as the subject is one of such vital importance, a further discussion might be held in about 6 months' time to report progress.

Mr. F. Recknagel also took part in the discussion and described the part which the American Westinghouse Co. had taken in developing the "constant torque" system for use with Diesel engines for traction purposes.

DISCUSSION ON

"THE MODERN USE OF PULVERIZED FUEL IN POWER STATIONS."*

NORTH-WESTERN CENTRE, AT MANCHESTER, 12TH NOVEMBER, 1929.

Mr. V. Walker: Many misunderstandings have been created by the statement that pulverized-fuel boilers can deal with any class of fuel. While most solid fuels can be burnt in the pulverized form, they cannot all be burnt in the same furnace, put through the same burner, or ground in the same mill. The author has proved that low-grade coal can be successfully used in a pulverized-fuel plant. An efficiency of 84·69 per cent, as shown by the test on the Simon-Carves boiler, over a period of 52 hours and using coal with an ash percentage of 21, is certainly good practice, and I doubt whether this performance could be beaten by stoker-fired boilers. The loss of 0·87 per cent due to radiation, given in this test, is rather low; I should imagine that it would be more like 3 to 4 per cent. Prior to 1926 the unit system was only considered in connection with relatively small plants, but now it is being installed for units of much larger size. Perhaps its chief advantage is the elimination of the complication and expense of drying. This was overcome by introducing hot air into the mill, the temperature of which can be raised to 600° F. In the case of the Hams Hall plant, the author is using a temperature of 350° F., which appears rather low if coal of a moisture content of over 10 per cent is used. The temperature of the coal leaving the mill should not be more than 150° to 180° F., otherwise trouble is caused by the volatile constituents of the coal adhering to the burner piping and hampering the travel of the coal. With the unit mill, wide variations of moisture content have a marked influence on output and fineness. With the storage system, the intervening equipment between boiler and pulverizer cuts these variations out. In some plants where a single pulverizer feeds a number of burners there has been considerable trouble in getting an even feed to each burner, but the difficulty has been overcome by the use of larger burners and an improvement in the design of the distribution system. I should like to know what the author considers to be the maximum heat-release per cub. ft. of furnace volume for air-cooled and water-cooled walls respectively, assuming an ash fusion-point above 2 500° F. Those given in the tests are relatively low, about 11 000 B.Th.U. per cub. ft. It would also be interesting to know whether any difficulty is experienced in dealing with the ash in the design shown in Fig. 2. Does the lining of the ash-pit cause trouble? What was the volatile content of the coal used during the tests? With regard to the elimination of grit, the large American stations have installed grit-catchers of the water type and, although the sulphur fumes are not greatly reduced in quantity, only about 5 per cent of the original ash is discharged from the chimney. The development of the stoker is worth noting. At one large London power station a stoker with a grate-width of 30 ft. is being installed. A few years ago at least 3 stokers would have been required for this particular boiler.

Mr. W. Bayliss: Regarding the statement that higher efficiency can be obtained with pulverized-fuel firing as compared with stoker firing, we must be careful only to make comparisons between up-to-date plants of each system, when we shall find that the gross efficiency in favour of pulverized fuel is not more than 1 per cent. In the application of pulverized fuel one has to look beyond the question of efficiency, even of net efficiency, and decide whether a process of firing has advantages in the direction of the utilization of coal which otherwise could not be burnt, or in some other respects. Actual records of pulverized-fuel-fired and stoker-fired boilers, both in this country and in America, show that quite as high an efficiency has been obtained from the latter as from the former, and the adoption of one or the other depends mainly on local conditions. As regards the possibility of the use of larger boiler units with pulverized-fuel firing as compared with stoker firing, this is a general statement and is correct only as regards magnitude. The United States is the home of large boiler units, and the following figures give the output of steam per hour for certain large stoker-fired units:

Beacon Street, U.S.A.	418 000 lb.
Hudson Avenue, U.S.A.	352 000 lb.
Norfolk Street, U.S.A.	275 000 lb.
Battersea, England	300 000 lb.

From these figures the possibility of large stoker-fired units is apparent. The largest pulverized-fuel units of which I have knowledge are those that are being installed by the United Electric Light and Power Co. for the Hell Gate power station. These boilers, which evaporate 800 000 lb. of water per hour (maximum rating), are of Babcock and Wilcox type, designed for a steam pressure of 400 lb. per sq. in. Each unit, operating at maximum capacity, will consume 1 000 tons of coal per day. Two boilers supply steam for one 160 000-kW turbo-generator. This unit is no doubt beyond the capabilities of stoker-firing. There is no doubt that, within the range of stoker-fired units, these are cheaper than pulverized-fuel-fired units of equal evaporative capacity. With reference to Fig. 1, with the later experience of pulverized-fuel firing it is easy to see where trouble will arise. The system of coal drying, as explained by the author, is unsatisfactory and more or less obsolete. The storage of pulverized fuel in bunkers is undesirable on account of moisture difficulties and the risk of spontaneous combustion; the brick combustion chamber will not permit of operation with high CO_2 content, otherwise maintenance will be very high, and trouble will arise due to slagging on the lower boiler tubes, and also the slagging of ash in the bottom of the combustion chamber, creating difficulties in the removal of ash. Fig. 2 shows a plant that is in some respects an advance on that illustrated by Fig. 1. The method adopted for drying the raw coal is not now regarded as the best practice; the central system is also out of favour, and the brick-lined combustion chamber, even when backed with water tubes, proves costly in maintenance and very liable to encourage slagging of the boiler heating surface when excessive CO_2 is present. The author mentions that the covering by refractories of the furnace water-tubes is to be abandoned and bare tubes adopted. This step is liable to introduce other troubles, such as failures of the bare tubes, or over-cooling of the combustion chamber, with the losses consequent upon the carbon contents of the ash passing through the boiler system, particularly if the coal grinding is coarse and when the boiler is operating at light loads. In published records of pulverized-fuel-fired stations in the United States, investigations have revealed a carbon content of from 12 to 30 per cent in the ash, due to various causes, and this is a matter which should not be overlooked. Regarding Fig. 3, this is again in advance upon Fig. 2. The unit system of pulverized-fuel firing has been adopted with turbulent burners. Bare water-tubes are arranged on three sides of the furnace, and may give trouble such as I suggest in the case of the boiler in Fig. 2. I should also expect the front refractory wall to involve high maintenance costs. As regards the test figures given at the end of the paper, I appreciate how difficult it is to obtain reliable figures from pulverized-fuel-firing equipments of the central system. Referring to the first test, 80·35 per cent overall efficiency is not good enough to sell, or to induce the installation of, pulverized-fuel plant. The loss of 7 per cent in radiation, combustible in ash and unaccounted for, is very high and is probably mainly accounted for by the combustible matter in the ash. With regard to the second test, I should like to know whether the dust-precipitation plant was in use before or after the test. It is probable that a very material quantity of combustibles escaped into the atmosphere. This test gives a better overall efficiency, namely 84·69 per cent, but this figure is unacceptable owing to the figure of 0·87 per cent loss on account of radiation, combustible in ash and unaccounted for. If this were corrected to read between 3 and 4 per cent, and the overall efficiency correspondingly reduced, the test would then reveal merely a normal operating figure. A plus water gauge in the combustion chamber is very undesirable, as it will involve high maintenance charges. The gases passing to the chimney have a high temperature in both tests. The liberation in the combustion chamber is only about 10 000 B.Th.U. per cub. ft., and the present-day practice for a pulverized-fuel combustion chamber is, under favourable conditions, three times that figure. Summarizing the points, the problem of successful pulverized-fuel firing is not simple. The character of the coals to be used must be known and understood. The plant must be of simple construction and very robust. The grinding of the coal must result in a fine and continuously fine product. The combustion chamber must be so constructed as to give low maintenance costs whilst being operated with high values of CO_2 to maintain the highest temperature possible whilst obviating slagging of boiler heating surface. It must permit of easy ash-removal and of a continuous CO_2 content at the boiler outlet of 14 to 16 per cent without introducing operating troubles or high maintenance charges. What percentage is it correct to subtract from the gross efficiency in order to arrive at a net efficiency? It is the latter which is important. What have been the maintenance costs per 1 000 lb. of steam evaporated? What has been the experience as regards the dust problem; i.e. what percentage of the total ash in the coal has been removed from the combustion chamber, the boiler and economizer and the dust collector arranged near the chimney? What is the average percentage of sulphur in the coal, and what is the average fusing temperature of the ash?

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* Paper by Mr. R. A. CHATTOCK (see vol. 67, p. 1213.)

Mr. H. C. Lamb: The figure of 72 per cent given for the boiler-house efficiency for stoker firing presumably refers to the relation between the heat value of the coal and the heat value of the steam leaving the boilers. It would be interesting if we could have the corresponding figure for the pulverized-fuel-fired boilers. I should also like to know the comparative net efficiencies of the two types of firing, after making allowance for the auxiliary plant; also the difference in the operating costs. Very few pulverized-fuel-fired plants exist in Lancashire, and Manchester, in particular, has strongly favoured mechanical-stoker firing. It would, however, be a mistake to infer from this that either Manchester or Birmingham is wrong in the decision which has been made. In my opinion both are right, because the problem in the two areas is entirely different. Pulverized fuel has the best chance where coal is very dear and the smallest gain in efficiency is important, or where there are large quantities of coal of low heating value available at a low price. This, I believe, is the position in Birmingham, where low-grade coal from the Warwickshire coalfields is obtainable at very cheap rates because the freightage costs are low. This slack cannot be fired efficiently in the solid condition but is quite suitable for use as pulverized fuel. In Lancashire, on the other hand, the quality of the coal is much better: at Barton power station, for instance, excellent slack is available at a reasonable price, whereas cheap, low-grade slack is only procurable in limited quantities owing to the high freight charges incurred in bringing it from the Midlands, whence the bulk of it is obtained. When the question of pulverized fuel was under consideration in connection with Barton power station, the problem had to be discussed with reference to a working boiler-house efficiency of 80 per cent over a period of 12 months, which is a great improvement on the Birmingham figure of 72 per cent. The reasons for this are (i) that the Barton plant, being equipped with economizers and air-heaters, is a more efficient unit than the stoker-fired boiler at Birmingham; and (ii) that, as already mentioned, the quality of the coal available in Manchester is very suitable for stoker-firing, whereas that obtained in the Birmingham area is not. It was decided some time ago to install an experimental pulverized-fuel-fired boiler at Barton, in order to obtain experience. Originally, this plant, which has a normal rating of 130 000 lb. per hour, was similar to that shown in Fig. 1. When it became apparent that an installation of that kind was rapidly becoming out of date, it was remodelled, and it now resembles that in Fig. 3. We have not, as yet, had much experience of the remodelled boiler, and I am unable to give any definite results. The general conclusions which have been reached, however, may be of interest. The difference in the annual capital charges of that boiler as compared with a stoker-fired boiler is approximately £600 per annum; that is, the capital charges for the pulverized-fuel boiler are £600 more than for the stoker-fired boiler. Coal of 11 500 B.Th.U. costs about 15s. per ton. The improvement in net *test* efficiency, making allowance for auxiliaries, when firing coal of this quality as pulverized fuel, compared with stoker fuel, is nil, but the improvement in net *working* efficiency is about 2 per cent. Such a boiler consumes 35 000 tons of fuel per annum and, with coal at 15s. per ton, an improvement of 2 per cent in boiler efficiency is equivalent to a saving of £500. Thus there is an increase in capital charges of £600 (neglecting altogether the question of maintenance) and a saving in the cost of coal of £500. The other comparison is with fuel of 9 000 or 10 000 B.Th.U. The author obtains this fuel at a very low price, but in Manchester 10s. per ton has to be paid; in fact, it is very often sold at as much as 12s. per ton in this district. Comparing the net test efficiency, when using this class of coal a pulverized-fuel-fired boiler shows a saving of about 2½ per cent, and we estimate that, on the working efficiency over a long period, there is an increase in the efficiency of 5 or 6 per cent, which represents a saving of £900 a year on 12 months' working, so that the balance in this case is on the right side. The quantity of such fuel available, however, is not large. We have no reason to regret these experiments, but shall require much more experience before we feel justified in installing more boilers for pulverized fuel and discarding the stoker-fired boilers.

Mr. H. L. Guy : The use of pulverized fuel as a firing agent for boilers is not new, and really owes its inception to work done in this country. We should all bear in mind the efforts of Mr. Bebbington in this connection. I remember seeing pulverized-fuel-fired boilers in operation in Trafford Park 18 years ago, and they will tell you in the United States that the system was an English idea which underwent development there because in that country financiers are more ready to take up and finance new developments than in our own. The situation appears to have changed considerably as compared with conditions 4½ years ago. The position is being stabilized. It is now appreciated that the correct system of firing by stokers or pulverized fuel depends on the character of the fuel to be burnt. It is impossible to say whether pulverized-fuel or stoker firing is the correct solution in a particular case, except by an examination of the fuel used and the local conditions at the station concerned. Claims made a few years ago in respect of both methods have had to be modified in the light of accumulated experience. In the early days, stress was laid on the claim that pulverized fuel enabled larger boilers to be operated than were possible with stoker-firing. Although that claim still holds good it is considerably modified by the fact that there are stoker-fired boilers in operation with an output of 400 000 lb. of steam per hour. As far as the requirements of this country are concerned, these cannot be regarded as small boilers. With regard to the difference in test efficiency, it has been established in American experience that the efficiencies obtained with stoker-fired boilers are much the same as can be obtained with pulverized-fuel-fired boilers. In commercial service the latter show a slight advantage over a long period, and the figure, which a previous speaker mentioned, of about 2 per cent is one which finds general acceptance among users of both types of plant in the United States. It also appears to be accepted that the higher efficiency obtained by the use of pulverized fuel does involve an increased capital expenditure. We hear less, too, of the claims made a few years ago as to the possibility of using a very poor-grade fuel by the adoption of pulverizers, because it has been recognized that the main disadvantage of the pulverized-fuel system is the capital cost of the plant, plus the maintenance and working charges. It is not an attractive proposition to pulverize 40 per cent of stone for the sake of burning 60 per cent of coal. I was interested in the passage dealing with boiler tests, in which the author indicates the difficulty experienced in assessing the quantity of coal burnt during the test. I gather that the calorific value which has been used as the basis of these calculations is the calorific value of the fuel as supplied to the boilers. In assessing the weight, the author mentions that the weight of fuel had to be "calculated forward to obtain the net weight of pulverized fuel fed to the furnace." I should be glad if he would explain what that means, i.e. whether the calorific value of the coal as fired into the boilers, and as the weight is assessed, could have been different from the calorific value of the coal as supplied to the boiler and used as the basis in these tests. Can he give us any information regarding his experience of the merits of the two particular types of mills which he used? I should also like to know whether the provision of the Lodge-Cottrell dust-eliminator represents a sensible increase in the cost of the plant. Finally, do the figures of tests include the auxiliary power required for the boiler services and the pulverizing services, and the steam or fuel used for drying?

Mr. A. B. Mallinson : It is interesting to see the great evolution which has taken place as a result of experiments on a large scale, gradually changing the complicated bin-and-feeder system to a comparatively simple unit pulverizing lay-out. There is one point on which I desire further information. Although the author adopts the unit system, he uses the peg type of pulverizer on what is rather a large unit for a unit pulverizer, viz. between 8 000 and 9 000 lb. per hour. My experience has been entirely confined to unit pulverizers. In the United States in 1923–4 the centrifugal type of pulverizer was in great demand, but in New York last month I ascertained that this type of mill was considered unsuitable for above 7 500 to 10 000 lb. ratings, and that, following the installation of some hundreds of peg and centrifugal pulverizers, the ball mill was now being adopted. My experience has been that, from the start, the efficiency of the pulverizer gradually drops due to the wear of the hammers, and that unless the operators are careful and systematic in maintenance the overall efficiency falls in proportion to the wear which must take place. In Mexico, the company with which I am associated has a battery of 6 Babcock and Wilcox boilers with unit pulverizers, burning native coal which contains from 20 to 22 per cent ash. Our experience over some 5 years' operation is that the cost of maintenance of the combustion chamber and arches is materially greater than that of pulverizer hammer renewals. What overload rating has been possible with the boilers of the different lay-outs? In the United States great claims are made for the overload capacity obtainable with pulverized-coal firing. Finally, I think we are all glad to have figures which, though perhaps not nearly as satisfactory as we may have expected, relate to British practice.

Mr. J. Frith: This discussion has demonstrated that some rational means of comparison between the various methods and performances is essential. Regarding the figures of efficiencies given, it is not stated whether these take into account the auxiliaries, nor are we told what sort of coal has been used. It is impossible, with the information given, to make any real comparison. The function of a boiler is to supply steam, and the real criterion is how much steam it can supply per pound sterling. This is a much more satisfactory basis for comparison between the various methods. A boiler with only 50 per cent efficiency, if it could supply 1 000 lb. of steam for less money than one having an efficiency of 85 per cent, would be the better proposition. Can the author tell us the cost, under the various systems, of raising 1 lb. of steam? Some plants work better with cheap coal and others with dear coal, and therefore the weight of steam per lb. of coal is not a sound basis of comparison.

[The author's reply to this discussion will be found on page 515.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 2ND DECEMBER, 1929.

Mr. E. F. Hetherington: Although the use of pulverized fuel is now well established in this country, the question still arises, when the design of a new power station is contemplated, as to whether the advantages of powdered-fuel firing are sufficient to justify its adoption in preference to a stoker-fired plant. A pulverized-fuel equipment offers the advantages of flexibility and ease of control, particularly to stations which operate at a variable load. These advantages are not so obvious in the case of stations designed for base-load operation. A further advantage claimed for this type of fuel is that of greater efficiency. While this claim is undoubtedly upheld so far as combustion is concerned, there is a much smaller margin of efficiency in comparison with the ordinary stoker when due allowance has been made for the power required for operating the auxiliaries. The extensive adoption of powdered fuel has, however, acted as a stimulus to the designers of stoker plant, and by considering alternative sets of equipment for a large station it is found that the guaranteed efficiencies of the two types of equipment agree very closely. The operation of powdered-fuel plant over long periods undoubtedly involves a saving, but on the other hand it cannot be denied that at present the most efficient stations in this country have stoker-fired plants. Powdered fuel, however, exhibits a decided advantage by reason of the wider variety of fuels which may be satisfactorily consumed; the stoker equipment is far more restricted in this respect. My own view is that for boilers up to a rating of about 100 000 lb. per hour there is very little to choose between the two systems, but apart from the fact that with larger units stoker equipment becomes very large and unwieldy, a definite saving in capital cost can be shown in favour of powdered fuel. I have found that a saving of about 15s. per kW of plant installed is obtained by employing three boilers each having a capacity of 225 000 lb. per hour and fired by powdered fuel instead of four stoker-fired units with boilers rated at 150 000 lb. per hour. The question of grit-catching is one upon which all engineers connected with either the design or the operation of powdered-fuel plant are at present very vitally concerned. The electrostatic system of grit-catching has proved very effective in certain cases, despite the fact that it is expensive and, in my opinion, somewhat difficult of application where large stations are concerned. Wet washing has also been successful in some instances, although it has unpleasant features. Because of the curvature of the smallest dust particles, it is difficult to break down the effect of surface tension and so allow the dust to become wet. Unless high-pressure sprays are employed the wetting process occupies a considerable time. To provide for this period large chambers are usually necessary, making the design even more intricate, especially where the plant has to be carried over the boiler house. The disposal of the effluent, heavily charged with sulphur products, is, however, a problem of even greater difficulty. When the power station is situated alongside a river such as the Thames, there is little difficulty, particularly as the waters of the Thames are definitely alkaline. The station with which I am concerned, however, will be situated on the banks of a river into which it is not permissible to introduce any effluent of this nature, and as no satisfactory and commercially practicable means has been found for treating the effluent it is necessary to rely upon cyclonic extraction. If the cyclone separators are too large their efficiency is very materially diminished; the solution of the problem of the use of this type of plant for grit-catching will probably be found in the application of smaller cyclones in multiple.

Mr. G. H. Rogers: During the discussions on this paper great prominence has been given to the grit problem which arises as the result of the use of pulverized fuel. No doubt this prominence is due to the serious difficulties which certain supply undertakings are experiencing because of their failure to prevent the escape of quantities of grit, soot, and sulphur fumes from the chimneys. The author states that it has been found possible to remove some 90 per cent of the grit before the gas is passed to the chimney, although this must clearly involve considerable expense. I should like to ask whether any attempt has been made to trap the 10 per cent of grit which now escapes. Would it not be possible to install a cowl, adapted for operation in the direction of the wind, into which the gases could be blown, and then sprayed by a pair of water sprays in series? Such an arrangement would not cost a great deal in the first instance and it would, I think, be quite successful in removing all traces of grit before the gases were allowed to escape into the atmosphere.

Mr. T. E. Boothby: From the thermal standpoint, the firing of fuel in pulverized form should be more efficient than other methods of combustion. In this, however, as in every other process of development, experiments have been necessary before the theory could be turned to practical account. In the early stages of its development pulverized fuel was a failure, not because the principle was at fault, but on account of the imperfect knowledge and unhappy experiments of the pioneers in the subject. The paper explains some of the troubles which occurred in connection with the earlier equipment. It was in France that I came across the two largest installations which I inspected while studying the question of pulverized fuel on the Continent. Both were in poor condition. In Belgium there were two plants similar in design, one clean and very efficient, the other dirty and giving poor results. A study of these two plants revealed factors which are, no doubt, universal; the former was worked by a man who was sympathetically inclined to pulverized fuel, and who aimed at efficiency, while the latter was under the care of one who, on his own statement, wished to reveal all its disadvantages. It was impossible for me to recommend the system which I saw in use there. The coal was raised about 100 ft. and placed in the overhead bunkers, dropped into a cellar through a drier and pulverizer, lifted to a powdered-fuel storage bunker, and finally lowered once more to the burners. Extensions for the Stourport station were being planned at that time. A specification which eliminated overhead bunkers and employed a simple system of direct firing with unit pulverizers was drawn up. The system now adopted by the Birmingham Electricity Committee marks, in my opinion, a further improvement in design, and a considerable reduction in capital cost. Whatever his previous experience with pulverized fuel, the author would be forced to adopt it in the new installation on account of the size of the boilers. It is interesting, however, to note that the stoker makers are putting forth every effort to hold their own against the serious competition offered by pulverized fuel. There is little doubt that the stoker-fired plant can produce results equal to those of the pulverized-fuel installations which have been described. Local conditions vary considerably; power stations situated near mines which can produce high-class fuel have an advantage over those less fortunately situated. As an example of the strides which are being made in stoker design, it may be mentioned that a new Stirling boiler of 90 000 lb. normal rating, fired by an "L" type underfeed stoker, has recently been installed at the Stourport station. It has a water-cooled arch and the side walls of the combustion chamber are also water-cooled. The installation includes an economizer and air heater. The contractors have guaranteed an overall efficiency of 86 per cent on this plant, but up to the present it has not been possible to carry out the necessary tests. In my opinion, equipment of this type will become increasingly popular in connection with boilers of upwards of 100 000 lb. evaporation. The engineers responsible for pulverized-fuel installations appear to be open to the criticism of everyone whose premises suffer from an accumulation of dust. Until those who control the electricity supply industry unitedly insist on clean coal, the grit problem will remain unsolved. There is an impression among mine owners, particularly in the Midlands, that electric power stations are really refuse destructors. If a particularly dirty seam containing some 30 per cent of ash is opened, it is always worked on the assumption that the coal will be burnt at the power stations. Although it is perhaps too early for the author to give us any figures of costs and efficiencies in connection with the new plant, I should be interested in the corresponding figures relating to the earlier equipment.

Mr. J. Burns: In the discussion before the Institution (vol. 67, p. 1220) I referred to the general design of the new Hams Hall power station and congratulated the author on his vision, not only in proceeding with two storage systems of pulverized fuel at Nechells, but also in making further advances at the new station. One speaker referred to the flexibility of pulverized-fuel firing in general, but thought that a unit system would be less flexible compared with the case in which a bin of pulverized coal is available. This is easily shown to be unnecessary, in view of the fact that the operation of a unit mill and burner can be closely controlled, particularly where the "Atritor" type of mill is used. Only a few pounds of coal are passing through the mill at any moment, and any variation in the coal feed produces an immediate effect upon the burner. Further, where, as at Hams Hall, there are five mills and five burners for each boiler, a temporary stoppage of one mill is of very little moment. The question of the emission of dust and sulphur fumes has become more acute in view of recent events at Manchester. Further developments with the wetted-surface flue-gas washer on the Continent and in this country make the problem appear much less difficult. With a guarantee of the removal of 90 per cent of the dust and at least 70 per cent of the sulphur content of the flue gases, this apparatus is well on the way to a solution. A small water-spray plant on the uptake from the washer should remove another 20 per cent of the sulphur. The removal of the ash and sulphur by wet or dry cleaning at the colliery would reduce the problem to very small dimensions. With regard to high rates of evaporation, a small boiler could be designed to give a large transference of radiant heat, but the outlet-gas temperature would of necessity be high. A set of air heaters or economizers would be necessary to ensure a reasonable outlet temperature of the flue gases.

THE AUTHOR'S REPLY TO THE MANCHESTER AND BIRMINGHAM DISCUSSIONS.

Mr. R. A. Chattock (*in reply*): Several speakers have referred to the very low loss of 0·87 per cent due to radiation, etc., on the Simon-Carves boiler, and suggested that this was too low. The boiler casing and combustion-chamber walls of this boiler were designed so that the external surface temperature should not exceed 130° F. with an air temperature of 75° F. This should account for a loss of approximately 0·25 per cent only, so that after adding other losses unaccounted for the figure given of 0·87 per cent seems fairly reasonable, especially as the combustion was perfect on this test.

Mr. Walker suggests that the temperature of the hot air introduced into the mills should be 600° F. The mills are designed to operate with air at any temperature between 250° and 400° F. and no difficulty is being experienced in practice. He also asks what was the maximum heat release per cub. ft. of furnace volume for air-cooled and water-cooled walls. The figures for the three installations described are as follows:—

Vickers-Spearing boiler (air-cooled walls)	10 880 B.Th.U.
Simon-Carves boiler (water-cooled walls)	14 450 B.Th.U.
Hams Hall boiler (water-cooled walls)	21 900 B.Th.U.

He inquires, in addition, as to the difficulty experienced in dealing with the ash on the Simon-Carves boiler. As I mentioned in the paper, it was found that the brick tiles in front of the tubes became burnt away if the proportion of CO_2 was allowed to rise above 14 per cent, and it had been decided to place the tiles behind the tubes so as to leave the latter exposed to the furnace gases. This arrangement has now been tried and found to be a complete success. The furnace has operated continuously for a period of 8 months without any injury, and the proportion of CO_2 has been raised to 16 per cent. The volatile content of the fuel used for the tests, expressed on a completely-dried fuel basis, was 30·4 per cent on the Vickers-Spearing boiler and 31·91 per cent on the Simons-Carves boiler.

As regards Mr. Bayliss's objection that the overall efficiency of 80·35 per cent during the test on the Vickers-Spearing boiler was too low for selling purposes, I explained in the paper that this figure included periods of 6 hours during each 24 hours when the boiler was banked; a comparable figure for stoker-fired boilers is 72 per cent. A test run at a continuous full load would, of course, give a higher figure. Mr. Bayliss's anticipation of trouble due to exposing the furnace tubes has not been borne out in practice. As explained above, this arrangement is operating with a high CO_2 percentage without any injurious results and with complete success. The sulphur content of the fuel is approximately 1·5 per cent. The fusing temperature of the ash lies between 2 250° F. and 2 600° F.

Mr. Lamb asks for a figure of overall efficiency of the boiler house for pulverized-fuel operation to correspond to an efficiency of 72 per cent for stoker operation. This is 80·35 per cent. The net efficiencies in each case, after allowing for the auxiliary power required by the two types of operation, are:—

For stoker-fired boiler house ..	71·5 per cent.
For pulverized-fuel-fired boiler house	76·5 per cent.

This shows an improvement in net efficiency for pulverized fuel of 5 per cent over the stoker-fired boilers. Mr. Lamb estimates a saving of only 2 per cent on the Manchester boiler, so that if 5 per cent can be obtained his cost figures should show a considerable improvement in favour of pulverized fuel.

None of the speakers has mentioned the question of the labour costs of operation. With the Hams Hall lay-out it is possible, owing to the large boiler units and to the simplicity of the controlling apparatus, to operate 60 000 kW of boiler plant with only 3 men per shift, compared with the 12 men required for stoker-fired boilers. This represents a saving of between £3 000 and £4 000 per annum.

Replying to Mr. Guy's questions, the calorific value used as the basis of the calculation of the test efficiencies is that of the fuel supplied to the combustion chamber. The net weight of the fuel fed to the furnace was "calculated forward" in the following way. The weight of the raw fuel fed to the driers was determined by actually weighing it. Samples of this fuel were taken and its moisture content was accurately determined. The total weight of moisture in the fuel was subtracted from the total weight of the raw fuel to obtain the weight of the fuel when completely dried. The percentage of moisture in the pulverized fuel as fed to the furnace was then determined from samples. The total weight of the moisture was calculated and this was added to the weight of the completely-dried fuel to obtain the actual weight of the pulverized fuel as fed to the furnace. This was the only method available as it is impossible accurately to weigh the fuel after it has been pulverized. The installation of the Lodge-Cottrell coal-dust interceptor increased the cost of the boiler equipment by about 6 per cent. In the Hams Hall lay-out the driers have been entirely eliminated, so that the Lodge-Cottrell plant is not required.

Mr. Mallinson is quite right in referring to the necessity for systematic maintenance of the pins or hammers of the mills. If these are given proper attention the efficiency of grinding can be maintained. A figure of under 2d. per ton of coal ground should cover these replacements. As regards overload ratings, the Vickers-Spearing boilers were designed for an overload of 20 per cent or 42 000 lb. per hour; this has been obtained for short periods only, as a harmful effect upon the furnace brickwork is feared. The Simon-Carves boilers were also designed for an overload of 20 per cent, or 180 000 lb. per hour. However, since the combustion chambers have been modified there has been no difficulty in obtaining an overload of 33 per cent or 200 000 lb. per hour.

The points raised by other speakers are all dealt with in the above or in my reply to the discussion in London.

STANDARDIZATION OF DISTRIBUTION VOLTAGE.

The Council have authorized the publication of the following statement for the information of members:—

A standard lamp voltage of 230 having been adopted by the British Engineering Standards Association (B.E.S.A. Publication No. 77—1925: British Standard Voltages for New Systems and Installations) for both alternating-current and direct-current systems, after prolonged consultation with all the interests affected, and having been approved by the Electricity Commissioners, the Council felt that it was desirable for consideration to be given to various problems arising therefrom. These problems have been reviewed under the following heads:

(A). The practicability and cost of raising or lowering to 230 the declared lighting voltage on the general supply networks of all systems in Great Britain which at present have a declared voltage below or above 230.

(B). The ways in which the Electricity Commissioners may be able to assist voltage standardization.

(C). Other matters affecting the general question of the standardization of voltage on low-voltage distribution systems.

As a first step in the study of the problem of voltage standardization, it was necessary to have some knowledge of the extent to which different voltages are at present in use on low- and medium-voltage distribution systems. As no such information was available the Electricity Commissioners were asked if they would be prepared to assist by taking a census. This they consented to do. Replies were received from practically all undertakers and were tabulated by the Commissioners' staff. This tabulation is given in an Appendix and it certainly emphasizes the confusion caused by the present medley of voltages. In many cases it was found to be impossible to allocate the number of lamps and other items of apparatus connected to the different voltage systems; the tabulation is, therefore, necessarily somewhat incomplete. It gives, however, quite a clear picture of the position and one which is certainly far more complete than any data hitherto available.

A general idea of the situation is given by the following figures, which refer to the total lighting connections in the country as at the 31st March, 1927. These are taken from the attached tabulation, but where figures are not allocated to specific voltages an assumed allocation has been adopted.

	230 volts	Range 220/240 volts (excluding 230 volts)	Range 200/215 volts	Above 240 volts	Below 200 volts
Connections expressed as equivalent number of 30-watt lamps	12¼ millions	18 millions	21 millions	2½ millions	2¼ millions

(A). Practicability and Cost of Standardization.

The Council can foresee no engineering or administrative difficulties in carrying out a policy of voltage standardization, and on several large systems a change in the general distribution voltage has already been successfully carried out.

It is the Council's opinion that, with assistance from the Commissioners as referred to later, declared voltages within the range of 220/240 volts can be standardized at 230 volts by a gradual adjustment over a period of a few years and with very little expenditure.

For voltages below 220, a change to the standard voltage would involve a considerable expenditure. It is not easy to estimate the actual amount of this, but from data at the disposal of the Commissioners it was found possible to make an approximate estimate for the country as a whole, on four different bases. The four figures obtained were £9 750 000, £14 000 000, £16 250 000 and £10 750 000 respectively. The last of these estimates is based on a detailed study of the estimated cost of standardizing a large municipal undertaking now operating at 200 volts. The second is based on actual costs incurred by two comparatively small undertakings which have changed their voltage. The first and third are based entirely on estimated figures. The Council consider that it would be safe to take the minimum figure as £10 000 000 and the maximum as £16 000 000.

For voltages above 240 the cost would be about 10 per cent of the above figures, but it is felt that it is not practicable to attempt any standardization of these at the present time. If, and when, the greater part of the country is using the standard voltage the addition of the undertakings now operating at 250 volts would probably take place automatically. At the present time, however, it does not seem fair to ask such undertakings to make an immediate sacrifice in distribution efficiency without a more immediate prospect than now exists of obtaining the more indirect benefits of standardization.

Undertakers with voltages below 220 would, by raising their voltages to the standard, gain very greatly in distribution efficiency and better utilization of mains. The extent to which this could be set against the cost of standardization depends largely on the rate at which the increased capacity of the existing mains can be absorbed by increased growth.

(B). Assistance from Electricity Commissioners.

In discussions which have taken place the Commissioners have assured the Council of their sympathy with all possible steps to extend the use of the standard voltage, and they are already taking steps to ensure that the standard voltage shall be adopted for all new areas.

The Commissioners fully appreciate the extent to which new developments frequently take the form of extensions of existing systems into adjoining areas, and they have promised to do everything possible to promote the adoption of the standard voltage in all extensions of old areas and in all changes of system. They have agreed that, in urging this policy on undertakings, they will make reference to any preferential terms for standard-voltage lamps and apparatus which may be arranged with the makers, and also to any special terms which may be arranged with the makers for lamps and apparatus bought as part of a standardization programme.

The Council feel, however, that the greatest assistance in promoting standardization is the Commissioners' agreement:

(1) To call the attention of all undertakers who have a non-standard supply voltage near the standard voltage of 230 (i.e. say within a range of 220–240 volts) to the powers reserved to the Commissioners under No. B3 of the Regulations for Securing the Safety of the Public and ensuring a Proper and Sufficient Supply of Electrical Energy, enabling them to modify the specified voltage variation; and

(2) To intimate to such undertakers their readiness to exercise such powers in favour of any undertaker who wishes to have a wider range of voltage variation for the specific purpose of making an immediate commencement with standardizing the distribution voltage.

(C). Other Matters Affecting the General Question of the Standardization of Voltage.

Conferences were arranged with the British Electrical and Allied Manufacturers' Association and the Electric Lamp Manufacturers' Association to ascertain whether the views of the general body of manufacturers were in support of standardization of voltage and whether they would assist by price differentiation in favour of standard apparatus and lamps.

As a result of these Conferences:—

(1) The B.E.A.M.A. Council agreed:

> "That this Council recognize the importance and value of voltage standardization and desire to encourage the more rapid adoption of the standard voltage of 230 throughout the country. Further, that this Council recommend each of the Sections concerned to take all practicable steps to assist in accelerating the change-over of existing systems to the standard voltage of 230."

(2) The Section of the B.E.A.M.A. dealing with domestic appliances agreed:

(*a*) "The Section fully appreciate the value of standardization of voltages in connection with the manufacture of domestic appliances of all kinds and will be glad to give their support to any steps which may be taken towards the more general adoption of a standard voltage of 230.

"The general adoption of 230 volts as the standard would be welcomed, particularly as this would bring about simplification in manufacture and consequent reduction in prices. This effect will be the more noticeable as the adoption of 230 volts becomes more nearly universal.

(*b*) "When the change-over is made in any particular district, they will be glad to assist as far as possible by giving a preferential discount on parts of apparatus supplied to replace those rendered useless by the change-over. It would facilitate matters greatly if this preferential discount were to apply only to orders received from supply authorities and not to replacement orders received from contractors, as it would be easier in this way to confine such orders to those for replacement parts only."

(3) The E.L.M.A. indicated their support of endeavours to induce the supply authorities to adopt one standard voltage for domestic use, and issued a notification to the public on the 2nd April, 1929, indicating that the prices of certain popular types of lamps for general lighting-service purposes were being reduced on and from that date, and that in each instance where a price reduction was taking place the list prices of the 230-volt lamps would be 1d. cheaper than the list prices of similar lamps in the 200/260-volt range.

(4) The E.L.M.A. addressed a letter on the 1st February, 1929, to the I.M.E.A. and other associations of supply authorities, stating that, with a view to facilitating the change-over of supply stations to a pressure of 230 volts and recognizing the expense to which such stations would be put, they were prepared to quote the following additional scale of discounts off the net invoice prices for lamps delivered to any supply authority which were bought directly from the members of the E.L.M.A.

for specific change-over work in connection with the adoption of a standard 230-volt pressure:—

Number of such lamps ordered within a period of three months	Additional discount off net invoice prices
5 000 or more	7½ per cent
25 000 or more	10 per cent
50 000 or more	12½ per cent
100 000 or more	15 per cent

As a result of the meetings and discussions which have taken place during this investigation the Council have been more and more impressed with the advantages which would result to the industry from a wider standardization of voltage throughout the country. This view is also strongly supported by the Electrical Contractors' Association, whose Council have recently been considering the matter. A copy of a letter addressed by their Secretary to the Electricity Commissioners was forwarded by him to the Council for its information. The following is an extract from such letter:

> "My Council, at its last meeting, considered reports from various centres as to the comparatively large extensions which were being carried out at the present time differing from the standard voltage of 230/400 volts. . . .
>
> "My Council does not think, for one moment, that the Electricity Commissioners are not doing their best to deal with the situation, but my object in communicating with you is to ask that every possible effort should be taken to ensure standardization as extension at non-standard voltage seriously affects the selling costs due to the large stocks of lamps and domestic appliances which it is necessary to manufacture and stock, and to the fact—and we regard this as a very important one—that it deters consumers who contemplate changing their residence, from purchasing electrical equipment which they would otherwise do at the present time. . . .
>
> "My Council would also be pleased to learn what steps, if any, the Commissioners have in view for the standardization of existing voltages of supply, particularly in adjoining areas, where the difference in some cases is only 10 or possibly 20 volts. . . ."

APPENDIX.

ELECTRICITY COMMISSION.

LOW AND MEDIUM VOLTAGE DISTRIBUTION.

(General supply, not exceeding 250 volts for lighting and 500 volts for power, etc.)

Analysis of returns from authorized undertakers, showing, for the different declared voltages, the number of lamps connected, the number and horse-power of motors connected, and the total kilowatts of heating and cooking apparatus connected to supply systems at 31st March, 1927.

LIGHTING SUPPLIES.

(A). *Voltages for which separate particulars have been returned by authorized undertakers.*

Voltage	Number of lamps connected at 31st March, 1927 (generally returned as equivalent to 30-watt lamps)
100	1 191 399
104	410 916
105	221 125
110	194 241
125	1 200
150	163 540
200	16 134 854
204	841 054
205	1 090 714
210	2 029 265
215	65 862
220	8 001 127
225	80 090
230	11 436 570*
240	8 872 028
250	2 297 150

* Includes 113 899 lamps representing the equivalent of the lighting, heating and cooking supplies for 2 undertakers.

(B). *Voltages for which grouped or amalgamated figures not capable of sub-division have been returned by authorized undertakers.*

Voltage	Number of lamps connected at 31st March, 1927 (generally returned as equivalent to 30-watt lamps)
100 and 110	46 101
100 and 200	275 807
105 and 210	976 428*
105 and 240	80 382
105, 210 and 230	126 225
110 and 220	423 254
110 and 230	41 184
110, 230 and 250	304 425
200 and 230	13 204
200 and 240	350 666
210 and 230	74 283
210 and 220	219 747
210 and 240	6 402
220 and 230	24 255
230 and 240	368 926†
230 and 250	344 143

* Includes 495 000 lamps representing the equivalent of the lighting, heating and cooking supplies for 1 undertaker.

† This total includes the equivalent of the heating and cooking supplies for 1 undertaker.

POWER SUPPLIES.

(A). *Voltages for which separate particulars have been returned by authorized undertakers.*

Voltage	Number of motors connected at 31st March, 1927	Horse-power of motors	Remarks
100	2 741	7 188	
105	836	2 549	
115	75	150	
150	391	312	
173	18	45	
190	Not stated	5 224	Of this total 5 030 h.p. is in respect of 1 undertaker, who states "includes large consumers"
200	56 270	274 702	(*a*) + 75 h.p. for which number of motors is not stated (*b*) + 1 400 consumers representing 45 094 h.p. (e.h.t. or h.t.)
205	5 599	27 997	
210	3 410	16 459	
220	19 263	62 304	+ 835 h.p. for which number of motors is not stated
225	27	26	
230	16 007	31 123	+ 5 150 h.p. for which number of motors is not stated
240	12 345	39 025	
250	12 276	24 438	
300	411	2 363	
346	2 565	33 388	
350	492	4 002	
365	174	1 755	
380	2 793	17 780	+ 82 h.p. for which number of motors is not stated
385	22	191	
400	32 046	259 248	(*a*) + 8 181 h.p. for which number of motors is not stated (*b*) + 103 750 h.p. in respect of 1 undertaker, who states "includes large consumers" (number of motors not stated)
405	10	271	
410	3 065	15 325	
415	4 231	34 848	+ 36 327 h.p. for which number of motors is not stated
416	301	3 491	
420	1 771	16 869	+ 68 h.p. for which number of motors is not stated
430	Not stated	13 763	
433	456	3 552	+ 6 942 h.p. for which number of motors is not stated
440	30 522	343 794	(*a*) + 5 318 h.p. for which number of motors is not stated (*b*) + 28 613 h.p. in respect of 1 undertaker, who states "includes large consumers but not bulk supplies." Number of motors is not stated
450	25	151	+ 1 047 h.p. for which number of motors is not stated
460	21 763	224 428	
480	13 668	109 747	+ 14 320 h.p. for which number of motors is not stated
500	5 533	62 484	
540	40	360	

(B). *Voltages for which grouped or amalgamated figures not capable of sub-division have been returned by authorized undertakers.*

Voltage	Number of motors connected at 31st March, 1927	Horse-power of motors	Remarks
100 and 200	1 469	4 715	
105 and 210	1 000	7 287	
105, 210 and 400	1 247	7 128	
110 and 220	1 786	15 238	
110, 220 and 440	Not stated	8 840	

POWER SUPPLIES—*continued.*

(B). *Voltages for which grouped or amalgamated figures not capable of sub-division have been returned by authorized undertakers.*

Voltage	Number of motors connected at 31st March, 1927	Horse-power of motors	Remarks
110, 220, 500 and 550	Not stated	12 641	
110 and 480	Not stated	647	
190, 400 and 500	Not stated	80 850	Total figures are for 1 undertaker, who states " includes large consumers "
190 and 460	Not stated	3 480	
200 and 240	Not stated	7 304	
200 and 345	Not stated	207	
200 and 400	21 158	114 101	+ 28 609 h.p. for which number of motors is not stated
200 and 416	135	550	
200, 230 and 400	91	615	
200, 230, 400 and 460	1 429	19 238	+ 1 399 motors representing { 1 062 h.p., 200 V 150 h.p., 230 V 7 133 h.p., 400 V 800 h.p., 460 V
210 and 420	161	1 985	+ 866 h.p. for which number of motors is not stated
210, 230, 400 and 420	717	4 324	
210, 250, 365 and 500	4 475	57 065	(These figures include the equivalent of the heating and cooking supplies for 1 undertaker)
220 and 440	2 587	13 208	(*a*) + 27 555 h.p. (number of motors not stated) which includes equivalent of heating and cooking supplies. (*b*) + 9 062 h.p., representing 777 motors at 220 V and 4 639 motors at 440 V (*c*) + 715 motors, representing 772 h.p. at 220 V and 2 184 h.p. at 440 V
220, 250 and 440	1 900	10 800	Sub-division of motors { 1 350 h.p., 220 V 50 h.p., 250 V 500 h.p., 440 V
220, 380 and 440	440	5 770	
230 and 240	1 561	8 138	
230 and 400	2 641	20 444	+ 1 498 h.p., representing 31 motors at 230 V and 197 motors at 400 V
230 and 460	2 876	20 076	+ 13 264 h.p., for which number of motors is not stated
230, 400 and 460	2 367	11 181	+ 8 500 h.p., representing 652 motors at 230 V 88 motors at 400 V 382 motors at 460 V
230, 250, 440 and 460	230	1 192	
240 and 415	2 270	12 150	
240 and 420	6	14	
240 and 480	2 997	13 697	(*a*) + 8 814 kW, for which number of motors is not stated and which includes heating and cooking supplies (*b*) + 3 222 h.p., for which number of motors is not stated (*c*) + 19 803 h.p., representing 1 012 motors at 240 V and 1 279 motors at 480 V
250 and 440	114	416	
250 and 433	41	462	
250, 440 and 500	343	1 716	+ 33 611 h.p., for which number of motors is not stated
380 and 420	1 059	9 049	
380 and 440	Not stated	2 200	
400 and 420	500	6 164	
400 and 440	7 336	138 442	+ 2 250 h.p., for which number of motors is not stated
400 and 460	1 377	8 438	
415 and 480	Not stated	522	
500 and 550	2 101	21 521	

HEATING AND COOKING SUPPLIES.

(A). *Voltages for which separate particulars have been returned by authorized undertakers.*

Voltage	Number of kW connected at 31st March, 1927
100	23 274
104	12 571
105	1 067
110	2 097
115	505
150	1 665
190	355
200	444 541
204	19 537
205	19 020
210	47 886*
215	405
220	170 376†
225	980
230	316 161‡
240	200 366§
250	124 378
400	144
440	65
460	502

* + 2 520 kW, which includes power supplies for 1 undertaker.
† + 3 499 kW, which includes lighting supplies for 1 undertaker.
‡ + 8 684 kW, which includes power supplies for 1 undertaker.
§ + 22 790 kW, which includes power supplies for 7 undertakers.

HEATING AND COOKING SUPPLIES.

(B). *Voltages for which grouped or amalgamated figures not capable of sub-division have been returned by authorized undertakers.*

Voltage	Number of kW connected at 31st March, 1927
100 and 110	467
100 and 200	312
100, 200 and 240	1 800
105 and 210	44
105 and 240	1 443
105, 210 and 230	4 452
110 and 220	8 011
190 and 230	1 210
190 and 250	5 263
200 and 230	17 882
200 and 240	14 477
210 and 220	21 028
210 and 230	6 210
210 and 420	1 207
230 and 115	104
230 and 240	4 883
230 and 250	20 115
230 and 460	181
240 and 480	3 854

INSTITUTION NOTES.

Graduateship Examination Results: November, 1929.

SUPPLEMENTARY LIST. *

Passed.†

Beaumont, G. H. (South Africa).
Mukerjee, H. N. (India).
Page, T. H. D. (South Africa).
Rhenius, S. T. (India).
Siret, E. C. (India).
Smith, J. A. (New Zealand).
Stephens, M. N. B. (South Africa).
Wadhera, C. L. (India).

Passed Part I only.

Dewan, H. G. (India).
Fisher, W. J. H. (New Zealand).
Grant, D. L. (New Zealand).
Krishen, B. (India).
Newman, P. L. (New Zealand).
Sagar, Y. P. (India).
Soin, P. N. (India).
Wadhwa, H. R. (India).

The Benevolent Fund.

On the last page of the cover of this issue of the *Journal* will be found an appeal for donations to the Benevolent Fund.

Proceedings of the Wireless Section.

80TH MEETING OF THE WIRELESS SECTION, 15TH JANUARY, 1930.

Captain C. E. Kennedy-Purvis, R.N., Chairman of the Section, took the chair at 6 p.m.

On the motion of the Chairman, votes of condolence were passed on the death of Dr. S. Z. de Ferranti, F.R.S. (a Past President and Honorary Member), and Admiral Sir Henry B. Jackson, R.N., G.C.B., K.C.V.O., F.R.S., the members standing in silence.

The minutes of the meeting of the Wireless Section held on the 4th December, 1929, were taken as read and were confirmed and signed.

A paper by Mr. H. A. Thomas, M.Sc., entitled "A Method of Measuring the Overall Performance of Radio Receivers" (see page 475), was read and discussed.

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* See page 314.

† This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

The meeting terminated at 8 p.m. with a vote of thanks to the author, which was moved by the Chairman and carried with acclamation.

81ST MEETING OF THE WIRELESS SECTION, 5TH FEBRUARY, 1930.

[Held at the City and Guilds (Engineering) College.]

Captain C. E. Kennedy-Purvis, R.N., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the 15th January, 1930, were taken as read and were confirmed and signed.

The following papers were read:—

"An Ammeter for Very High Frequencies." By Prof. C. L. Fortescue, O.B.E., M.A., Member, and Mr. L. A. Moxon.

"A Method of Measuring Mechanical Impedance." By Prof. E. Mallett, D.Sc.(Eng.), Member, and Mr. R. C. G. Williams, B.Sc.(Eng.), Graduate.

"Some Notes on the Design of a Gramophone Pick-Up." By Mr. G. W. Sutton, B.Sc.

"Frequency Stabilization of Valve Oscillators." By Prof. E. Mallett, D.Sc., Member.

"An Instrument for Projecting and Recording the Response Curves of Electrical Circuits." By Prof. C. L. Fortescue, O.B.E., M.A., Member, and Mr. F. Ralph.

An adjournment was then made to the laboratories of the College, where the apparatus described in the above papers was demonstrated and informally discussed.

At the dinner held at the Imperial College Union after the meeting the Chairman proposed a vote of thanks to the Delegacy of the College, to which Mr. W. M. Mordey (one of the Governors of the College) and Prof. C. L. Fortescue responded.

Elections and Transfers of Members.

At the Ordinary Meeting held on the 23rd January, 1930, the following elections and transfers were effected:—

ELECTIONS.

Associate Members.

Albertyn, Adriaan Moorrees, B.Sc.
Barratt, Gilbert Alfred, Commander R.N.
Berg, Gustave, B.Sc.(Eng.)
Bowen, William Oswald, Captain R.C.S.
Briggs, William Thomas.
Brock, John Frederick.
Brown, George Anthony D.
Cecil, The Hon. Henry Mitford A., Lieut.-Commander R.N.
Chatterjee, Satyendra N., B.Sc.
Crabtree, John Ashworth.
Currey, Charles Norman E.
Debenham, William Richard, B.Sc.
Dixon, Murray Deighton, M.A.
Dupere, Thomas Rex.
Everitt, Richard Allen, Lieut.-Comdr. R.N.
Fegen, Richard Fogarty, Lieut.-Comdr. R.N.
Fisher, Harry.
Fry, Cedric Edmund.
Gardner, Fred Gilpin.
Gemmell, William Thomas.
Grace, George Edward.
Groves, Robert.
Harpham, Arthur Thomas.
Kinsman, Clarence.
Kirk, John Henry.
Knight, Henry de Boyne, B.Sc.
Leighton, Leopold.

Associate Members—continued.

McClean, Herbert George, B.Sc.(Eng.).
MacSheehy, James Graham J.
Meynell, Guy D'Arcy.
Minter, John Henry C., Lieut.-Comdr. R.N.
Mulleneux, Harry Joel.
Murphy, Frank, B.Sc. (Eng.).
Noakes, Cecil Stanley D., Lieut.-Comdr. R.N.
Pendry, Samuel Dunsdon.
Roberts, David William A.
Roberts, Kenneth William D.
Sarginson, Richard, B.Sc. (Eng.).
Slight, George Mure.
Smith, Dudley Sharrington, B.Sc., B.E.
Somerville, Henry Benson.
Ta'Bois, Percival Leo.
Thompson, Derrick Henry H., Lieutenant R.N.
Towers, Herbert Cecil.
Vaughan-Williams, Hugh Laurence, Lieut.-Comdr. R.N.
Waddington, Henry Randall.
Watson, Louis Robert C.
Whitehead, George Ethelbert.
Wield, Ronald Cunningham, Lieut.-Comdr. R.N.
Williamson, Hubert.
Winch, Gordon Thomas.

Companion.

Haigh, Alfred.

Associates.

Baskerville, James J.
Best, Eustace Charles.
Burbridge, William.
Champion, George Thomas.
Clift, William Harry.
Forrester, John.
Griffin, Ernest Philip.
Harbottle, George Robert.
Hodge, George Nicholl.
Jeffs, Arthur Joseph.
Jolly, Richard Ward.
Jones, George Bickerton.
Lindley, Norman Macdonald.
Long, Frederick Henry.
Mackenzie, Francis James R.
Moody, Wilfred.
Penrose, John.
Price, Benjamin Thomas Ll.
Ridler, Percival Herman.
Robinson, Bernard Carlton.
Shreder, Peter.
Spurling, Walter Everard.
Taylor, James Edward.
Vandal, Sidney.
Ward, John Gillies.
Whittick, Robert Baker.
Willey, Arthur Martin H.
Wilson, Milton Boss.

Graduates.

Ambady, Govindan Kutty M., B.Sc.Tech.
Andrews, Robert Cyril P., B.E.
Bates, Herbert Owen.
Bayles, John Wallis, B.Sc. (Eng.).
Capp, Percy Frederick.
Cliffe, Allen William F., B.Sc.(Eng.).
Deakin, George Woolliscroft.
Espley, Dennis Clark, B.Eng.
Fyfe, Leslie John G., B.E.
Gill, William Ernest.
Hay, George Bertram M.
Henderson, George, B.Sc.
Hollingworth, Charles Eric, B.Eng.
Humphreys, Meredith Noel, B.A.
Innes, John, B.Sc.(Eng.).
Jackson, Arthur Norman, B.Sc.(Eng.).
Kalra, Dharm Chand, B.Sc.(Eng.).
Kerse, William Harold.
Laing, Walter Barron.
Langshaw, William Greenhough.
Levy, Joshua.
McKenzie, Duncan Buchanan, B.Sc.
Marks, Horace Beaumont, B.E.
Mason, Cyril Arthur, B.Sc. (Eng.).
Millar, Thomas.
Mowat, James McKinnon, B.Sc.

Graduates—continued.

Murchison, Roderick Impey, B.Sc.(Eng.).
Narayanaswami, N. V., M.A.
O'Donovan, Thomas J.
Oldham, Bernard Cyril.
Palmer, Hugh Leslie, B.Sc. (Eng.).
Paul, Shudhir Kumar.
Petch, Thomas Hayes, B.A.
Pither, Thomas Frederic.
Pontifex, Claud Edmund C.
Rooney, James Louis, M.Eng.
Rouse, Edward Kenneth, B.A.
Sanderson, William Troutbeck, B.A.
Singh, Bhagwan, B.Sc., B.Eng.
Smith, Frank Arthur.
Sowter, Robert John, B.Sc.
Spence, James Allan, B.Sc.
Stevenson, Allan Brown, B.Sc.
Swan, Earle Percy.
Swan, Stanley Robert B., B.Eng.
Taylor, Ernest George, B.Sc.(Eng.).
Tregurtha, Frederick Charles P.
Tsao, Tsen Cha, B.Sc.

Students.

Adams, Robert Whitehouse, B.Sc.
Advani, Ramchand Chainrai, B.Sc.Tech.
Ahuja, Chuni Lal.
Ahuja, Indar Sain.
Aitken, James Glendinning.
Allen, Douglas Charles.
Allured, Basil Murray.
Anderson, Richard Henry.
Baker, Charles Henry.
Bana, Minoo Bejonji.
Barber, Bernard Davie.
Barford, Frank Cecil.
Barham, Donald William C.
Barnard, John Henry.
Barrie, Edward Foster.
Bates, Frederick William.
Bayford, Arthur.
Beasant, Frederic Harry.
Beaumont, Arthur.
Beaumont, George Harold.
Bhavnani, Narain.
Bird, John.
Blakeley, William Firth.
Blakey, Albert Edward H.
Blount, James Arthur.
Blythe, Henry Stephen.
Bourne, George Ronald.
Bourne, Harry Kebbell.
Bowen, William Harold.
Bowman, Henry Charles R.
Bowyer, Kenneth Charles.
Boyd, John S.
Boyton, Edward Morris.
Brace, Edward Charles.
Bradwell, John Arthur.
Braithwaite, Robert Cecil.
Bramhall, Ervin Hicks.
Bristow, Kenneth Walter.
Brunner, Henry Theodore.
Brunton, Robert Laurence.
Buswell, Harry.
Buttle, Arthur Vickery.
Byford, Max Arnsby.
Calvert, Rupert Hector.
Cameron, Ewen.
Candler, John Lawrence.
Carpenter, John Ernest.
Carr, George Ralph.
Carr, Thomas Henry.
Carroll, Desmond Conway.
Carstairs, Eion.
Cary, Anthony Lucius.
Caton, George.
Cayton, Joseph.
Chambers, Arthur Oswald.
Chappell, Albert William T.
Chopra, Kundan Lal.
Clark, Francis James.
Clark, William Brindley.
Clarke, Ralph Charles.
Coles, Raymond Schofield.
Cook, Joseph Edward.
Cornfield, Maxwell.
Cornish, Lionel James.
Coundon, Leslie.
Craig, Donald Hugh C.
Craster, Thomas Yvo.
Crawford, William George B.
Cundill, George Douglas.
Dancy, Charles Romney.
Davidson, Kenneth.
Davies, Arthur Cyril, B.Sc. (Eng.).
Davies, Trevor Hewitt.
Davis, John Sydney.
Day, Benjamin Lionel.
Day, William John.
Desbruslais, Eric Leonard, B.Sc.(Eng.).

Students—continued.

de Villiers, John Henry P.
Dewan, Har Gobind.
Elliott, Joseph.
Evans, Geoffrey.
Evans, William.
Fairbairn, Edward Patrick.
Fairey, Reginald.
Fells, Arthur Donald.
Fenwick, Christopher Evelyn.
Fowler, Reginald Archer.
Foxen, William Walter.
Fuad, Ibrahim.
Fuller, Raymond Alan.
Gaff, Henry Douglas, B.Sc. Tech.
Garside, Colin Pearson.
Garner, William Weston.
Ghosh, Kironmay.
Gillanders, Kenneth Henry.
Goodall, William Ernest.
Gooding, John Francis.
Gosling, Ernest Bedford.
Greening, Frank Charles G.
Gruby, George Alec.
Hadfield, Bertram Morton.
Hall, Wilfrid.
Hallam, Reginald.
Hamid, Ch. Abdul.
Hammad, El-sayed Helmy.
Handa, Mool Raj.
Hanson, George Raymond.
Haq, Mazhar-ul.
Harding, Alan Douglas.
Hargreaves, James, B.Sc. Tech.
Hargreaves, Robert Stewart.
Haring, Guy.
Harman, Harold Arthur.
Hawker-Smith, Richard Elmhirst.
Haywood, Frank Harold.
Heath, Henry William.
Henry, Herbert Middleton.
Hessen, Victor Boris.
Hill, Ernest.
Hill, Owen Clay.
Hill, Percy.
Hills, Robert Mitchell.
Holgate, Alan.
Holt, Clifford Morton.
Horn, James Kawarau, M.Sc.
Houldsworth, Walter William W.
Hounson, George Ronald.
Hubbard, Cecil Edward.
Hulme, Clement.
Hunter, George Douglas A.
Hurtley, John Hilary.
Inchley, Frank.
Irwin, John.
Jayaratne, Morgan Wilfred F.
Joglekar, Narayan Dattatraya.
Johnson, Arthur James.
Jones, David Joseph.
Kinvig, Henry Cooil.
Knapp, Harold Spencer.
Knight, Reginald Frederick.
Krishen, Bal.
Kurien, George.
Lancaster, John Bretland.
Lawden, Cyril Alfred.
Lawson, Charles John Vivian.
Leicester, Raymond William.
Lewis, Douglas Percy.
Lomas, Jack.
Lough, Jack Reginald.
McCormack, Joseph Michael.
McCulloch, John Stanley.
McElwaine, James Graham.
McHenry, Cecil F.
Mackintosh Philip Kilgour.
McLennan, George Ballantine.
Maharaja, Shantilal Sakarlal.
Maiden, Frederick Hugh.
Maltby, John Henry.
Manning, Charles Clifford.
Markwick, Charles Inglefield.
Marsh, Arthur Hireson.
Marshall, Joseph Ernest.
Martin, Bertram Ronald.
Martin, George Stewart T.
Martin, Harold Picton.
Martin, Reginald.
Massey, Noel Gisborne.
Matthews, Harry.
Matthews, Henry Charles H.
Michael, Clem Herbert.
Milne, John Charles.
Morgan, Arthur Harold.
Morris, Harold Gerard.
Morris, Thomas Bilson.
Morton, William Loudon.
Muir, John Malcolm.
Nazir, Mirza Ahmad.
Neale, Ronald Douglas.
Nicholson, Gordon William
Niyogi, Sailesh Kumar, B.Sc.
Oddy, Arthur Herbert S.

Students—continued.

Packard, John Laurence.
Paddock, William Thomas.
Page, Geoffrey.
Pakeman, Kenneth John.
Parker, Albert Raymond.
Parsons, Aubrey Lacey.
Parsons, William Richard.
Partridge, Frederick George.
Partridge, Reginald Wilson.
Pass, Charles William.
Paton, Alexander James.
Paul, Matthew Leonard.
Pearson, Lewis Arthur.
Philip, William McLaren.
Pike, Charles Henry.
Pikett, Frank Herbert J.
Proctor, George Burdett.
Pullar, Ian Douglas.
Rajagopal, Pillai, B.A.
Ramamurti, Krishnasamy, M.A.
Ramasubbu, Vudayagiri.
Rao, Molahalli Sanjiva, B.A.
Ratcliffe, Maurice Vernon.
Richards, Frederick Harry A.
Richardson, Robert Burgon.
Roach, William.
Robertson, David Campbell.
Robins, Herbert Edgar I.
Robinson, Francis Arthur.
Robinson, James Edwyn L.
Rosenstein, Benjamin.
Ross, Thomas Sabiston.
Row, Dhareshwar Prabhakar.
Ryan, Richard Gerald Ll.
Sagar, Yashpal.
Sayers, James Edmund.
Scott, Bernard Arthur.
Sherlock, Francis John.
Shires, Thomas Atherton.
Shroff, Tehemurasp Rustomji, B.Sc.
Simpson, John.
Singh, Gur Charan.
Singh, Kartar.
Singh, Sadhu, B.Sc.
Smith, James Walter.
Snelson, John Harold.
Srinivasan, Raghavachari.
Stanfield, James Armstrong.
Stock, Leslie George.
Strongetharm-Smith, Theodore.
Swaminathan, R.
Tatum, Raymond Bert.
Taylor, John William.
Thomson, William.
Thynne, Arthur William.
Titchener, Edmund Hickman R.
Tolputt, Cyril Brian.
Tomar, Ratansingh Raghunathsingh.
Treadwell, Cyril Gordon.
Tuddenham, Robert John S.
Tuffnell, Reginald Charles.
Vasudev, Sri Ram, B.A.
Vincent, Russell Swale.
Waddon, Ernest Avant.
Wade, Geoffrey Parkes.
Waite, David.
Walker, John Stanley.
Walton, Norman.
Watts, Percy.
Webb, Charles Henry.
Weerasinghe, Christopher Reginald.
Wellwood, Walter Douglas.
Welsh, Ernest.
White, Declan Celsus.
White, James Clarence.
White, Stuart.
Whitehead, Edward Daniell.
Wilkie, John McKenzie.
Willis, William Henry.
Willy, John Reginald.
Wilson, Claude Arthur.
Wood, Alexander.
Wood, Arthur John.
Wood, Raymond Charles.
Youatt, David.

TRANSFERS.

Associate Member to Member.

Bailey, David Edward.
Barnard, George.
Burton, William, M.Eng.
Clarke, Joseph Bernard.
Field, Harold Victor, B.Sc.(Eng.).
Forster, John Percival.
Gilbert, William.

Associate Member to Member—continued.

Gregory, George Francis.
Gregory, Hugh Welbourn.
Hollyer, George John.
Kerridge, Fred Bernard.
May, William Richard.
Moore, Percy Gordon.
Nichols, Ernest Josias.
Pask, Vincent Alexander.
Pratt, Arthur James.
Sherratt, Thomas.
Taplin, Arthur Harold.
Turnbull, Walter Alexander.
Warner, Arthur.
Whitaker, Lionel Bertie.

Associate to Associate Member.

Berry, Edgar.
Brown, Edward.
Evans, David Beynon.
Fraser, John Andrew.
Prescott, Charles William W.

Graduate to Associate Member.

Barnes, Richard Wynne.
Barrow, Lucien Leacock.
Bennett, Percy Thomas.
Bonell, Arthur William.
Bunt, Noel Barnden.
Cave, Percival William, B.Sc.
Crowley, Cornelius.
Dalman, Frederick Narborough, B.Sc.
Dennis, Reginald Burton, B.Sc.(Eng.).
Dennison, James Derry.
de Steiger, Frederick Bernard.
Egeberg, Harold.
Evans, Rhydwyn Harding, M.Sc.
Francis, Maurice Hart.
Gill, Thomas, B.Sc.Tech.
Graham, Alexander, B.Sc.
Hill, Lionel Gordon.
Joshi, Gopal Anant, B.A., B.E.
Keevil, Leopold George M.
King, Wilford Bertrand.
Kuperman, Moshe, B.Sc. Tech.
Kingsbury, Derrick.
Kinnersley, John Robert.
Langridge, William Lutener.
Larkin, Charles Neville.
Lennox, Edwin Arthur, B.Sc.
Linay, Edward Curzon.
McCulloch, Robert.
McLennan, Roderick Arthur, B.E.
Mayo, Charles Gilbert, M.A., B.Sc.
Milsom, Charles David.
Moscrip, William Roswell, B.A.
Nixon, Reginald James.
Orme, Basil Shelton.
Preston, Henry Reginald S.
Sanderson, Edward Robson.
Sims, Lionel George A., M.Sc.
Stanley, John Frank, B.Sc.(Eng.).
Stapleton, Stanley John.
Stephenson, Robert Maxwell, B.Sc.
Tayler, Frederick William.
Taylor, David Bruce, B.Sc. (Eng.).
Taylor, Eric James.
Underwood, Gilbert Vivian.
Usher, Frederick Francis C., B.Sc.(Eng.).
Verano, Ernest Augustus A.
Walker, Gerald Nicholson, B.Sc.
Whyman, Frank, B.Sc. Tech.
Williams, George.

Student to Associate Member.

Arnold, Alan Hugh M., Ph.D.
Astley, Ronald.
Harris, Cyril Edward.
Mumford, Albert Henry, B.Sc.(Eng.).
Preston, Charles Ernest, M.Eng.
Tolley, Lionel Lawrence, B.Sc.(Eng.).
Williams, Harold.
Wilmot, Reginald Hilton, M.Sc.

SURGES AND OVER-VOLTAGE PHENOMENA ON TRANSMISSION LINES, DUE TO LIGHTNING.

By Dr. H. Norinder.

(*Lecture delivered before* The Institution *5th December, and before the* Scottish Centre *16th December,* 1929.)

Introduction.

Lightning surges on high-voltage transmission lines have always been a very troublesome source of disturbance, and their importance has grown with the general development of overhead transmission systems. This is particularly the case in the United States, where electrification is highly developed and many long overhead lines are already in existence.

The yearly losses due to lightning surges will thus increase as transmission systems are more widely adopted. When electric power is more generally used for specialized purposes—for instance, for railway electrification—interruptions due to lightning will have much more serious effects than was the case when electric power was used in smaller machines and for less important purposes.

It will thus be seen that the problem of protection against lightning surges is a very important one. This must be borne in mind when the attempts that have already been made to solve the problem of surges are considered.

The Lack of Suitable Research Methods.

The problem of lightning surges on transmission lines arose right at the commencement of high-voltage transmission, but for some years its solution has been slow, due not to lack of interest, but to the absence of suitable instruments and research methods.

In the early days the surge problem was attacked by some very simple methods. From observations of the damage by lightning to transformers and other plant in electrical installations, conclusions were drawn as to the nature of surges. The method was analogous to the study of a disease by superficial observation. It sometimes resulted in the employment of protective devices that were potentially more dangerous to the transmission systems than were the lightning surges themselves. It must not, however, be thought that I am of the opinion that all existing protective devices are valueless.

With the growth of knowledge, scientific methods can now be applied to the problem. The construction of effective protective devices against lightning surges involves an exact knowledge of the source of the trouble—the natural lightning surges themselves.

The Development of Specific Methods of Research.

The great development which has taken place in electrophysical methods during the last 15 years, especially in connection with high vacuum, has led to the introduction of special devices for research on the effects of lightning on transmission lines. There are three chief groups of instruments or devices, and these are in many respects complementary. They are the klydonograph, the cathode-ray oscillograph and the lightning-surge generator.

By a cathode-ray oscillograph is meant an oscillograph in which the cathode rays impinge upon a photographic film or plate situated within the vacuum tube. The intense bombardment of the electron jet on the plate makes it possible to record transient phenomena of as short a duration as 10^{-6} sec.

The first to construct such an oscillograph was A. Dufour. The original instrument with its accessories has now been perfected, and a modern cathode-ray oscillograph, with its accessories in the form of kenotron rectifiers, oscillator circuits and evacuation systems, represents quite a laboratory in itself.

The klydonograph, on the other hand, is an astonishingly simple piece of apparatus. The principal part of the klydonograph is a small insulated electrode which is pressed against the sensitive layer of a photographic plate, the other side of which is covered by an earthed metal plate. An impulse voltage of slightly more than 2 kV causes a Lichtenberg figure to develop. The duration of an impulse capable of affecting the plate need only be of the order of micro-seconds, and it is possible to estimate the impressed voltage and its polarity from the diameter and shape of the figure.

The klydonograph and the cathode-ray oscillograph can be used to record lightning surges produced either naturally on transmission lines under full-load conditions, or artificially in a laboratory, and they may thus be regarded as controlling devices for lightning surges.

The surge generator, on the other hand, is a device for producing surges. The artificial production of surges under controlled conditions, either in the laboratory or on the line, will, without doubt, considerably facilitate the work of providing effective protection against lightning troubles.

Some Experimental Difficulties and Limitations.

(*a*) *The Klydonograph.*

This device is, as I have already mentioned, very simple in its operation, and this has been one of the reasons for its widespread use on transmission systems. It gives the amplitude and polarity of a surge, but it fails when an analysis is required in which it is necessary to determine the time within a few micro-seconds. On the other hand it is a very reliable control instrument for recording surges on transmission-line systems, and should be more widely used.

(*b*) *The Cathode-ray Oscillograph.*

The only device by means of which complete records of lightning surges can be obtained is the cathode-ray oscillograph. The main difficulty in the way of using this instrument for recording lightning surges is that the time of incidence of the surges cannot be predicted. This means that the instrument must be kept in readiness for perhaps an hour or more, during which time the film must be protected from the cathode beam and its stray radiation. If this were not done the rays would blacken the film in a fraction of a second and no trace of a record would be visible. Further, when a record has been taken the film must again be protected against the radiation from the electron beam. The whole operation must be performed within a period of time not exceeding some fraction of a millionth of a second.

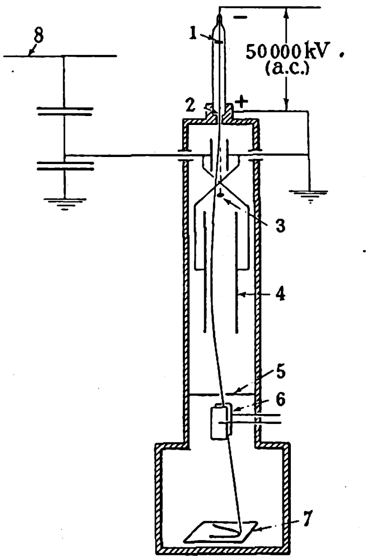

FIG. 1.

This special problem can be solved in two different ways. In each the cathode ray is kept at its normal strength in the instrument during the whole time of exposure. The beam is, in one of the methods, prevented from striking the photographic layer by a special device, comprising an external relay, sometimes composed of a set of electron tubes. If such tubes are used the relay is tripped by the first impulse of the surge and will cause the beam to enter for recording purposes. Such a complicated electron-tube device must, however, give rise to a great deal of trouble and disturbance in recording phenomena of such variable nature as lightning surges.

I have developed another method in which the electron beam itself is used in the oscillograph as a kind of relay. Fig. 1 shows its operation, in which no relay leading to loss of time is used, the whole process being performed by the electron beam of the oscillograph. The electron jet from the cathode (1) passes through the anode hole (2) straight along the central axis of the instrument. The jet is stopped by a small bar of metal (3), the target. This device cannot prevent all stray radiation; therefore in order to prevent the stray rays from blackening the film a diaphragm (5) with a central small hole is arranged. The instrument has a double pair of deviation plates (4) situated above the diaphragm and cross-connected. Below the diaphragm is mounted a second system of deviation plates (6) connected to an oscillator circuit.

The function of the device can easily be explained in the following manner. A surge coming from the line is impressed upon the potentiometer (8), which is connected to the deviation plates (4). These plates above the target bend the beam, let us say, to the left in the figure. The beam is bent back by the lower plates and directed through the hole in the diaphragm. By carefully selecting the length and spacing of the two pairs of deflection plates the beam is made to pass through the hole in the diaphragm. Its deflection is proportional to the voltage applied.

The deviation plates below the diaphragm are so situated that a voltage impressed on them will cause the beam to deviate in a direction at right angles to that produced by the upper plates. The lower plates will thus give a time axis to the record if the plates are connected to an oscillator circuit with a constant and known linear or sinusoidal time variation.

(*c*) *Surge Generators.*

The construction of surge generators gives rise to some difficulty with regard to high-voltage insulation and elimination of superimposed high-frequency currents in the circuits. The voltage at which kenotrons can be operated is limited to about 200 kV, and for a surge generator it will sometimes be necessary to go up to more than 10 times this value. Another inconvenience is the necessity of relatively high effects in the surge generators. Fig. 2 shows how these difficulties can be avoided. This construction has proved to be of great flexibility as a lightning-surge generator device, and has been developed by the Westinghouse Electric and Manufacturing Co., of East Pittsburgh, U.S.A. The generator (see Fig. 2) consists of several groups of condenser banks, spark-gaps and resistances in a special connection. The condensers (C_1 to C_{10}) are charged from a kenotron rectifier (A) over resistances (R_1 to R_{10}) of the order of 1 megohm. One of the spark-gaps (G_2) is set to about 20 per cent lower spark-over voltage than the others. By regulating the voltage of the rectifier a voltage can be reached in the system so high that G_2 breaks down. When this occurs two condenser groups will be charged to a higher voltage than the other groups, and the spark-gaps of all these groups immediately break down. The condensers are con-

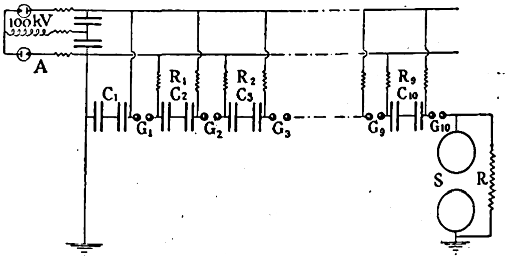

FIG. 2.

nected in series via the spark-gaps. A voltage 10 times as high as the kenotron voltage appears at the terminal gap. Such a generator for 3·5 million volts has been built in the high-tension laboratory of the Westinghouse Co. A portable lightning-surge generator of the Westinghouse Co. for 1 million volts was used last summer for artificial surge generation on a 220-kV line. It might be thought that the generator would give an irregular voltage variation, owing to the spark-lag effect and to other local disturbances, at least in the first micro-seconds of rising voltage; but this is not the case, as may be seen from an inspection of oscillograms.

External Arrangements for Connecting Oscillographs and Klydonographs to Transmission Lines.

One of the predominant advantages of the klydonograph and of the cathode-ray oscillograph is the relatively small effects that are necessary to produce records. The connection to a high-tension line can thus be made by means of condensers, and it is sufficient to use a string of insulators in the form of a capacitative potentiometer. It is obvious that precautions must be taken with regard to natural oscillations in the circuit leading to the oscillograph. The influence of leakage over insulators during rain, and of disturbances by corona, must also be avoided. This can easily be done by using air condensers in series in the circuit. Sometimes we have used strings suspended within the laboratory in combination with air condensers.

One of the difficulties when connecting a cathode-ray oscillograph to a transmission line under full load is the elimination of the normal-load voltage which is impressed on the deviation system of the oscillograph. One method is to use a relatively wide target. The normal voltage in such a case is so regulated that the electron jet will oscillate over the target at normal-load voltage, and only a voltage in excess of the normal will cause the jet to leave the target and impinge on the film.

Sometimes it is convenient to use a non-inductive leakage resistance above the instrument condenser.

The device must be so balanced with regard to the capacity and leakage resistance that it will, without any appreciable disturbance, reproduce impulses of a given wave-form. The action of this resistance may easily be controlled by well-defined impulses from a laboratory circuit.

Electrical Conditions for Lightning Surges.

Lightning surges are supposed to be produced either by direct strokes on the lines or by induced bound charges. From a physical point of view there is a distinct difference between those two kinds of surges.

(a) *Surges by Direct Strokes.*

Let us suppose that a cloud is highly charged and with some of its parts situated vertically above the line. The discharge process is preceded by a slow local accumulation of charge within the cloud itself. This will disturb the equipotential surfaces below the cloud and they will slowly move downwards.

At the commencement of the discharge process we can consider a thunder-cloud as a body with suspended charged particles. From this non-conducting but charged body an electrostatic field radiates out. With increasing accumulation of the charge the field force also will increase and along the lines of forces partial glow-discharge streamers are developed. This will cause certain parts of the cloud and its surroundings to be semi-conducting bodies within which a concentrated lightning path can develop. This path will follow the partial glow-discharge streamers and will thus pass along the general direction of the lines of force, which are emanating from the charged cloud downwards. In this connection the time necessary to break down the insulation between the cloud and the line is of interest. It can sometimes be appreciable, as will be seen later, and it is not surprising that direct strokes to the transmission line will also produce surges in which the peak value is reached within several micro-seconds.

(b) *Surges by Induced Charges.*

Surges caused by bound charges can easily be deduced by theoretical methods. Two factors are of importance when the development of indirect surges is under consideration. Their form is a function both of the distribution of the bound charge along the line before the discharge and of the time function for the release of the charge. This is shown graphically in Fig. 3, which I published earlier.*

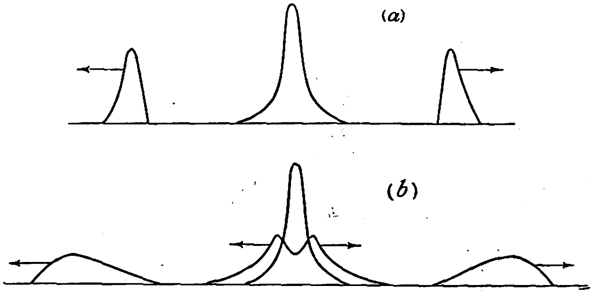

Fig. 3.

A sudden discharge gives rise to two surges with very steep fronts (Fig. 3*a*). On the other hand, a slow discharge results in surges with sloping fronts (Fig. 3*b*). The velocities of the lightning discharges are generally, as we shall see later, relatively slow. The release of the bound charges will thus give rise to indirect lightning surges with very sloping fronts and small amplitudes. They will therefore not be harmful on a transmission-line system. This is in accordance with the views of Dr. G. C. Simpson.†

Experimental Data in Connection with the Rate of Cloud Discharge.

It has been possible to observe the lightning discharges in the atmosphere by aid of the cathode-ray oscillograph in connection with a short antenna circuit. Our first observations along these lines at the Royal

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* *Teknisk Tidskrift*, 1923, vol. 53; *Elektroteknik*, p. 184.

† "Lightning" (The Twentieth Kelvin Lecture), *Journal I.E.E.*, 1929, vol. 67, p. 395.

Board of Waterfalls Research Station, Uppsala, were carried out in 1921 with an ordinary Braun tube connected to an antenna circuit. The following year we obtained our first records, which have since been much improved upon, by the use of a specially constructed cathode-ray oscillograph. Our observations are of special interest when we have to consider the general physical conditions of lightning surges on transmission lines.

A diagram of the circuit is reproduced in Fig. 4. The antenna capacity was connected to earth through a small non-inductive resistance R_2 of such a value that the time-constant of the circuit was a few micro-seconds. An air condenser of the same value as the capacity of the antenna circuit was shunted across the resistance R_2. Both ends of the resistance R_2 were connected to the deviation system of the oscillograph. The object of the resistance R_1 was to damp the natural oscillations of the circuit.

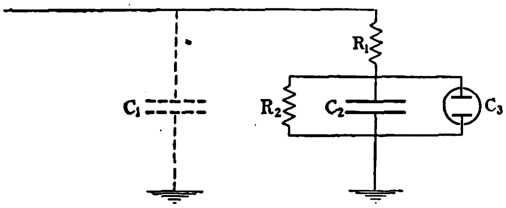

Fig. 4.

The function of the circuit is exemplified by Fig. 5. The voltage of a discharge between two different parts of a cloud in air varies with time, as shown by the curve for *V* in Fig. 5. The variation in the antenna circuit and above the deviation plates of the oscillograph will thus take the form of the curve *dV/dt*.

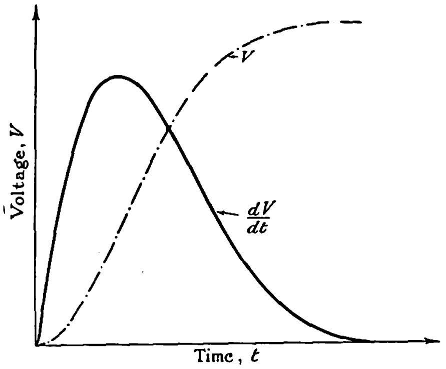

Fig. 5.

I have already pointed out that the discharge in the atmosphere grows, at least in its first stages, relatively slowly. The ordinary lightning stroke is thus generally preceded by partial glow discharges in the form of streamers, which sometimes last for 1 000 to 2 000 micro-seconds.

How the lightning discharge affects the antenna circuit in a given case is exemplified in Fig. 6. The field slowly increases up to the point 1, and is prevented by the leakage resistance of the antenna circuit from giving any charge to the circuit. At this point very rapid glow discharges commence. These are easily absorbed by the antenna circuit, if this is situated near the region of glow discharges. The lightning discharge proper begins at the point 2 and gives a maximum charge to the antenna circuit at the point 3. Superimposed high-frequency variations can be seen at points 4 and 5. Sufficient experimental data are not yet available to permit of an explanation of this superimposed high frequency. It may be caused by some interaction between a partial discharge branch and the main branch of the lightning path, and by some part of the connection taking place over a space filled by partial glow-discharge streamers.

Some Characteristic Records of the Discharge Rate.

In Figs. 7, 8 and 9 are shown some oscillograms of lightning discharges taken in the laboratory of the Royal Board of Waterfalls Research Station during the last two summer seasons. As I have already mentioned, we have, in addition to our work on transmission lines, for several years been occupied with cathode-ray oscillographic studies of the mechanism of lightning discharges. We early discovered that the lightning discharge was itself unidirectional, but our first oscillographs would not allow our investigations to reach the stage to which we have now been able to take them.

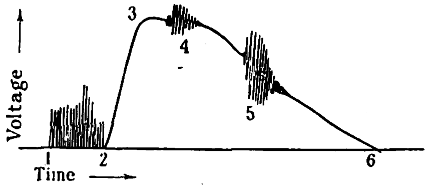

Fig. 6.

Fig. 7 shows four different types of discharge, A, B, C, and D. A and D gave a positive charge to the antenna circuit, B changed the polarity and C gave a pronounced negative charge. The total duration of A was about 1 000 micro-seconds and some pronounced irregularities can be seen at the commencement.

For B the distance between the point at which the lightning stroke occurred and the observation point was about 0·9 km. There is a distinct superimposed high-frequency oscillation which has nothing to do with the production of lightning surges on transmission lines, but it provides the solution of another disturbance problem, viz. the atmospherics in radio receiving sets during thunderstorms. When I have obtained some further experimental data on this subject I hope to revert to this question.

If Figs. 7 and 8 are studied together a remarkable resemblance will be found between curve C of the former and curves A and B of the latter. The lightning discharges, as we shall see later, occur in the same region, and we have here a case of repeated lightning discharges in the same region between cloud and earth. All the discharges show at some point small bands of superimposed high frequency.

Fig. 9 shows two discharges with small amplitudes, but they are quite different in type. For a period of 1 000 micro-seconds discharge B was preceded by a great number of partial discharges.* These partial discharges indicate the period during which a lightning path is built up.

The curves show that the lightning discharges develop slowly and very often indicate single polarity. This provides an explanation of a phenomenon which I have observed for several years when making experiments with the cathode-ray equipment for recording lightning surges. Sometimes very heavy thunderstorms passed near the transmission-line systems without producing any surges at all, whereas one would naturally expect to find induced surges, at least. No doubt such processes took place during the storms, but so slowly and smoothly that no surges above line voltage occurred. I have not yet been able to find any definite evidence of the existence of such indirect surges.

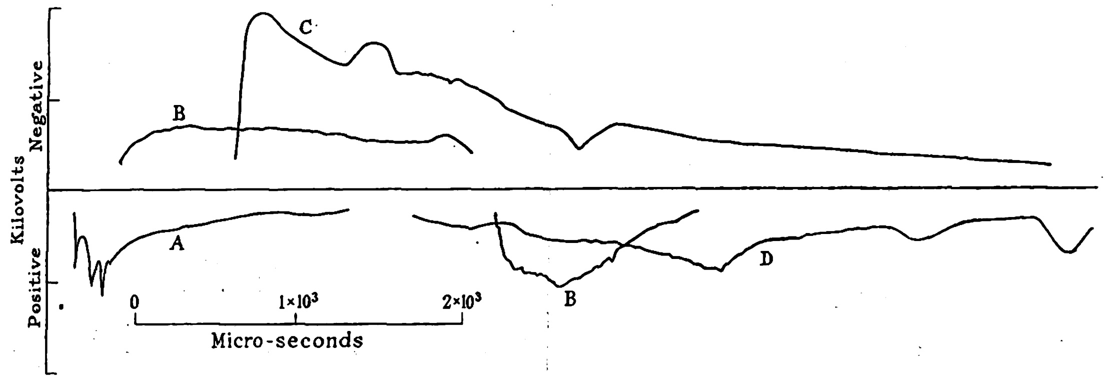

FIG. 7.

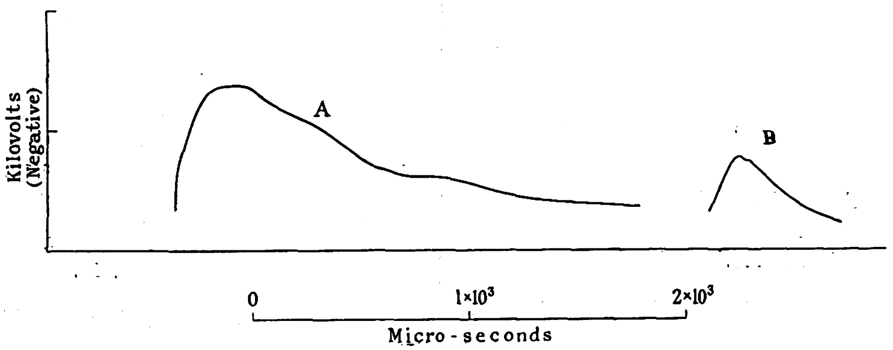

FIG. 8.

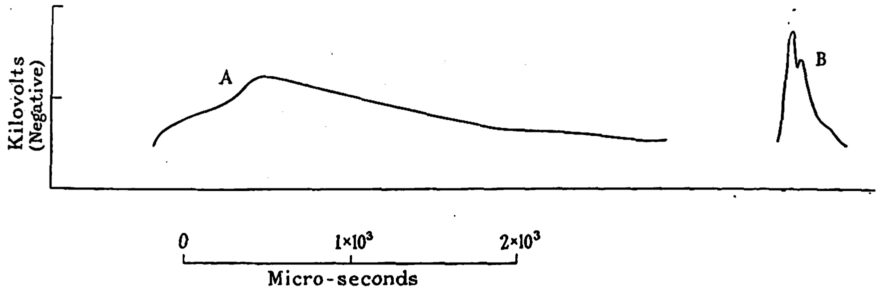

FIG. 9.

We have been able to get some interesting observations on direct lightning strokes to transmission lines. Either discharge C of Fig. 7 or A of Fig. 8 was a direct stroke to transmission lines in the vicinity, a pole of a 3-kV line at 2 km from the laboratory being struck. The 3-kV line was at the time connected by a transformer to a 20-kV line, and this experienced a heavy surge manifested by a short-circuit on the system. The other lightning stroke produced a heavy surge on another 20-kV line at a distance of some 100 m from the former. It must be remembered that a discharge curve similar to the two last-mentioned curves gives an indication that a lightning stroke has occurred between earth and cloud. It seems to be clear that a discharge between a perfect conductor (in this case the earth's surface) and a semi-conductor (a cloud) will give rise to discharge curves similar to those already mentioned.

Only a small proportion of the total number of lightning strokes in any thunderstorm will produce surges on a transmission line in the vicinity of the thunderstorm, and but few of these surges will cause serious damage.

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* These could be seen in the original oscillogram, but they are not shown in the figure as reproduced.

DIRECT RECORDS OF LIGHTNING SURGES ON TRANSMISSION LINES.

One feature of interest in lightning surges is the time which the surges take to reach their maximum or peak value. Other features are also the peak values of the surges, their total duration and the slope of their tails.

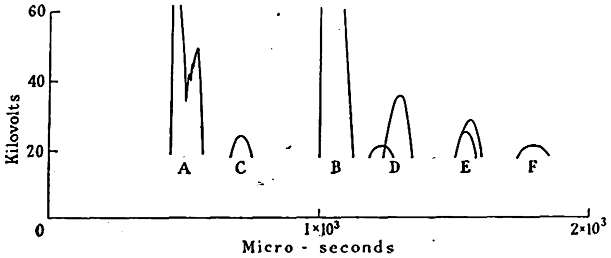

FIG. 10.

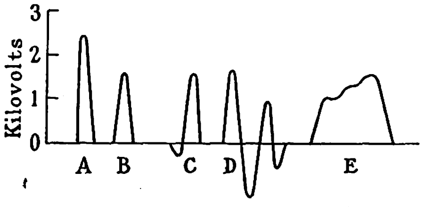

FIG. 11.

The polarity may also be of interest if we consider the problem from a physical point of view.

The maximum value of a surge on a transmission line is limited by the insulation of the line against such a surge, and in this connection the question of time-lag flash-over characteristics has to be taken into account. A surge with a very steep front in which the maximum value is reached within 1 micro-second can pass an insulator string without flashing over, if the value is nearly twice the insulation value at 50 cycles, but if the surge reaches its full value within, say, 10 micro-seconds the insulator will flash over at the value for 50 cycles. It is thus very important to have a knowledge of the surge time-characteristics if we wish to consider the insulation of the line from the point of view of its immunity from surges.

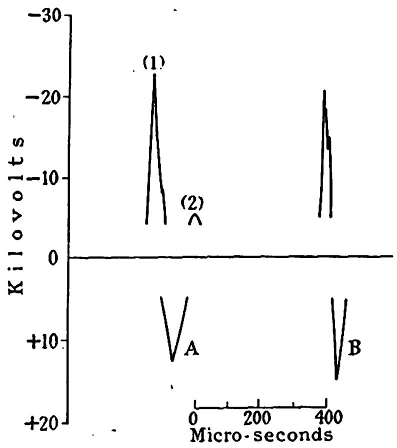

FIG. 12.

Flash-overs on insulators of transmission lines under load make it more difficult to obtain valuable records of the surges. The flash-over from the surge is followed by a short-circuit of the line, and this spoils the film. To avoid this trouble the ideal method would be to run an idle highly-insulated line near to the line conductors.

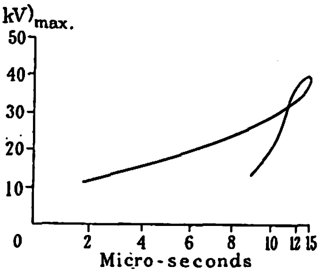

FIG. 13.

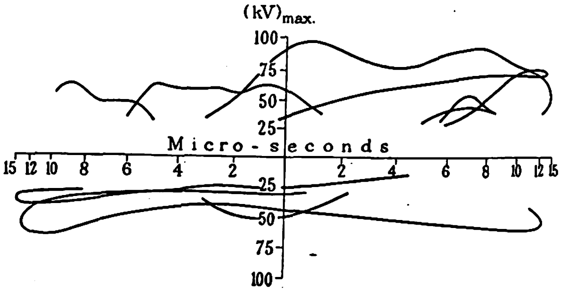

FIG. 14.

THE FIRST LIGHTNING-SURGE RECORDS.

The first lightning-surge record, which was followed three years later by a similar one in another locality, was taken at Uppsala during a severe thunderstorm in July 1925. The record, which is reproduced in Fig. 10, was taken at one end of a 42-km 20-kV line under load.

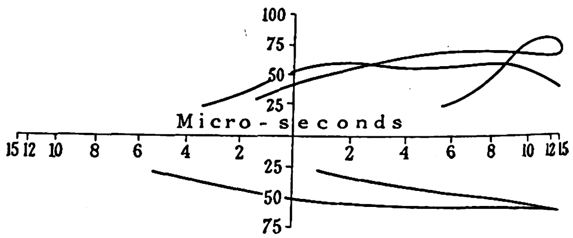

FIG. 15.

In this record it is possible to observe two different primary surges (A and B), both with steep fronts and a peak voltage of about 60 kV. The peak value of one of the surges was considerably beyond the limit of the oscillograph. Surges C and D, and probably E and F, are marked reflections of the primary surges. Surge A, after having travelled to the other end of the 42-km line and returned, shows an attenuation of about 60 per cent. The attenuation for B is also very well marked, with two reflections. The effect of corona attenuation is very pronounced at higher amplitudes of the surges, the slope of the wave-front being especially influenced.

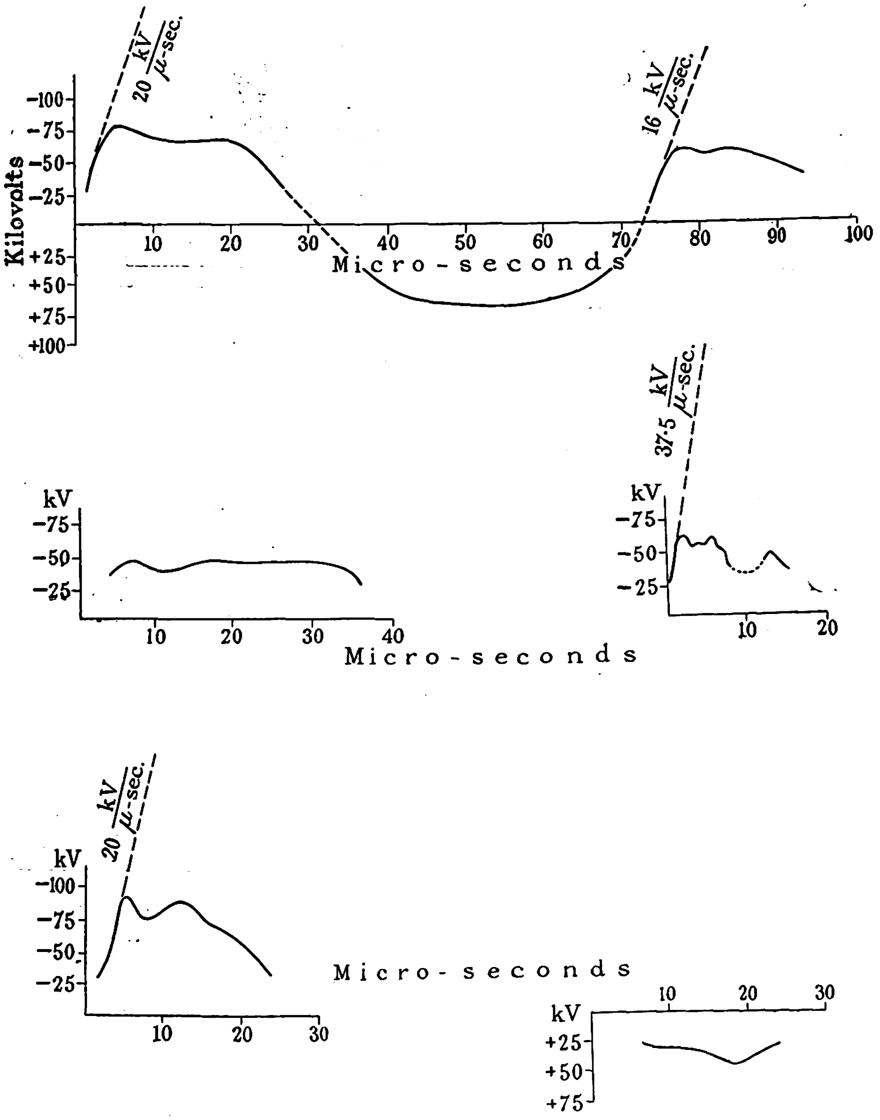

Fig. 16.

During 1926 we had no opportunity of recording lightning surges on transmission lines, but during the summer of 1927 we obtained several records under different conditions. These are shown in Fig. 11. Types A, B and C are pure surges. Type D is probably caused by some kind of natural oscillation of the line, produced by a distant surge. I can give no explanation of type E.

The most frequent surges were of the unipolar type, such as A or B. The slope of the wave-front was sometimes very steep, the peak value in some cases being attained within a few micro-seconds. In other cases the peak value was reached in 50 micro-seconds or more. It must be noted that the steepness of a wave-front depends upon the distance from its origin on the transmission line, and only surges generated quite near to the observation point will show very steep wave-fronts.

During 1928, researches were commenced in the United States with the type of oscillograph used in Uppsala. The Westinghouse Electric and Manufacturing Co. erected, in co-operation with the American Aluminium Co., two research laboratories in Tennessee on a 150-kV line. The first lightning surge recorded on this line had a total duration of 80 micro-seconds. The wave-front was very steep, with a peak value of 750 kV. During the season of 1929 three new stations were operated by the Westinghouse Co., and it is hoped that the results will soon be published. They are in good agreement with our own.

Last summer the Royal Board of Waterfalls Research Station was able to use an improved equipment, and some of the most interesting results are reproduced here in Figs. 12 to 15. Fig. 12 shows two lightning surges which occurred on the same transmission line within a short interval of time. The time scale of the original film on which they were recorded was 1 mm = 24 micro-seconds.

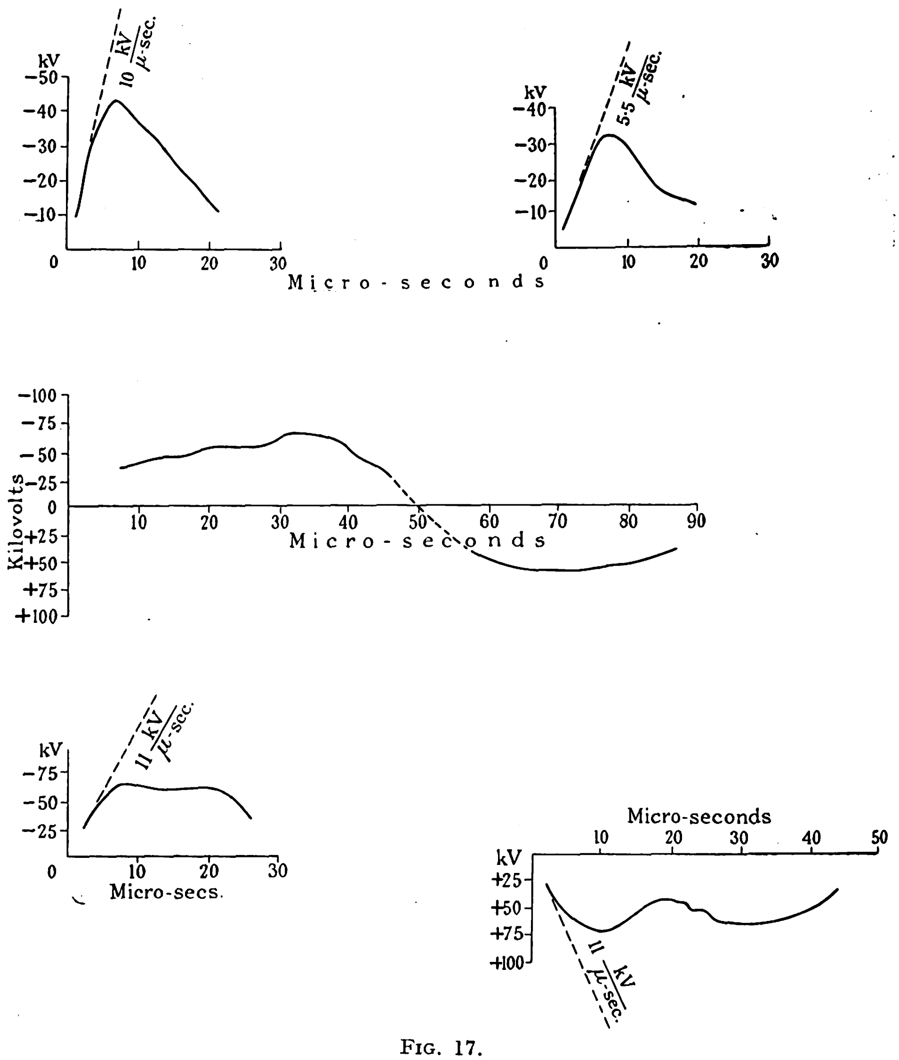

Fig. 17.

The two surges showed a very marked double polarity with a negative charge given to the line at the commencement. Their general character was similar, as can be seen from the records, and they were both produced from the same thunderstorm near the line and at 1 km from the laboratory. The total duration of the surges was about 100 micro-seconds. On the negative side of the surge A in Fig. 12 can be seen the top (2) of the wave reflected from the other end of the line after travelling 84 km, the attenuation thus being about 70 per cent. Some surge records are reproduced in Figs. 13, 14 and 15. For the time scale in these records an oscillator with sinusoidal time variation and with a frequency of 17 000 cycles per sec. was used. It will be seen that the oscillograph gave very sharp records for time intervals of the order of micro-seconds.

Some of the more interesting records have been replotted in Cartesian co-ordinates and are reproduced in Figs. 16 and 17.

For several of the surges the peak value is reached within 2 to 10 micro-seconds, but for others the increase of voltage is much slower. The steepest wave-fronts observed were 38 and 20 kV per micro-second. The total duration of the surges varied between 20 and 100 micro-seconds.

General Conclusions.

The records of lightning surges are hardly sufficient to enable us to obtain definite data, and much caution must therefore be exercised in interpreting the results.

Much work still remains to be done if our knowledge of the subject is to be complete. In the future we are sure to obtain results that are quite as variable in their general aspects as the physical conditions that govern them—the lightning discharges. The investigation of lightning surges will show us how to prevent their effects on transmission lines. The work may be divided into two stages: (1) rational research into the surges under natural conditions in the transmission lines, and (2) the reproduction of surges under controlled conditions in order to study their influence in distribution systems. We shall thus be able to determine the effectiveness or otherwise of protective devices against surges, and we shall also gain information in regard to the best method of constructing such devices.

A DIRECT-READING PHOTO-ELECTRIC PHOTOMETER FOR THE COMMERCIAL MEASUREMENT OF INCANDESCENT ELECTRIC LAMPS.[*]

By G. T. WINCH, Associate Member.

[COMMUNICATION FROM THE STAFF OF THE RESEARCH LABORATORIES OF THE GENERAL ELECTRIC CO., LTD., WEMBLEY.]

(*Paper first received 3rd July, and in final form 8th November, 1929.*)

SUMMARY.

This paper describes the practical difficulties experienced and overcome in the development and construction of a type of photo-electric photometer suitable for measuring incandescent electric lamps of the vacuum and gas-filled 10-watt to 100-watt types. Measurements are made on one direct-reading lumen scale. The apparatus is capable of measuring lamps at commercial speeds under continuous service conditions. The construction is simple and uses mainly standard component parts.

(1) INTRODUCTION.

Experiences in the development and maintenance of a precision photometric standardizing laboratory, coupled with the maintenance of a number of integrating photometers used for initial rating in a factory and measurements on incandescent electric lamps during life test, have shown that it is impracticable by visual means to reduce the probable error of such commercial measurements below ± 2 per cent, and errors up to ± 4 per cent are experienced in such routine work.

The continual improvement in lamp-making has created the need for higher accuracy in commercial photometry, combined with a high speed of measurement. Investigations in this direction were commenced in the summer of 1927 and the following developments have led to the construction of the simple and robust instrument shown in Figs. 1, 2 and 3.

The earlier work carried out in these laboratories,[†] and investigations at the National Physical Laboratory,[‡] had shown that photo-electric methods of measuring light flux and colour temperature can be devised that are far more sensitive and accurate than any visual method. These methods, however, are suitable only when a few observations have to be made by skilled observers. The problem with which this paper is concerned is that of developing photo-electric methods, necessarily of lesser accuracy, suitable for continuous use in the commercial testing of lamps. During the progress of this work important papers have been published describing various photo-electric photometers,[*] sometimes of a form generally similar to that described

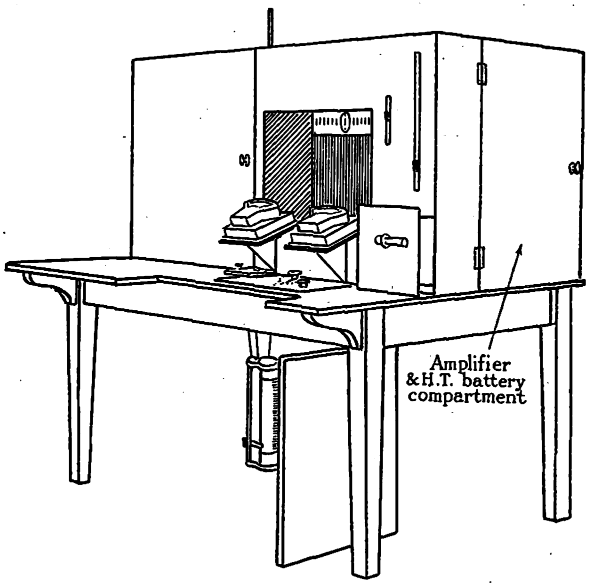

FIG. 1.

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (excepting those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] N. R. CAMPBELL and H. W. B. GARDINER: *Journal of Scientfiic Instruments*, 1925, vol. 2, p. 177; N. R. CAMPBELL and E. G. NEW: *ibid.*, 1925, vol. 7, pp. 2, 38 and 77; N. R. CAMPBELL and M. K. FREETH: *Proceedings of the Optical Convention*, 1926, part 1, p. 253.

[‡] T. H. HARRISON: *Proceedings of the Optical Convention*, 1926, part 1, p. 245.

[*] F. K. MOSS: *General Electric Review*, 1924, vol. 27, p. 592; C. H. SHARP and C. KINGSLEY: *Transactions of the Illuminating Engineering Society*, 1925, vol. 21, p. 117; C. DESHLER and H. SCHROEDER: *ibid.*, 1927, vol. 23, p. 391; W. F. LITTLE and C. E. HORN: *ibid.*, 1927, vol. 23, p. 419; C. H. SHARP and H. A. SMITH: *ibid.*, 1927, vol. 23, p. 429; C. MÜLLER: *Zeitschrift für Technische Physik*, 1928, vol. 4, p. 154.

here, but these authors do not give the structural details or discuss fully the difficulties which the everyday worker is likely to meet with under conditions of continuous service. Whilst this paper describes a final and simple form of photometer which was exhibited at the Physical Society Exhibition in January 1929, the main object is to set forth the experiences gained during its development, in the hope that it will serve a useful purpose to designers and users of similar apparatus.

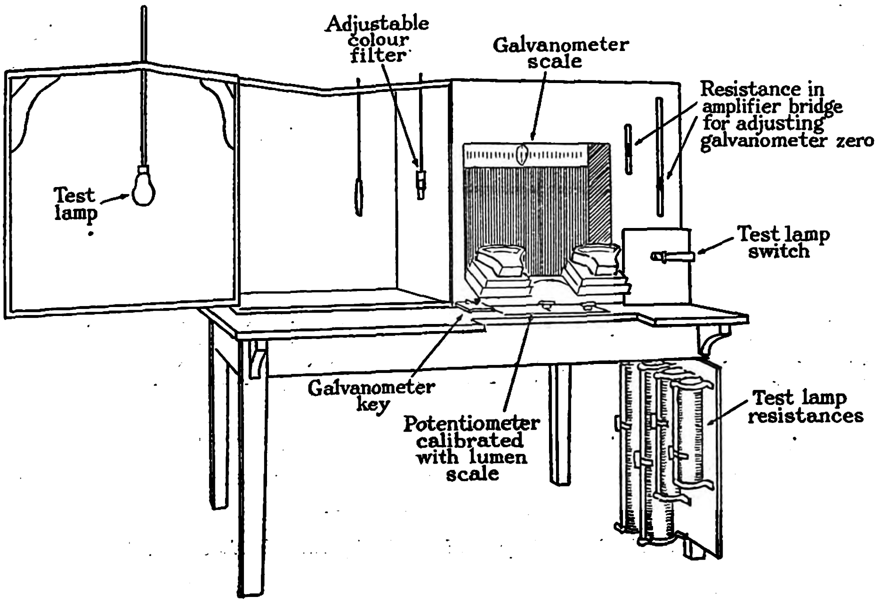
Adjustable colour filter
Galvanometer scale
Resistance in amplifier bridge for adjusting galvanometer zero
Test lamp
Test lamp switch
Galvanometer key
Potentiometer calibrated with lumen scale
Test lamp resistances

FIG. 2.

(2) DEVELOPMENT.

It was evident from earlier work * using vacuum cells that some revolutionary design was necessary in order to adapt photo-electric photometry to commercial needs. Owing to the small photo-electric current obtainable from the vacuum-type cells (i.e. 10^{-9} ampere) the gas-filled cell † promised greater possibilities for commercial work as it was more robust and gave a considerably greater photo-electric current.

In November 1925 Sharp had published a description of a photo-electric photometer utilizing a method which did not depend on the relation between illumination on the cell and the photo-electric current remaining constant for any appreciable period of time, and it seemed that a development of this method might be suitable for use with the gas-filled ‡ cells as developed up to that time. Such cells could not then be relied on to be sufficiently stable for use in any method depending on a constant relation between illumination and photo-electric current.

(3) THE PHOTOMETRIC INTEGRATOR.

In order to make clear the reasons for adopting certain lines of design of the photometric apparatus, it is desirable to refer to experiences with ordinary visual photometers. The result of careful visual investigations carried out by the author and his colleagues over a period of 3 or 4 years was communicated to the B.E.S.A. Committee on "Photometric Integrators." * These investigations showed the advisability of dispensing with diffusing glass windows in the wall of the integrator as a means of providing a test surface for determining changes of brightness of the inside wall of the integrator.†

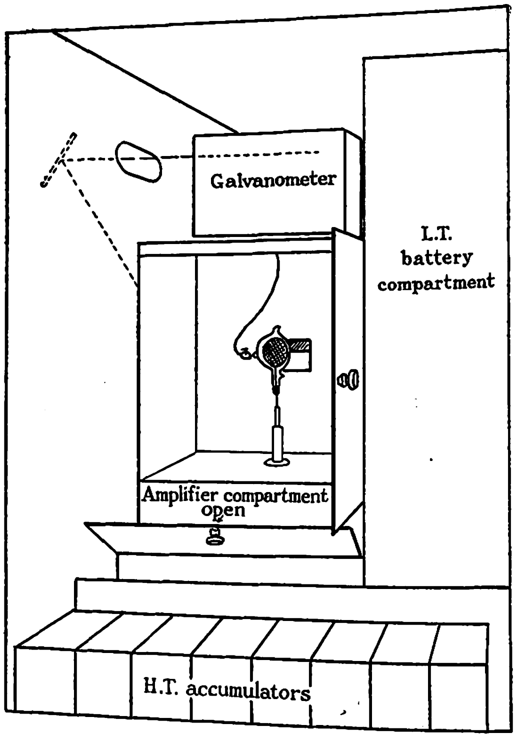
Galvanometer
L.T. battery compartment
Amplifier compartment open
H.T. accumulators

FIG. 3.—View through right-hand door shown in Fig. 1, with door of subsidiary integrator open.

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* N. R. CAMPBELL: *loc. cit.* † *Loc. cit.*
‡ N. R. CAMPBELL: *Philosophical Magazine*, 1927, vol. 3, pp. 946 and 1041; also 1927, vol. 4, p. 726.

* B.S.S. No. 354—1929.
† B. P. DUDDING and G. T. WINCH: *Journal of Scientific Instruments*, 1928 vol. 5, p. 312.

Hence in the work hereafter described the opal window has not been used but the cell has been generally arranged in a subsidiary integrator.

The study of the relative behaviour of cubical and spherical integrators had also shown that lamps having fairly uniform polar distributions, such as squirrel-cage vacuum and wreath type gas-filled lamps, when operated at the centre of a cube would produce results in agreement with those obtained in a spherical integrator, within ± ¼ per cent for squirrel-cage vacuum lamps and ± 1 per cent for wreath type gas-filled lamps. As the particular apparatus in course of development was intended for measuring commercially these types of lamp this accuracy was considered satisfactory for this purpose, as gas-filled lamps of normal design are subject to intrinsic light fluctuations of this order.

Throughout this development work on photo-electric photometers cubical integrators have been used for convenience and ease of construction. Substitution of a sphere in all cases herein described would not alter the principle or general structure of the apparatus but would increase the absolute accuracy of measurement on photometric standard lamps designed specially to avoid small variations in light output.

It would be advisable to use spherical integrators even for commercial measurements on lamps and fittings having asymmetric polar distributions.

FIRST EXPERIMENTAL APPARATUS.

The preliminary step was to study the behaviour of apparatus constructed on lines found by the author and his colleagues to be preferable for visual work, but employing the principles involved in apparatus described by Sharp,* in which he used a revolving mirror to illuminate the photo-electric cell alternately with the diffusing window in the integrator wall and the comparison lamp.

As it was not possible to obtain sufficient illumination on the photo-electric cell by adapting the preferred visual method which dispenses with a diffusing window, an arrangement was used in which the light flux received at the screened portion of the wall of the integrator containing the test lamp was allowed to enter a subsidiary integrator from which the cell received diffused illumination. The apparatus is shown diagrammatically in Fig. 4. A revolving shutter was so arranged that the subsidiary integrator received light, through two holes, alternately from the test lamp integrator and the comparison lamp.

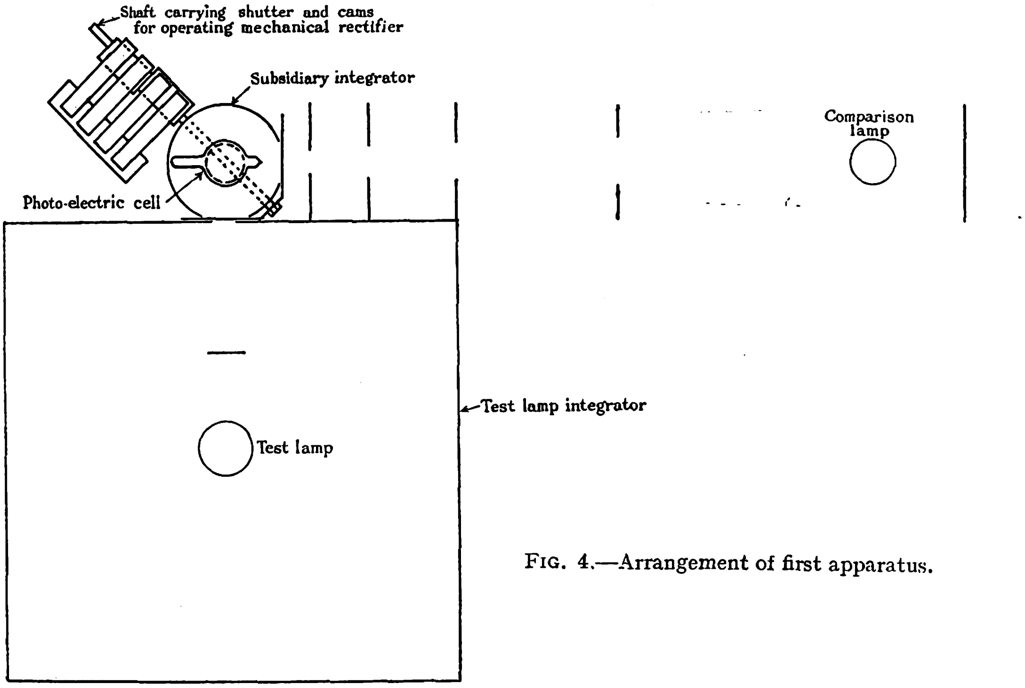

FIG. 4.—Arrangement of first apparatus.

The circuit used for the amplifier is shown in Fig. 5 and is similar to that used by Sharp.* It will be seen that the photo-electric cell is connected to the grid of one valve in the amplifier bridge, and consequently any change in intensity of illumination on the cell due to the alternate shutter positions produced corresponding alternations in an intervalve transformer connected across the valve bridge. The resultant low-frequency alternating current was rectified by a commutator arranged on the same shaft as the shutter and suitably timed. The rectified current operated a galvanometer which deflected to the right or left of zero, depending on the position of the comparison lamp with respect to a photometric balance.

The possibility of using valve rectification was considered but was rejected because with such an arrangement an opposing voltage would be required in order to bring the galvanometer to zero when a photometric balance existed. Also the indications of the galvanometer would always be in one direction irrespective of whether the illumination on the photo-electric cell was higher or lower than that required for photometric balance. This would be very inconvenient on a commercial photometer.

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* C. H. SHARP and C KINGSLEY: *loc. cit.*

* *Loc. cit.*

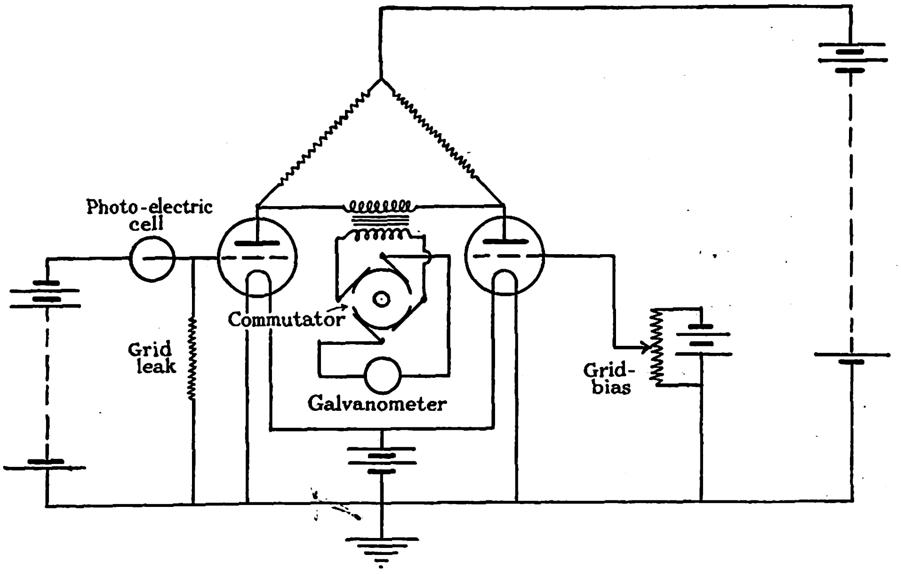
Photo-electric cell
Grid leak
Commutator
Galvanometer
Grid-bias

Fig. 5.—Circuit of first apparatus.

Originally the shutter was driven at a speed of approximately 200 r.p.m. by a small electric motor, but, despite the fact that the valves were in an earthed screened box, the disturbance of the amplifier due to the electric motor resulted in fortuitous kicks of the galvanometer. The motor was, therefore, replaced by a small air turbine.

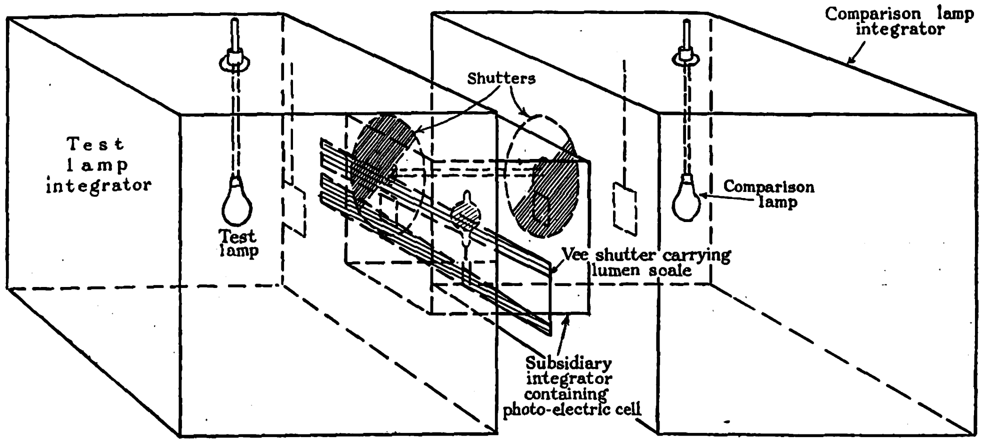
Comparison lamp integrator
Shutters
Test lamp integrator
Test lamp
Comparison lamp
Vee shutter carrying lumen scale
Subsidiary integrator containing photo-electric cell

Fig. 6.—Arrangement of second apparatus.

The commutator used originally was of normal construction, having segments mounted on a shaft, and stationary brushes, but subsequently it was replaced by butt-ended contacts working from cams on the shutter shaft. This was tried in an endeavour to overcome contact troubles which manifested themselves in unsteadiness of the galvanometer.

The results obtained with this apparatus were rather disappointing as it was only with considerable difficulty that agreement could be obtained to within ± 1½ per cent on a few vacuum lamps (20–100 watts) of the squirrel-cage construction.

Two main difficulties were experienced with this apparatus:—

(*a*) *Electrical.*—Unsteady galvanometer readings due to erratic functioning of the commutating device and the necessary mechanical complications.

(*b*) *Photometric.*—As the result of using the subsidiary integrator to receive illumination from the comparison lamp through a small aperture, the resultant lumen scale did not follow the inverse-square law.

The latter is only a minor objection as it would have been possible to calibrate a scale, but considerable inconvenience was caused during experimental work owing to the impossibility of quickly determining the source of error. This difficulty had been anticipated but it was not thought that it would cause the inconvenience subsequently experienced.

SECOND EXPERIMENTAL APPARATUS.

With the object of overcoming the scale difficulty and improving the commutating arrangements, a new experimental apparatus was built incorporating the improvements shown diagrammatically in the general arrangement in Fig. 6. Pneumatically operated commutating gear was employed and three integrators were arranged so that two thin revolving sectors allowed the central small integrator, containing the photo-electric cell, to receive illumination alternately from the test and comparison integrators arranged on either side. A V shutter was arranged to control the light entering the test lamp integrator so that the lumen scale would be proportional to the movement of this shutter. All the apparatus was electrostatically screened in order to obtain freedom from external electrical disturbances. The best results obtained were with vacuum lamps over a range from 200 to 600 lumens, and the agreement was within ± 1½ per cent of the visual values. The lumen scale was limited in range owing to the lack of perfect integration when large changes were made in the window size by adjustment of the V shutter.

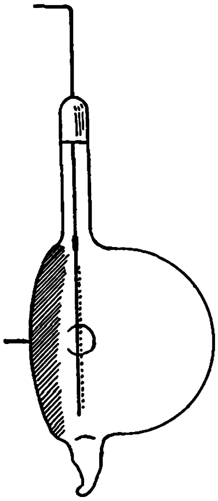

FIG. 7.

These results were not very satisfactory and the apparatus still involved mechanical complications which are always objectionable in an instrument to be used commercially where maintenance attention must be reduced to a minimum.

The inherent difficulties of the alternating light method led to the investigation of the possibilities of other more convenient methods.

THIRD EXPERIMENTAL APPARATUS.

The Red-Sensitive Cell.—At this juncture the red-sensitive photo-electric cell (Fig. 7) was developed,* and its more useful frequency range gave promise of important application to photometry. An investigation of the relation between illumination and photo-electric current indicated the possibility of a much simpler form of apparatus free from moving parts. In order to carry out these measurements an apparatus of the form shown in Fig. 8 was built. The circuit shown in Fig. 9 is a convenient form of amplifier which has been used by Sharp and others and consists of two valves connected in bridge form so that small changes in filament and H.T. voltage do not cause serious changes in the voltage between A_1 and A_2 (Fig. 9). It is clear from the diagram that if the grid bias G.B. is so adjusted, while the cell is dark, that a balance is obtained on the galvanometer, any subsequent change in grid potential due to the photo-electric current can be measured by the extra grid-bias voltage required to restore the bridge to the balanced condition indicated by zero deflection of the galvanometer. This grid-bias voltage, which is applied by means of the potentiometer, was originally measured by a voltmeter as shown in Fig. 9. Several lamps operating at the same colour temperature were put in the integrator in turn and the grid-bias voltage necessary to restore balance was measured. Over a range of 20 to 1 in lumens this method gave a linear relation between grid-bias voltage and lamp lumens.

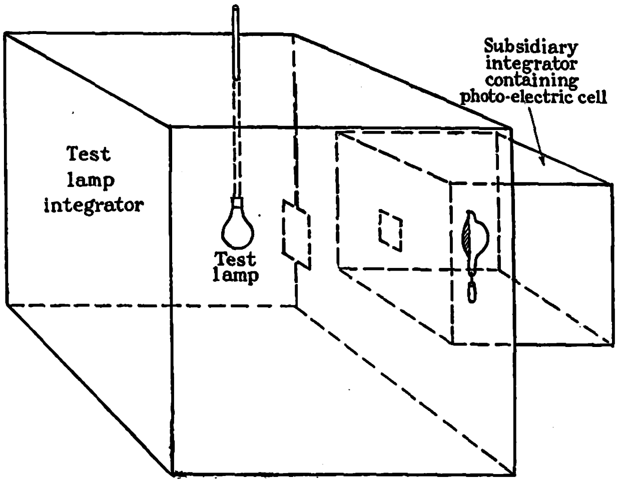

FIG. 8.—Apparatus used to test characteristics of photo-electric cell.

In the light of these promising developments, and owing to the disappointing results obtained from the apparatus involving rectification by commutation, this latter method was abandoned. Publications by Sharp and Smith * indicated that they had been experiencing similar difficulties which, however, they had eventually overcome by employing special, accurately made, commutating gear.

It was clear that some development of the arrangement shown in Fig. 8 would have the advantage of simplicity of design and operation, and it was this apparatus which formed the basis on which the final form of photometer was designed. The difficulties encountered in the perfection of this apparatus will therefore be discussed in detail, as an apparatus working on this principle has been in successful continuous operation for the past 6 months on the industrial measurement of large numbers of lamps.

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* N. R. CAMPBELL: *Philosophical Magazine*, 1928, vol. 6, p. 633.

* *Loc. cit.*

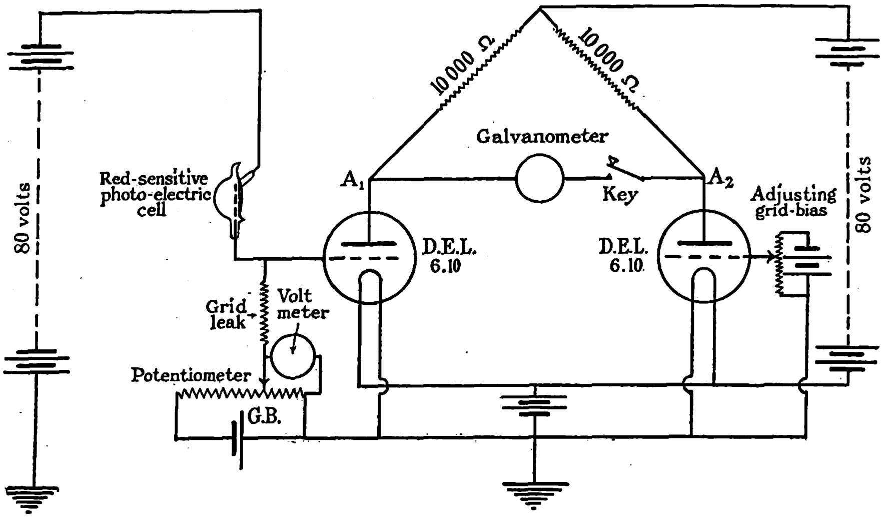
10000 Ω
10000 Ω
Galvanometer
A₁
A₂
Key
Adjusting grid-bias
80 volts
80 volts
Red-sensitive photo-electric cell
D.E.L. 6.10
D.E.L. 6.10
Grid leak
Volt meter
Potentiometer
G.B.

Fig. 9.

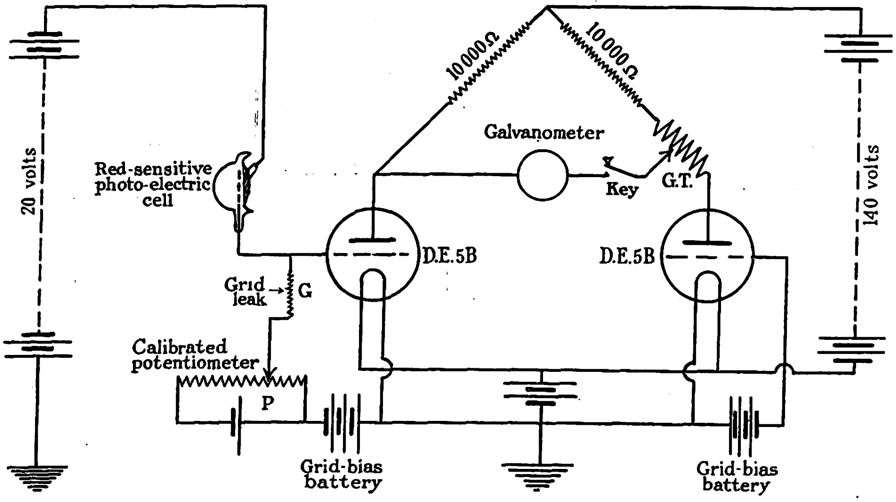
10000Ω
10000Ω
Galvanometer
Key
G.T.
20 volts
140 volts
Red-sensitive photo-electric cell
D.E.5B
D.E.5B
Grid leak
G
Calibrated potentiometer
P
Grid-bias battery
Grid-bias battery

Fig. 10.

Valves for the Amplifier.—Since valves were employed in all the apparatus using the commutation system to amplify the low-frequency alternating current produced as the results of the shuttering of the cell, drift of the valve characteristics had been unimportant and therefore great attention had not been given to the amplifier design. With the development of the method involving the measurement of changes of grid potential due to the photo-electric current, several difficulties were encountered, the most serious being that of the choice of suitable valves which would have characteristics sufficiently stable to avoid serious zero drift. This is important in industrial apparatus. Adjusting the zero with the cell dark is an operation which, if it had to be performed before each measurement, would probably outweigh all the advantages of such an apparatus.

D.E.L.610 valves were used in the earlier experiments, but the drift produced apparent changes in calibration of the order of 1 per cent per 10 minutes. Subsequent investigations with this type of valve showed that by operating it at 4 volts instead of 6 volts sufficient amplification could be obtained and the drift reduced to about 1 or 2 per cent per hour after having allowed a period of about 20 hours for them to reach a steady state. Providing the H.T. supply was never disconnected, the filaments could be switched off and when reconnected a period of 3 or 4 hours instead of 20 hours was required to reach the steady state. Drift of this order was still very inconvenient owing to the inevitable breaking of the H.T. supply to permit of battery charging. In an endeavour to overcome this difficulty many types of valves were tried, the most satisfactory being the D.E.5 B type, specially aged and selected for this purpose. These, if operated at 4 volts, were found to be free from serious drift about 1 hour after connection to H.T. and L.T. batteries. About 4½ volts negative grid bias corresponded to the correct working characteristics. Dry batteries used for this purpose need to be very carefully watched as they eventually develop unsteadiness which may at first be attributed to the photo-electric cell or to the lamps being tested. For this reason accumulator grid-bias and H.T. batteries are desirable.

Amplifier Circuit.—Certain minor objections were found to the circuit shown in Fig. 9 which, for the following reasons, was modified to that in Fig. 10. These objections were as follows:—

(*a*) As it would have been necessary to use a potentiometer with very smooth adjustment from about 0 to 0·6 volt, in order to obtain a measure of the light falling on the photo-electric cell (and therefore the lumens of the lamp under test), and furthermore because a voltmeter of this low range would have been required, it was simpler to use a potentiometer with calibrated dial and slide wire. This also had the advantage of being more accurate and easier to read to high precision.

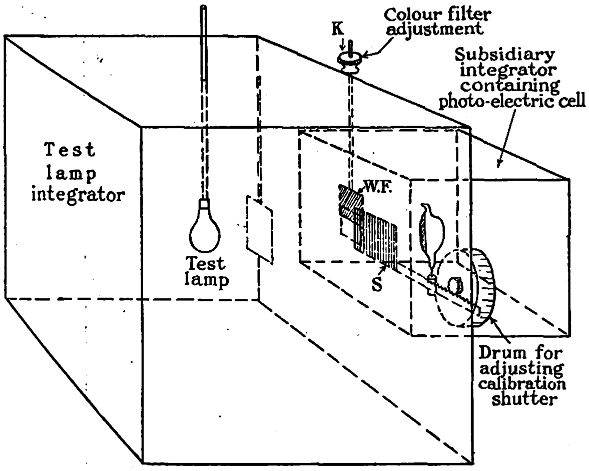
Colour filter adjustment
K
Subsidiary integrator containing photo-electric cell
Test lamp integrator
W.F.
Test lamp
S
Drum for adjusting calibration shutter

FIG. 11.—Arrangement of final form of photometer.

(*b*) When D.E.L.610 valves were used which would operate satisfactorily with their grids at earth potential, it was more convenient to adjust the galvanometer to zero by using a sliding resistance in series with one of the anode resistances of the valves so that the galvanometer tapping could be adjusted to obtain a balance (see G.T., Fig. 10). This avoided the necessity at the time for an extra accumulator and potentiometer, but as in the later experiments D.E.5 B valves were used which required a permanent grid bias of $4\frac{1}{2}$ volts, preferably from secondary cells, an adjustable grid bias would be equally convenient.

COLOUR CORRECTION.

The red-sensitive cell employed in this apparatus was found to give linear response with changes in illumination at constant colour temperature and to depart slightly from this relation with lamps operating at colour temperatures varying from about 2 350° (vacuum lamp colour) to 2 700° C.[*] (small-wattage gas-filled lamp colour). There also appears to be a slight drift in the response to such changes of temperature. Hence a suitable variable colour filter was needed to correct this error if it were required to measure lamps operating at various colour temperatures within the range mentioned above, without the application of a correction for colour. The requirement was met by the use of a Wratten colour filter (colour not critical but dependent on particular integrator paint and cell used) arranged to slide vertically over the aperture between the two integrators W.F. (Fig. 11). The area of aperture covered by this filter is adjustable by the knurled nut K which raises or lowers the filter.

The final form of the apparatus is shown in Figs. 1, 2 and 3.

LUMEN SCALE CALIBRATION.

There are two methods of adjusting the potentiometer P (Fig. 10) to read direct in lumens:—

(*a*) By varying the value of the grid leak G (Fig. 10) and thus varying the sensitivity of the amplifier.

(*b*) By varying the amount of light entering the photo-electric cell.

A compromise between these two methods was found to give the most satisfactory results. The grid leak had a total value of about 60 megohms [*] which could be tapped at approximately 40, 50, 55 and 60 megohms. This gave a suitable sensitivity with the colour filter in its normal position.

In order to obtain fine adjustment so that the potentiometer could be made to read correct values, a thin aluminium shutter was arranged between the two integrators S (Fig. 11) moving at right angles to the colour filter. This could be varied without altering the ratio of filtered to unfiltered light entering the photo-electric cell integrator.

It was found possible by use of this shutter to halve the normal working lumen scale and so make possible the measurement of lamps having lumen values in excess of the normal full-scale value (1 500 lumens).

THE APPARATUS IN USE.

The photometer is very simple to use and for routine measurements is capable, with one operator, of handling 150 lamps per hour. It is found convenient to leave the valve filaments and H.T. batteries connected day and night as this reduces the time wasted when waiting for the batteries and valves to reach the steady state. Filament batteries are charged at week-ends and the H.T. and potentiometer batteries need charging only about once a month, so that inconvenience of charging is not great. Automatic charging equipment to operate during the night or week-ends is scarcely necessary but could be installed if necessary.

METHOD OF CALIBRATION.

Calibration of the apparatus is carried out in the following manner:—

(*a*) The colour sensitivity is conveniently checked by using two standard lamps calibrated at voltages such that they both have the same or closely similar values

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[*] Absolute values.

[*] Made up of the Dubilier "Dumetohm" type of grid leaks.

TABLE 1.

Lamp No.	Volts	Observer No. 1		Observer No. 2		Means of 2 observations at each set-up	Mean of 8 measurements	Maximum percentage deviations of any one visual reading	One photo-electric observation		Percentage deviation of photo-electric from visual	
		Observation	Mean	Observation	Mean				Large sub-standard voltmeter	Normal sub-standard voltmeter		
1	2	3	4	5	6	7	8	9	10	11	12	13
	volts	lumens	lumens	lumens	lumens	lumens	lumens	per cent	lumens	lumens	per cent	per cent
R47 A	100	538	$537\cdot_5$	552	544	545	$540\cdot_8$		539	545	$-0\cdot3_3$	$+0\cdot7_5$
		542		545		$543\cdot_5$		+2·0				
		533		537		535		−1·4				
		537		542		$539\cdot_5$			539		$-0\cdot3_3$	
B	100	550	551	563	558	$556\cdot_5$	$554\cdot_4$		555	—	$+0\cdot1_1$	—
		554		561		$557\cdot_5$		+1·5				
		550		561		$555\cdot_5$		−1·3				
		549		547		548			554		$-0\cdot0_7$	
C	100	548	550	553	$553\cdot_5$	$550\cdot_5$	$551\cdot_6$		551	$554\cdot_7$	$-0\cdot1_1$	$+0\cdot5_5$
		555		554		$554\cdot_5$		+0·7				
		552		550		551		−0·6				
		544		557		$550\cdot_5$			550		$-0\cdot2_9$	
D	100	542	$544\cdot_5$	552	550	547	$547\cdot_4$		$546\cdot_5$	$547\cdot_4$	$-0\cdot1_6$	—
		551		551		551		+1·4				
		545		547		548		−1·3				
		540		551		$545\cdot_5$			548		$+0\cdot1_1$	
E	100	547	546	551	$545\cdot_5$	549	$545\cdot_6$		$543\cdot_5$	551	$-0\cdot3_8$	+1·0
		551		543		547		+1·1				
		543		543		543		−0·7				
		542		545		$543\cdot_5$			545		$-0\cdot1_1$	
F	100	382	377	384	382	383	$379\cdot_6$		$381\cdot_5$	—	$+0\cdot5_0$	—
		374		381		$377\cdot_5$		−2·0				
		372		378		375		+1·1				
		$380\cdot_5$		385		$382\cdot_5$			382		$+0\cdot6_3$	
G	100	381	379	385	383	383	$381\cdot_1$		382	—	$+0\cdot2_4$	—
		381		385		383		+1·0				
		377		381		379		−1·4				
		376		$382\cdot_5$		379			383		$+0\cdot5_0$	
H	100	384	385	388	387	386	$386\cdot_1$		385	—	$-0\cdot2_9$	—
		385		389		387		+0·1				
		384		385		$384\cdot_5$		−0·6				
		387		$386\cdot_5$		387			385		$-0\cdot2_9$	
J	100	378	$376\cdot_5$	378	$377\cdot_5$	378	$377\cdot_1$		374	—	$-0\cdot8_2$	—
		377		377		377		+0·2				
		377		381		379		−0·7				
		$374\cdot_5$		$374\cdot_5$		$374\cdot_5$			377		$-0\cdot0_3$	
K	100	$380\cdot_5$	382	381	$382\cdot_5$	381	$382\cdot_1$		$380\cdot_8$	—	$-0\cdot3_4$	—
		380		380		380		+0·9				
		385		388		$386\cdot_5$		−0·6				
		$381\cdot_5$		381		381			381		$-0\cdot2_9$	
L	100	$372\cdot_5$	372	372	$374\cdot_5$	372	$373\cdot_3$		$371\cdot_8$	—	$-0\cdot4_0$	—
		373		376		$374\cdot_5$		+1·5				
		373		379		376		−1·0				
		$369\cdot_5$		$371\cdot_5$		$370\cdot_5$			372		$-0\cdot3_5$	
M	110	267	265	$266\cdot_5$	264	267	$264\cdot_6$		$263\cdot_5$	—	$-0\cdot4_2$	—
		$263\cdot_5$		$262\cdot_5$		263		+0·5				
		266		$266\cdot_5$		266		−0·7				
		263		262		$262\cdot_5$			$262\cdot_5$		$-0\cdot8_0$	
N	110	264	265	$265\cdot_5$	265	265	$265\cdot_0$		$264\cdot_6$	$265\cdot_8$	$-0\cdot1_5$	$+0\cdot3_0$
		$266\cdot_5$		$264\cdot_5$		$265\cdot_5$		+1·4				
		$268\cdot_5$		268		268		−1·7				
		$260\cdot_5$		262		261			265		0	

TABLE I—*continued.*

Lamp No.	Volts	Observer No. 1		Observer No. 2		Means of 2 observations at each set-up	Mean of 8 measurements	Maximum percentage deviations of any one visual reading	One photo-electric observation		Percentage deviation of photo-electric from visual	
		Observation	Mean	Observation	Mean				Large sub-standard voltmeter	Normal sub-standard voltmeter		
1	2	3	4	5	6	7	8	9	10	11	12	13
	volts		lumens	lumens	lumens	lumens	lumens	per cent	lumens	lumens	per cent	per cent
R47 O	110	$269\cdot_5$	$268\cdot_5$	$270\cdot_5$	269	270	$268\cdot_8$	$+0\cdot6$ $-0\cdot4$	$268\cdot_2$	$269\cdot_2$	$-0\cdot2_2$	$+0\cdot1_5$
		270		269		$269\cdot_5$						
		268		$268\cdot_5$		268						
		267		$267\cdot_5$		267			$269\cdot_8$		$+0\cdot3_7$	
P	110	$264\cdot_5$	266	$268\cdot_5$	$267\cdot_5$	$266\cdot_5$	$266\cdot_8$	$+0\cdot6$ $-0\cdot6$	$266\cdot_7$	$267\cdot_5$	$-0\cdot0_4$	$+0\cdot2_6$
		$267\cdot_5$		267		267						
		268		268		268						
		265		266		$265\cdot_5$			267		$+0\cdot0_7$	
Q	110	262	265	$262\cdot_5$	263	262	$263\cdot_9$	$+1\cdot9$ $-1\cdot2$	262	—	$-0\cdot7_2$	—
		263		262		$262\cdot_5$						
		$268\cdot_5$		266		267						
		$266\cdot_5$		$260\cdot_5$		$263\cdot_5$			$262\cdot_5$		$-0\cdot5_3$	
R	100	$170\cdot_8$	168	$171\cdot_2$	$168\cdot_8$	171	$168\cdot_5$	$+1\cdot4$ $-1\cdot7$	167	—	$-0\cdot9_0$	—
		169		$168\cdot_5$		$168\cdot_8$						
		$168\cdot_3$		$168\cdot_8$		$168\cdot_5$						
		$165\cdot_3$		$166\cdot_3$		$165\cdot_8$			$167\cdot_3$		$-0\cdot7_1$	
S	100	$171\cdot_6$	172	$171\cdot_5$	$172\cdot_5$	$171\cdot_5$	$172\cdot_4$	$+1\cdot4$ $-0\cdot6$	$173\cdot_3$	$172\cdot_5$	$+0\cdot5_2$	$+0\cdot0_6$
		$172\cdot_5$		173		$172\cdot_8$						
		$173\cdot_2$		$174\cdot_7$		174						
		$171\cdot_2$		$171\cdot_2$		$171\cdot_2$			$172\cdot_2$		$-0\cdot1_2$	
T	100	169	168	$168\cdot_8$	$167\cdot_5$	$168\cdot_9$	$168\cdot_0$	$+0\cdot8$ $-1\cdot3$	$168\cdot_3$	$168\cdot_5$	$+0\cdot1_8$	$+0\cdot3_0$
		$166\cdot_3$		$165\cdot_6$		166						
		$169\cdot_3$		$169\cdot_3$		$169\cdot_3$						
		$168\cdot_4$		$167\cdot_2$		$167\cdot_8$			$169\cdot_1$		$+0\cdot6_6$	
U	100	$172\cdot_3$	$173\cdot_5$	173	174	$172\cdot_7$	$173\cdot_6$	$+1\cdot4$ $-1\cdot3$	$172\cdot_9$	$174\cdot_5$	$-0\cdot4_0$	$+0\cdot5_2$
		174		174		174						
		$176\cdot_1$		$174\cdot_7$		$175\cdot_4$						
		$171\cdot_3$		$173\cdot_2$		$172\cdot_3$			$173\cdot_6$		0	
V	100	175	$175\cdot_5$	$176\cdot_3$	176	$175\cdot_6$	$176\cdot_0$	$+1\cdot3$ $-1\cdot0$	$175\cdot_8$	—	$-0\cdot1_1$	—
		175		$175\cdot_8$		$175\cdot_4$						
		$178\cdot_3$		$178\cdot_3$		$178\cdot_3$						
		$174\cdot_2$		$174\cdot_7$		$174\cdot_5$			$175\cdot_6$		$-0\cdot2_3$	
W	100	$174\cdot_2$	175	$174\cdot_3$	$175\cdot_3$	$174\cdot_3$	$175\cdot_0$	$+1\cdot6$ $-1\cdot1$	$174\cdot_9$	$174\cdot_8$	$-0\cdot0_6$	$-0\cdot1_1$
		$173\cdot_8$		175		$174\cdot_2$						
		$177\cdot_8$		177		$177\cdot_4$						
		$173\cdot_3$		175		$174\cdot_1$			$175\cdot_3$		$+0\cdot1_7$	
X	110	$79\cdot_6$	$80\cdot_0$	$79\cdot_4$	$79\cdot_5$	$79\cdot_5$	$79\cdot_9$	$+0\cdot6$ $-0\cdot7$	$79\cdot_7$	—	$-0\cdot2_5$	—
		$80\cdot_4$		$80\cdot_1$		$80\cdot_{25}$						
		$80\cdot_2$		$80\cdot_3$		$80\cdot_{25}$						
		$79\cdot_9$		$79\cdot_3$		$79\cdot_6$			$79\cdot_6$		$-0\cdot3_8$	
Y	110	$74\cdot_7$	$75\cdot_5$	$74\cdot_9$	$75\cdot_0$	$74\cdot_8$	$75\cdot_3$	$+1\cdot4$ $-0\cdot8$	$75\cdot_2$	—	$-0\cdot1_3$	—
		$76\cdot_3$		$75\cdot_4$		$75\cdot_{75}$						
		$75\cdot_4$		$75\cdot_3$		$75\cdot_{35}$						
		$75\cdot_4$		$75\cdot_3$		$75\cdot_{35}$			$75\cdot_2$		$-0\cdot1_3$	
Z	110	$78\cdot_4$	$79\cdot_5$	$78\cdot_3$	$79\cdot_0$	$78\cdot_{35}$	$79\cdot_1$	$+1\cdot8$ $-1\cdot0$	$79\cdot_7$	$79\cdot_7$	$+0\cdot7_6$	$+0\cdot7_6$
		$79\cdot_0$		$78\cdot_8$		$78\cdot_9$						
		$79\cdot_9$		$79\cdot_5$		$79\cdot_7$						
		$80\cdot_5$		$78\cdot_5$		$79\cdot_5$			$79\cdot_8$		$+0\cdot8_8$	

Mean error of photo-electric from visual readings in col. 12 = $-\ 0\cdot1$ per cent.
Mean error of photo-electric from visual readings in col. 13 = $+\ 0\cdot3_7$ per cent.

of lumens but operate at temperatures of about 2 350° K. and 2 700° K. respectively. These lamps represent the limits of the working range of colour temperature of lamps normally measured on this photometer. The colour filter is then adjusted until the two lamps balance at their nominal value on the potentiometer.

(*b*) The potentiometer is next set to zero and the galvanometer balanced by adjusting the position of the bridge arm tapping G.T. on the sliding resistance (Fig. 10) while the cell is dark.

(*c*) A standard lamp is then put in the photometer, the potentiometer scale adjusted to the value of lumens of the standard lamp and the galvanometer balanced by adjusting the sliding shutter S (Fig. 11). The photometer is then ready to measure lamps of vacuum and gas-filled types from about 80 to 1 500 lumens.

The vacuum lamps were of squirrel-cage construction free from internal contact variations.

The gas-filled lamps had a special construction which rendered them free from momentary small fluctuations. They also had a symmetrical polar distribution in order that the effect of imperfect integration of the cubical integrator might be reduced to a minimum.

(5) VISUAL CALIBRATION OF STANDARD LAMPS.

These specially prepared lamps were calibrated visually in the photometric standards laboratory, where electrical measurements are to an accuracy of 2 parts in 10 000. Photometric measurements were then made in a 1-metre sphere against 110-volt, 20-, 40- and 60-watt vacuum lamps which had been standardized by the National Physical Laboratory.

TABLE 2.

Lamp No.	Volts	Observers						Mean visual value	Maximum percentage deviation of any one visual reading	One photo-electric observation using norma sub-standard voltmeter	
		No. 1	No. 3	No. 4	No. 5	No. 6	No. 7				
1	2	3	4	5	6	7	8	9	10	11	12
	volts	lumens	lumens	lumens	lumens	lumens	lumens	lumens	per cent	lumens	per cent
R15 A	110	1 040 1 031	1 060 1 056	1 083 1 062	1 082 1 070	1 072 1 070	1 038 1 050	1 060	+ 2·1 − 2·7	1 063	$+ 0{\cdot}2_8$
B	110	1 120 1 109	1 132 1 121	1 142 1 130	1 150 1 142	1 131 1 137	1 122 1 118	1 130	+ 1·7 − 2·0	1 122	$- 0{\cdot}7_1$
C	115	590 638	632 638	637 647	626 645	644 644	613 627	632	+ 2·4 − 6·6	Broken	
D	115	653 623	653 633	647 639	653 642	642 637	617 628	637	+ 2·5 − 3·1	643	$+ 0{\cdot}9_4$
E	115	671 672	673 659	689 676	699 687	681 685	664 670	677	+ 3·3 − 2·6	680	$+ 0{\cdot}4_4$
G	115	633 634	642 638	663 646	655 645	649 654	631 647	645	+ 1·6 − 2·0	648	$+ 0{\cdot}4_7$

(*d*) Measurements can now be made by substituting test lamps in the integrator and balancing the galvanometer by adjusting the potentiometer, which will then indicate the lumen value of the lamp.

(*e*) By suitably closing the sliding shutter the photometer can conveniently be made to read double the actual scale values, thus extending the lumen range to 3 000 lumens.

(4) COMPARISON OF PHOTO-ELECTRIC AND VISUAL MEASUREMENTS.

From the experience gained with this apparatus it has been found useless to compare the relative accuracy of visual and photo-electric measurements by individual results obtained on normal commercial lamps. This is because of the continual small changes inside the lamps, which cause lumen fluctuations. For such comparisons a special set of light standards was made.

The vacuum lamps were measured by two observers on four separate occasions and the gas-filled lamps by six observers on two separate occasions so as to minimize the error introduced by the colour difference.

Each observer's reading on any one occasion is the mean of six settings.

(6) RESULTS OF VISUAL AND PHOTO-ELECTRIC MEASUREMENTS.

The results of the visual measurements on vacuum lamps are given in Table 1, together with values obtained on the photo-electric photometer. The means of the visual observations are given in col. 8. Col. 9 contains two sets of observations measured photo-electrically, using a large sub-standard voltmeter to set up the lamps.

Col. 11 contains results obtained by using a normal sub-standard precision voltmeter with which the apparatus is ordinarily equipped to set up the lamps, the observations being representative of the normal accuracy obtained.

Table 2 contains the individual observers' visual values for the gas-filled lamps together with the photo-electric measurements, the voltage being measured to the same degree of accuracy.

(7) Discussion of Results.

It will be seen from the tables that when a large sub-standard voltmeter was used to set up the lamps the accuracy of repetition was better than ± 0·5 per cent. The deviation from the mean visual value in several cases is greater than ± 0·5 per cent, but it is obvious from the individual visual values that the mean value of this deviation for individual lamps may possibly be as great as 1 per cent in a few cases, and it seems probable that the mean of the photo-electric values given in col. 10 of Table 1 are more nearly the correct values than the mean of the visual values. This seems highly probable when it is realized that the mean error of all results given in col. 10 of Table 1 is − 0·1 per cent from the mean visual values for all lamps.

In the case of the measurements given in col. 11 of Tables 1 and 2, where a normal sub-standard voltmeter was used for setting up the lamps, the photo-electric values are in agreement with the mean visual values within ± 1 per cent and the mean deviation from the visual values is + 0·37 per cent.

(8) General Survey of Experiences Gained During Six Months' Daily Use of the Photo-Electric Photometer for Commercial Measurements.

The existing apparatus, shown in Figs. 1 to 3, has given general satisfaction in regular service and the following points cannot be over-emphasized in connection with the design of such apparatus for commercial use.

In order to ensure trouble-free working the apparatus should be designed as a complete unit and attention to the following details is essential.

(*a*) The whole of the photo-electric cell circuit, amplifier, potentiometer, batteries and wiring, must be thoroughly screened from electrical disturbance.

(*b*) The highest insulation is desirable in the photo-electric cell and grid circuits. Stiff wire, mainly air-insulated and held at intervals in sulphur bushes, is very satisfactory.

(*c*) All batteries should be of secondary cell type, as sooner or later dry cells will give inconsistent results even when used as grid bias.

(*d*) All component parts should be rigidly fixed in relation to the surrounding screening, as movement of apparatus due to vibration may result in variable charges being impressed on the grid of the amplifying valves. In this connection it is found that the valves themselves are sensitive to heavy vibration of the apparatus even when mounted in holders on sorbo rubber, and it is desirable to "nest" them in cotton-wool in order to overcome this trouble. It might be wise, in a design required for use under factory conditions, to mount the whole of the cell and amplifier equipment on a mounting separate from the photometric integrator equipment in order to insulate the valves from shock.

(*e*) The potentiometer, whilst being electrostatically screened, should be easily accessible as it is submitted to very strenuous treatment. It should, therefore, be designed accordingly.

(*f*) It is essential that suitable valves should be used for the amplifier, otherwise very serious inconvenience may be suffered and spurious results obtained. The valves at present found most suitable for this work are specially selected D.E.5.B type with the filaments operated at 4 volts. In cases where the highest precision is required it is advisable to use the valves uncapped in order to secure the best insulation. For commercial work, valves carefully capped with caps slotted between the contact pins in order to reduce surface leakage have given satisfaction.

(*g*) Best-quality grid leaks and anode resistances should be used in order to ensure freedom from amplifier variations.

The results of this development work have suggested many possibilities in photometric technique. Whilst the eye must, of necessity, be the ultimate source of reference there seems every reason to hope that in the near future commercial and sub-standard photometry will nearly always be carried out photo-electrically. This should result in increased accuracy and speed, and at the same time it should decrease eye fatigue in the laborious task of visual photometry.

As an instance of the saving of time without loss of accuracy, the measurements given in Tables 1 and 2 occupied the equivalent of 5 observers for 4 days, apart from the time taken to calculate the results. This same series of measurements was carried out photo-electrically by one observer in about 4 hours and no calculations were involved. There is every reason to believe that if an apparatus were built for precision work, incorporating spherical integrators and further improved electrical arrangements for setting up the lamps, still higher accuracy could be obtained.

THE DEVELOPMENT OF A PRECISION AMMETER FOR VERY HIGH FREQUENCIES.[*]

By E. B. MOULLIN, M.A., Associate Member.

(*Paper first received* 6*th November*, 1929, *and in final form* 15*th January*, 1930.)

SUMMARY.

This paper describes the principles and development of an ammeter which has been made for measuring current of very high frequencies, such as 30 000 kilocycles per sec. The instrument is of the dynamometer type and has a geometrical form for which all the changes of current distribution can be calculated. The correcting factors approach a limiting value and do not increase continuously with frequency as they do in thermal instruments. A special feature of the design is that an instrument can be made to carry unshunted a current of any magnitude. This removes all uncertainty about shunting ratio and so the instrument should be more reliable than one in which the current is supposed to divide evenly among a number of resistance wires in parallel.

Methods are described for checking the calculated correction factors and there are also some calibrations at frequencies round about 1 000 kilocycles per sec. In addition, measurements are described of the high-frequency resistance and of the inductance and terminal capacity.

(1) INTRODUCTION.

The difficulty of measuring currents of very high frequency has again been made prominent by the development of short-wave telegraphy. The instruments in use at present are no doubt relatively correct at any one frequency, but possibly they may have an appreciable frequency error. Thermal instruments, with or without a current transformer, have been used almost exclusively for measuring radio-frequency currents, and, since the resistance of all conductors increases continuously with frequency, all such instruments must become progressively more sensitive as the frequency rises. The heated element is made from a wire the diameter and material of which are such as to make the probable increase of resistance small at the highest frequency required, but when frequencies of the order of 10^8 cycles per sec. are contemplated the wire must be so fine that it can scarcely carry a current of 1 ampere. Many wires must be placed in parallel, and then it is difficult to ensure that the fraction carried by each one is independent of frequency. To this end, usually the wires are arranged as generators of a surface of revolution, for example a cylinder, hyperboloid or double cone. Given perfection of manufacture this device must achieve the required result in respect of the effect of one wire on the others, but it affords no protection from a magnetic field penetrating the whole cage. If the cage is placed concentrically within a long and thick screen tube of copper, then the current will divide evenly between all the wires at all frequencies and in all circumstances. The instrument will still have a frequency error due to the increase of resistance of each wire, but this should be calculable with a high degree of accuracy. It will have a further frequency error due to capacity effects, and this may not be readily calculable.

The author has been concerned in making an ammeter which can carry a current of any magnitude unshunted and which has a geometrical form for which the various frequency corrections can be calculated exactly. Uncertainty in respect of unconstant shunting ratio is then removed entirely and the frequency corrections are known and are, in fact, very small. This ammeter has been described already [*] and the analysis of the various correction factors developed in great detail. Since then considerable experience has been gained in the construction and use of the instrument, and this paper is concerned chiefly with such recent developments. It will be necessary first to describe briefly the principle of the instrument and to enumerate the cause and magnitude of the three separate frequency corrections, after which the constructional details and methods of testing will be given.

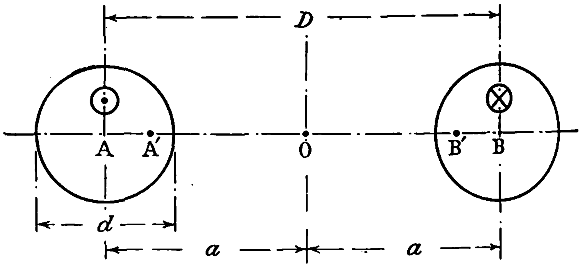

FIG. 1.

(2) ELEMENTARY SYSTEM OF THE AMMETER.

Consider two long, straight, solid circular cylinders of diameter d, placed parallel to one another at a distance D apart, and let them carry the same current in opposite directions; the system is shown diagrammatically in section in Fig. 1. The two cylinders will repel one another with a force $F = 2i^2/D$ per unit length if the current i is distributed uniformly over the cross-section. If the current is alternating and of R.M.S. value I, the mean value of the repulsive force is $F = 2I^2/D$. If the force can be measured in any convenient manner the system becomes an ammeter which can be calibrated with steady current and used to measure alternating current. But an alternating current is not distributed uniformly over the cross-section, and the force is no longer given accurately by the equation $F = 2I^2/D$ and the instrument requires a frequency correction. In the limiting condition of infinite frequency or perfect conductivity there is no magnetic field within the cylinders and then each circumference must coincide with a line of force. It is well known that each circumference would coincide with a line of force of two line currents situated at the points A′ and B′ which are mutually inverse points for the circles centred at A and B. So ultimately we have

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (excepting those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[*] *Proceedings of the Royal Society*, A, 1928, vol. 121, p. 41.

$$F = \frac{2I^2}{\mathrm{A'B'}} = \frac{2I^2}{\sqrt{(D^2 - d^2)}} \quad . \quad . \quad . \quad (1)$$

We see that the ultimate increase of force is small so long as D is considerably greater than d.

A frequency correction which comes to a limiting value is in striking contrast with the frequency correction for thermal ammeters, which does not come to a limiting value but increases continuously. Furthermore, the limiting correction is sensibly attained at finite frequencies. Very complicated analysis is required to express the force as a function of frequency, but the result is expressed by the following series:—

TABLE 1.

D/d	F_0	F	F/F_0
1½	1·296	1·340	1·032
2	1·13	1·15	1·02
3	1·048	1·06	1·01
4	1·026	1·031	1·005

$$F = \frac{2I^2}{D}\left\{1 + \frac{1}{2}\frac{d^2}{D^2} + \frac{3}{8}\frac{d^4}{D^4} - \frac{1}{\sqrt{2z}}\cdot\frac{d^2}{D^2}\left(1 + \frac{d^2}{D^2}\right) + \ldots\right\} \text{with } z > 3\cdot5 \ldots \quad (2)$$

where we have the well-known parameter $z^2 = \pi\omega d^2/\rho$, in which $\omega = 2\pi f$ and ρ is the resistivity of the material. Substitution in (2) will show that the limiting value has sensibly been attained when z is, say, greater than 10, and this is illustrated by Table 1, in which F_0 is the force for zero frequency.

So if $D/d = 3$ the limiting increase is less than 6 per cent and this has been attained within about 1 per cent of itself when $z = 10$. This will occur at frequencies less than 300 kilocycles per sec. for all copper wires larger than No. 16 S.W.G.

But the two cylinders, as depicted in Fig. 1, will inevitably be situated in a magnetic field arising from the remainder of the circuit, and this field will produce an additional force. Therefore the wires must be shielded from external fields by placing them within a thick copper tube in the manner shown diagrammatically by Fig. 2. This tube will prevent the penetration of any external field, but the currents situated at A and B will induce in the screen tube eddy currents whose field will modify the force on the wires. The screen tube is comparable with the short-circuited secondary of a transformer, and so the currents in it are substantially in antiphase with the currents at A and B. The field between A and B due to the eddy currents in the screen is therefore opposed to the field created by the currents at A and B and consequently lessens the force on each. If the small non-uniformity of current density round the circumferences of the cylinders at A and B is now ignored, it follows readily that in the limit the field of the eddy currents within the screen tube is the same as would be the field of image currents placed at A′ and B′, the inverse points of A and B with respect to the circle of radius r centred at O. It follows from this that

$$F = \frac{2I^2}{D}\left(1 - \frac{4\mathrm{OA}\,.\,\mathrm{OA'}}{\mathrm{A'B}\,.\,\mathrm{B'B}}\right)$$
$$= \frac{2I^2}{D}\left(1 - \frac{4r^2a^2}{r^4 - a^4}\right) \quad . \quad . \quad . \quad . \quad (3)$$

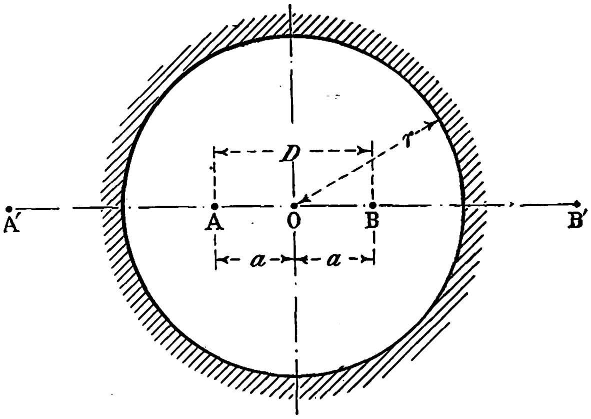

FIG. 2.

Since the eddy currents in the screen reduce the force between the cylinders, they tend to counteract the increase of force due to non-uniform current distribution round the cylinders. We may superpose the two effects without sensible error (see Appendix), and since $r >> a$ and $D > d$ the two effects will neutralize each other approximately when a, r, etc., are so chosen that $D^2 = rd/\sqrt{2}$. If $r/a = 8$ (approx.), then in the limit either effect by itself would change the force due to a specified current by about 6 per cent, or the current required for a given force would differ by 3 per cent from that required at zero frequency, since the force varies as the current squared. The difference between two approximately equal effects, each comparatively small in value, must be a quantity of negligible magnitude. The effect of the screen approaches close to its limiting value at a frequency of a few hundred cycles per second, but this may be considered more appropriately later.

We now have to consider the effect of longitudinal distribution, which is important only when the length of the system is comparable with the wavelength. Two parallel cylinders which are not in a screen tube may be represented by the circuit system shown diagrammatically by Fig. 3, which represents a uniform short-circuited line of length l and having a capacity and inductance per unit length of C and L respectively. If the current entering at A is $-I\cos\omega t$, and that leaving at B is $I\cos\omega t$, it is well known that the current i at a distance x along the line is given by the equation

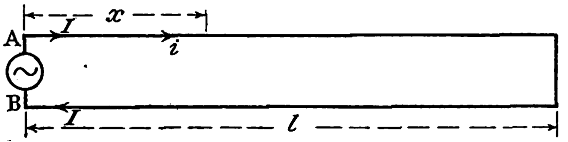

FIG. 3.

$$i=-I\frac{\cos\omega a(l-x)}{\cos\omega al}\cos\omega t$$

where $a=\sqrt{(LC)}$. The voltage between the ends of the line is expressed by the equation

$$v=\frac{I}{2}\sqrt{\frac{L}{C}}\frac{\sin\omega a(l-x)}{\cos\omega al}\sin\omega t$$

(The resistance of the line is ignored, but this makes only a second-order difference to the current distribution.)

If the surrounding medium has unit permeability and dielectric constant ϵ, and if c is the ratio of the electromagnetic to the electrostatic absolute unit of current or charge, then for a parallel-wire system we have $LC=\epsilon/c^2$. The force per unit length between the cylinders is a repulsion of value $2i^2/\sqrt{(D^2-d^2)}$ due to the magnetic field and an attraction of value $2q^2/\epsilon\sqrt{(D^2-d^2)}$ due to the electrostatic field. Hence for the electrostatic attraction F_e we have

$$F_e=2\cdot\frac{4C^2v^2C^2}{\epsilon\sqrt{(D^2-d^2)}}=\frac{2I^2}{\sqrt{(D^2-d^2)}}\frac{\sin^2\omega a(l-x)}{\cos\omega al}\sin^2\omega t$$

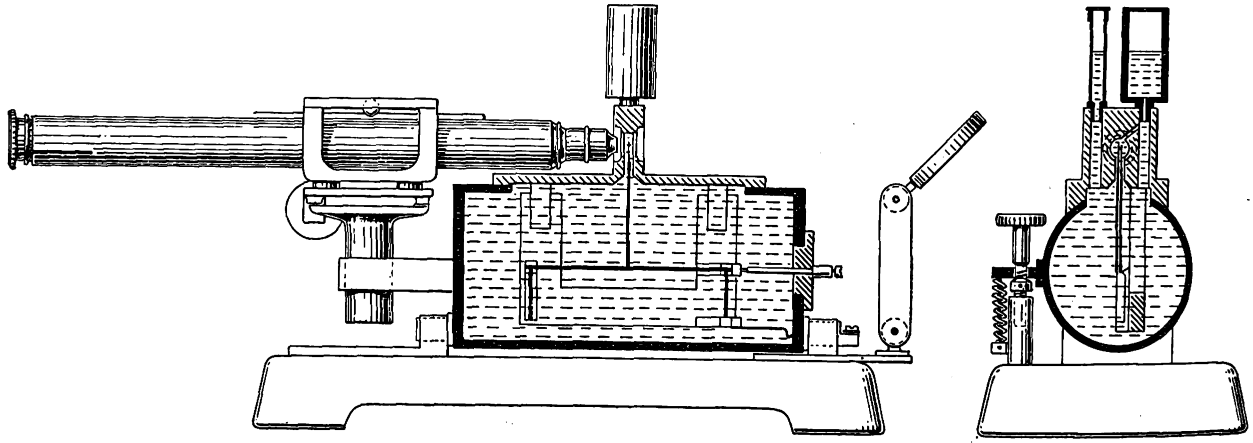

FIG. 4.

and so for the mean total force we have

$$F=\frac{I^2}{\sqrt{(D^2-d^2)}}\int_0^l\frac{\cos^2\omega a(l-x)-\sin^2\omega a(l-x)}{\cos^2\omega al}dx$$

$$=\frac{I^2}{\sqrt{(D^2-d^2)}}l\frac{\tan\omega al}{\omega al}\quad .\quad .\quad .\quad .\quad .\quad (4)$$

$$=\frac{I^2l}{\sqrt{(D^2-d^2)}}(1+\tfrac{1}{3}\omega^2a^2l^2+\tfrac{2}{15}\omega^4a^4l^4)$$

$$\text{approximately, if } \omega al<<1\quad .\quad (4a)$$

Equation (4a) may be interpreted more readily in terms of wavelength than of frequency. When $\pi al=\frac{1}{2}\pi$ the length of the system equals a quarter wavelength of current; since the system is immersed in a dielectric of constant ϵ the length of the current waves on it are thereby made $1/\sqrt{\epsilon}$ of the length they would have in a dielectric of constant unity. Let the wavelength in free space, corresponding to a frequency $f=\omega/(2\pi)$, be λ. Then we may rewrite (4a) as follows:—

$$F=\frac{I^2l}{\sqrt{(D^2-d^2)}}\left(1+\frac{4}{3}\cdot\frac{\pi^2\epsilon l^2}{\lambda^2}+\frac{32}{15}\cdot\frac{\pi^4\epsilon^2l^4}{\lambda^4}\right)\quad .\ (5)$$

So if $\epsilon=2$ and $l/\lambda=1/25$ the force is 4·5 per cent greater for a given current than it is at zero frequency. We are contemplating a system in which l is about 20 cm, and then a given current will produce 2·2 per cent more deflection at a wavelength of 5 m than it did at zero frequency. The correction term is therefore quite definite and calculable but it is so small as to be unimportant for the wavelengths in use at present.

This analysis is incorrect for a system enclosed in a screen tube. The correct analysis has been developed,* but it is very complicated and it is unnecessary to reproduce it in this paper. When the system is in a screen tube the point B in Fig. 3 will be connected to the screen, and then the complete analysis shows that the correcting factor within the screen differs insensibly from that calculated from (5), provided l is replaced by $2l$. So if the instrument has been arranged with $D^2=rd/\sqrt{2}$, the only resultant correcting factor is that due to longitudinal distribution of current: for a system 20 cm long this will not have reached 2·5 per cent even when the wavelength is reduced to 10 m.

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* *Proceedings of the Royal Society*, loc. cit.

(3) CONSTRUCTIONAL DETAILS OF THE AMMETER.

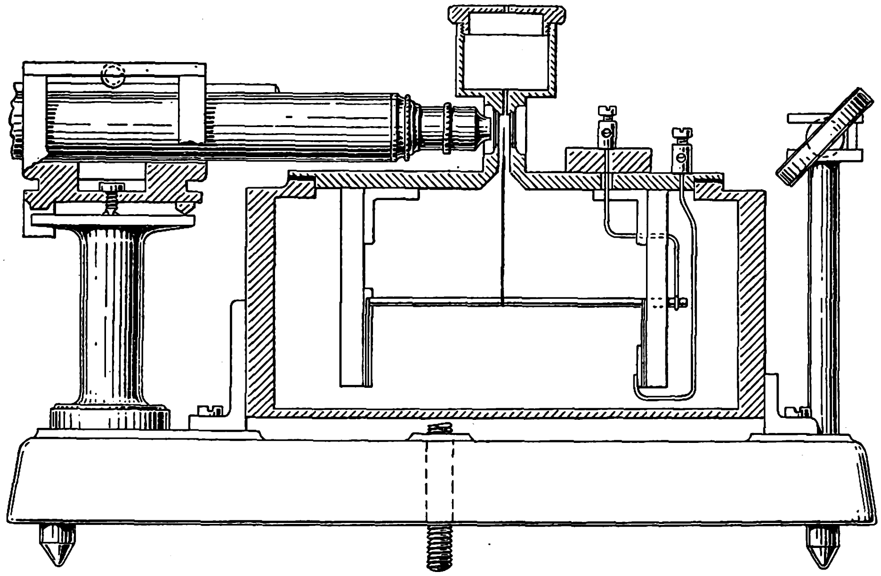

FIG. 5A.

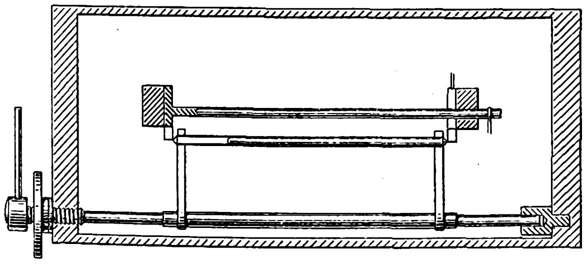

FIG. 5B.

So far only two of these ammeters have been made, the first for currents up to about 2 amperes and the second for currents up to about 25 amperes. A longitudinal and transverse section of the first instrument is shown in Fig. 4 and two longitudinal sections of the second instrument in Figs. 5A and 5B. These drawings show clearly the arrangement of the cylindrical copper screen tube, which in both instruments is 3 mm thick and 77 mm internal diameter and 190 mm long. One cylinder is fixed rigidly to an ebonite frame attached to the under side of the thick copper cover-plate of the screen tube. The other cylinder stands on spring legs which conduct the current to it and also provide most of the elastic constraint to resist the repulsive force between the two cylinders. The repulsive force of the current moves the two cylinders further apart and it is this spread which provides the indication of the ammeter. The repulsive force is very small, about $2I^2/10^4$ grammes weight in the instrument of Fig. 5, and this necessitates the spring legs being weak and the total spread very small. The spread is measured by observing with a microscope the movement of a thin quartz pointer attached to the middle of the moving cylinder. This pointer passes through a hole in the cover plate of the screen and is viewed through a glass window in a small chamber. The arrangement of pointer, window and microscope may be seen in Figs. 4 and 5 and requires no further explanation. The pointer tip magnifies the movement of the cylinder about five times; the microscope has a 1-inch objective with a 10-inch tube length and an eyepiece scale 1 cm long divided into 100 parts. Consequently the maximum spread of the cylinders is about 0·2 mm, and this is 2 per cent of their central distance for the instrument of Fig. 5. If the spread is x, then the law relating x to the current I is

$$I = A\sqrt{x}(1 - \tfrac{1}{2}x/D),$$

and this differs inappreciably from a simple square law since the greatest value of x/D is only 2/100. Also it is clear from equations (1) and (3) that if D increases by 2 per cent there is a negligible change in the correction factor. In the instrument of Fig. 5 the correction factor would change from zero at no deflection factor to + 0·25 per cent at full scale. The spring legs are made from standard cadmium-copper alloy, and this is a great improvement on the phosphor-bronze used originally in the small instrument. The cadmium-copper strip is 3 mm wide and 0·08 mm thick in the 25-ampere instrument and 0·5 × 0·035 mm in the 2-ampere instrument. The current density in the strips is very high, about 11×10^3 amperes per cm^2, and for this reason the whole screen tube is filled with a high-grade oil. Besides helping to cool the strips, the oil damps the movement and makes the instrument dead-beat and at the same time makes a cushion for the movement when the instrument is carried about. The 2-ampere instrument would be very fragile without the oil; but with the oil it is perfectly portable and has withstood several long journeys standing unpacked on the floor of a light motor-car. The 25-ampere instrument is thoroughly robust and would not need oil to make it portable; the comparatively heavy cylinder renders a clamp desirable and its arrangement is shown in Fig. 5B. Two light phosphor-bronze fingers are fixed to the clamp rod, and a quarter-turn of this lifts the fingers so that the cylinder is cradled in forks at their ends. It will be noticed that the end bearing of the clamp rod is of ebonite, and this prevents a flow of induced current along the rod and back by the screen.

The terminal arrangement differs from that illustrated in Fig. 4 and will be discussed later.

The oil immersion is useful also for reducing the load carried by the spring legs, and in the 2-ampere instrument these are in tension. At the same time it reduces sensitivity as it reduces the gravity control, which control is negative when the net weight is positive.

In the small-current instrument the moving cylinder is an aluminium tube 10 cm long and having an external diameter of 1·1 mm with walls 0·025 mm thick. In the large-current instrument it is a tube of copper-alloy (verging on brass) 10 cm long, 3·19 mm external diameter and having walls 0·4 mm thick and weighing about 2·5 grammes in oil.

The force of gravity is used to place the cylinders at the exact central distance obtaining at the time of testing and calibration. A fixed fiducial pointer is mounted inside the pointer chamber, and the microscope, which has a short cross-traverse, is placed so as to bring the fixed pointer exactly at one end of the eyepiece scale. The levelling screw, shown in Figs. 4 and 5, is then turned until the gravity control brings the moving pointer to the other end of the scale; this setting is taken as standard. Having set the pointers, the microscope is further cross-traversed until the fixed pointer has moved out of the field of view and the moving pointer stands at the zero of the eyepiece scale. The width of the pointer chamber is such that the central distance of the cylinders cannot change by more than 0·6 mm in 10 mm, and experiment with the larger instrument shows that a given current can produce an extreme range of deflection of ± 5 per cent above and below the mean and ± 1 per cent in the smaller instrument. The setting-up process therefore does not require to be done with very great care.

It was found that a deflection due to heating was present in the 25-ampere instrument (but not in the 2-ampere instrument). This was traced to imperfect parallelism of the spring legs. The mounting has been fitted with an adjustment which twists slightly the bottom of one spring. The slow drift deflection due to heat effect can be made positive or negative by this adjustment, which is so set as to make it zero before the instrument is sealed up. Experience shows that this adjustment remains permanent. In addition to this there may possibly be a slow drift of about 2 mm due to convection currents in the oil. Apparently this can often be neutralized by slight adjustment of the levelling screw. However, searching tests show that if the deflection is observed and the zero is read at the instant of switching off, a given current produces the same deflection consistently to within less than ± 0·3 mm in 100 mm. This means that full-scale deflection represents a given current to within ± 0·15 per cent, and so the instrument justifies the correction factors which are to be applied to it.

The pointer chamber is fitted to take a condensing lens so that the image of the pointer may readily be thrown on a screen. The instrument is perhaps more convenient to use in this manner and there is a large gain in the obtainable accuracy of reading.

The pointer chamber is surmounted by a cylindrical reservoir to form a breathing chamber for the oil.

(4) CALIBRATING AND TESTING THE AMMETER.

It is not easy to set up the system on its spring legs so that the cylinders are at precisely the desired distance apart, and it is desirable to check this distance after the ammeter has been sealed up in its case. This may be done by placing parallel currents at external points such as A′ and B′ in Fig. 2. Thus, referring to Fig. 2, let there be a winding of N turns with its sides at A′ and B′ and connected in series with the ammeter in the sense to reduce the deflection. By a suitable choice of N and the distances AA′, BB′ it is easy to make the deflection almost zero for any current. A permanent magnet should be placed near the ammeter to neutralize the vertical component of the earth's magnetic field. The method of adjustment is to approach the magnet until there is no change of deflection on reversing the direction of a steady current of given value. (Note that during this adjustment the external winding is cut out.) If this adjustment is imperfect, so that a small remaining field V produces a difference of deflection which is a fraction y of the mean deflection due to a current I, then we have $VD/(2I) = y$. Now let the external winding be put in series with the ammeter, having one coil side at a distance b from A, in Fig. 2, and the other at a distance b'. Also let the deflection due to I be now a fraction x of its value without the external winding, then it follows readily that

$$D = \frac{(1 + x)\,(1 + y)bb'}{N(b + b')}$$

$$= \frac{bb'(1 + x + y)}{N(b + b')}$$

since both x and y are very small. So by measuring b and b', D may be deduced. Naturally the system will be arranged with b nearly equal to b', and then it is worthy of notice that a given fractional error in measuring b makes a very much smaller fractional error in the value deduced for D. So D may be deduced to about the same accuracy that $(b + b')$ can be measured. As an example of such a test in the 25-ampere instrument, $x = 2\cdot9$ per cent, $y = 0\cdot8$ per cent, $bb' = 18\cdot4$ cm, $b = 6\cdot8$ cm and $N = 4$, whence we find $D = 1\cdot11$ cm. The internal diameter of the screen tube was 77 mm, and so it follows from (3) that the limiting reduction of deflection due to the presence of the screen should be $4(11\cdot1/77)^2 \times 1/100$ per cent = 8 per cent. The cylinders are a little too far apart for perfect compensation, since the relation $D^2 = \frac{1}{2}Rd$ would require that $D = 0\cdot935$ cm. So the two limiting correcting factors do not balance by 4·15 per cent and in the limit the ammeter would read 2·07 per cent lower than the steady-current calibration.

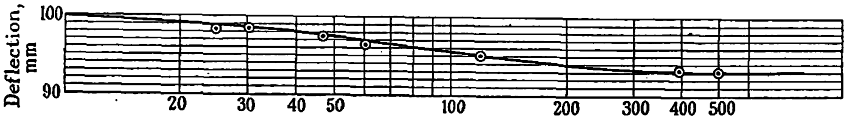

FIG. 6.

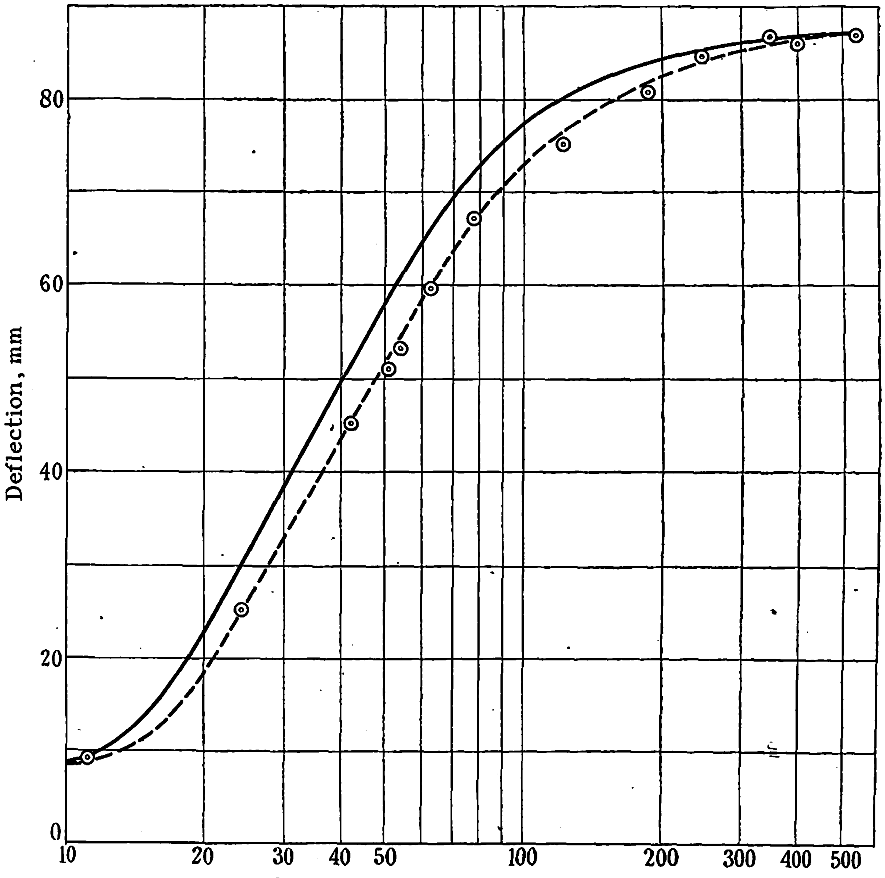

FIG. 7.

Let us now consider the rate at which the effect of the screen approaches the limiting value. If the non-uniformity of current density across the thickness t of the screen tube is ignored, it may be shown * that equation (3) should be written

$$F = \frac{2I^2}{D}\left\{1 - 4\sum_1^\infty\left(\frac{a^2}{r^2}\right)\frac{qm^2}{m^2 + q^2}\right\} \quad . \quad . \quad (6)$$

$$\doteqdot \frac{2I^2}{D}\left\{1 - 4\frac{a^2}{r^2}\cdot\frac{m^2}{m^2+1}\right\} \text{ since } \frac{a^2}{r^2} << 1$$

where $m = 2\pi t\omega r/\rho$, in which $\omega = 2\pi \times$ frequency, ρ is the resistivity of the tube whose mean radius is r, and q is every odd integer. Taking $t = 0{\cdot}3$ cm, $r = 4$ cm and $\rho = 1{\cdot}68$ microhms per cm^3, we find $m = 0{\cdot}028\,f$. On substitution it will be found that $m^2 = 197$ when the frequency is 500 cycles per sec., so that at this frequency the screen correction will have reached its limiting value to within 0·5 per cent. Over this range it is a simple matter to plot experimentally a curve connecting the deflection due to a given current and the frequency; in this way the accuracy of the predicted correcting factor can be tested. This has been done for the 25-ampere instrument and the result is illustrated in Fig. 6, and from this the limiting reduction appears to be 6·6 per cent, which is 1·7 per cent less than was anticipated. These tests took a considerable time to make and are obviously very difficult since the differences are so small. It was thought that a more reliable method of making the test would be to switch over instantly from steady

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* *Proceedings of the Royal Society*, loc. cit., p. 53; also F. W. CARTER: *Proceedings of the Cambridge Philosophical Society*, 1927, vol. 23, p. 902.

current to 500 cycles per sec. Three readings were taken with the steady current in each direction and with current at 500 cycles per sec., and the greatest departure from the mean was 0·5 mm. The deflections are as follows: steady current 97·5 mm, steady current reverse 96·8 mm, mean 97·15 mm; at 500 cycles 89·5 mm. According to this the reduction of sensitivity is 7·9 per cent, and this agrees with the predicted value of 8·3 per cent to well within the limits of experimental error.

The calculated correcting factor might be inexact because the analysis assumes that the cylinders and the screen tube are infinitely long, whereas the length of the cylinders is in reality only $2\frac{1}{2}$ times the radius of the screen. A large portion of the screen tube, at its ends, is not acted on by magnetic field and this might well be expected to reduce the eddy currents flowing. An indirect method of checking the correction factor is to see whether the deflection with the external coil in use varies in the correct manner with frequency. With steady current the external field neutralizes the deflection, but as the frequency increases less and less of this field penetrates the screen and the deflection will tend to the value it has with no external coil. This experiment will surely be an exacting test of the applicability of analysis appropriate to very long cylinders. If, in the previous notation, we take $b = b'$ it may be shown that

$$F\Big/\frac{2I^2}{D} = \frac{m^2}{m^2+1}\left[\frac{x}{m^2} + \left(1 - \frac{4a^2}{r^2}\right)\right]$$

A certain current was found to give a deflection of 87·2 mm at 560 cycles per sec. and 2·5 mm at zero frequency. The curve of Fig. 7 has been drawn from values calculated from the above equation, in which $[1 - (4a^2/r^2)]$ has been given the value 87·2 and x the value 0·03; the observed deflections at various frequencies are shown by observation points near the dotted curve. Experiment shows that the external field which penetrates the screen is a little more than the calculated value; this is doubtless due to the resistance of the copper end-pieces. However, the observed and calculated deflections are in substantial agreement, and the fractional difference between the two curves must represent very closely the fractional error in the calculated correction factor at a given frequency. Fig. 7 is surely good evidence to prove that the calculated limiting values of the correction factors are substantially accurate, and that if the two factors are arranged to neutralize approximately then the error in the calculated value of their small difference must be quite unimportant. If a curve corresponding to Fig. 7 could be obtained for the cylinders, presumably it would fit the calculated values still more closely, for there the end effect is relatively much less important. That one of the correcting factors can readily be measured experimentally, as shown by Fig. 6, is perhaps a feature of the instrument.

The central distance between the cylinders of the smaller instrument was deduced in the same manner. With a compensating winding of 6 turns the net deflection was negative and with 5 turns it was positive, and from the observed values of these deflections the central distance was calculated to be 8·7 mm and 8·65 mm respectively. For this distance the screen should reduce the deflection by 4·7 per cent. The steady-current deflection was deduced from the mean of three readings between three-quarters and full scale, and likewise the deflection for currents at 500 cycles per sec. The reduction of deflection at 500 cycles per sec. was thus found to be 4·9 per cent, and this again verifies the method of calculating the correction factor. The correction factor for cylinders 1·1 mm diam. and 8·7 mm apart has a limiting value of 0·7 per cent, and will have approached closely to this value at a frequency of 1 megacycle per sec.*

(5) RESISTANCE, INDUCTANCE AND CAPACITANCE OF THE AMMETER.

(a) *Estimated values.*

The steady-current resistance of the larger instrument is 14·0 milliohms, which is composed as follows:—

	mΩ
Lead from earth terminal to moving cylinder ..	1·0
Lead from fixed cylinder to terminal	0·6
Moving cylinder	1·6
Fixed cylinder	0·2
The two spring-legs	10
	13·4

The fixed cylinder is solid copper and the moving cylinder is a tube of resistivity 6·2 microhms per cm³. The total length of circuit from terminal to terminal is 43 cm. The power input at full scale is about 7·5 watts at low frequencies. About 70 per cent of the total resistance is in the spring legs, which are too thin for their resistance to increase appreciably at any frequency likely to be used. Thus, supposing the current to penetrate into them as though they were plates of infinite width, then the current density at mid-thickness is still 10 per cent of its surface value at a frequency of 3×10^7 cycles per sec. ($\lambda = 10$ m) and 47 per cent at $\lambda = 50$ m. The increase of total resistance should, therefore, be mainly due to the cylinders and leads.

It may be shown that the resistance per unit length of each cylinder enclosed in a screen tube, as depicted in Fig. 2, may be calculated from the equation

$$R_n/R_0 = \frac{\sqrt{2z}}{4}\left\{\frac{D}{\sqrt{(D^2-d^2)}} + \frac{D^2rd}{2(r^4-a^4)}\right\}$$

$$\doteqdot \frac{\sqrt{2z}}{4}\left(1 + \frac{1}{2}\frac{d^2}{D^2} + \frac{1}{2}\frac{d}{r}\cdot\frac{D^2}{r^2}\right)$$

This equation shows that the presence of the screen and the proximity of one cylinder to the other cause a negligible increase of resistance; accordingly these effects will be ignored. Assuming that the resistance of the strips does not increase appreciably, then the resistance of the ammeter should be about 42 milliohms at $\lambda = 50$ m and 64 milliohms at $\lambda = 15$ m. At this wavelength the case will have to radiate about 0·4 watt per square inch of cooling surface.

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* *Proceedings of the Royal Society*, loc. cit., Table 3.

The steady-current resistance of the smaller instrument is 83 mΩ and is composed as follows:—

	mΩ
Moving cylinder	33
Fixed cylinder	1·5
The two spring-legs	47

The fixed cylinder is solid No. 18 S.W.G. copper, and the moving cylinder is an aluminium tube 1·1 mm diameter and 0·025 mm thick. The total length of the circuit is about 43 cm and the power input at full scale is about 0·4 watt at low frequencies.

If the effect of the screen is ignored, the limiting value of the inductance of the cylinders is

$$L = 4 \log_e \frac{D + \sqrt{(D^2 - d^2)}}{d} \text{ per unit length.}$$

If the effect of non-uniform current distribution round the circumferences of the cylinders is ignored, then the inductance in the screen is

$$L \doteqdot 4 \log_e \frac{2D}{d}\left(1 - \frac{a^2}{r^2}\right)$$

Combining these two we have as a first approximation

$$L = 4 \log_e \frac{2D}{d}\left(1 - \frac{1}{4}\frac{d^2}{D^2} - \frac{a^2}{r^2}\right)$$

and the correction term, as part of a logarithm, is evidently negligible. Taking $D = 1$ and $d = 0\cdot3$ we have $L = 7\cdot28 \times 10^{-3}$ μH per cm, or, taking $D = 0\cdot5$, then $L = 5 \times 10^{-3}$ μH per cm, so L is insensitive to the ratio D/d. At low frequencies, when the current is distributed uniformly, we should have respectively $8\cdot28 \times 10^{-3}$ and $6\cdot28 \times 10^{-3}$ μH per cm. Thus for any ammeter of this type the inductance will be roughly 7×10^{-3} μH per cm of cylinder. The change from cylinder to spring leg or terminal lead will evidently make very little difference and we shall estimate the inductance at 7×10^{-3} μH per cm of the system. Accordingly either instrument should have an inductance somewhere between 0·15 and 0·17 μH. Similarly the capacity of the system, if on open circuit at the far end of the loop, would be about 3·2 μμF, and twice this amount when immersed in oil.

Reduction from the exact equation * shows that the apparent input impedance is

$$Z \doteqdot \omega Ll\left\{1 + \frac{8\pi^2 l^2}{3\lambda^2} \cdot \frac{2\alpha - 1}{\alpha - 1}\right\}$$

where l is the length of the loop, λ is $1/\sqrt{\epsilon}$ times the wavelength in the ether and α is a constant such that $\alpha = (\log_e 2r/d)/(\log_e r/D)$, numerical substitution will show that α has a value not far removed from 2. Alternatively this equation may be interpreted as showing the apparent input impedance to be due to the inductance shunted by a capacitance of value $\frac{1}{3}Cl(2\alpha - 1)/(2\alpha + 1)$, where C is the capacity per unit length in oil. Accordingly we must consider the ammeter to be shunted by a capacity of about 2·5 μμF, and in parallel with this capacity is the capacity due to the terminals external to the case.

(b) *Measured values.*

The resistance of both ammeters has been measured at various wavelengths between 50 and 150 m. The process was to connect a coil, whose apparent inductance was either 1 μH or 2 μH, in parallel with a variable condenser and to deduce the effective resistance of this system by plotting a resonance curve. The ammeter was then added to the circuit and the effective resistance again determined, the difference being ascribed to the ammeter. The earth terminal of the ammeter was in both measurements connected to the earth terminal of the condenser, and the ammeter was included by moving one end of the inductance from this terminal to the other terminal of the ammeter. The inherent resistance of the circuit was about 0·2 ohm over the range of wavelength used. Though the operation of including the ammeter makes a negligible disturbance to the coil, yet it is not necessarily correct to ascribe the difference of resistance to the ammeter because the capacity has to be reduced to compensate for the inductance of the ammeter. When the ammeter is not included, then R_1, the total apparent resistance, is composed of R_c, the effective resistance of the condenser, and R_L, the effective resistance of the coil. After including the ammeter we have

$$R_2 = R_c' + R_L' + R_A$$

It is fair to assume $R_L' = R_L$, but it is probable that R_c' is greater than R_c because the capacity has been decreased. So R_A is probably less than $R_2 - R_1$. Some values determined with the 2-μH coil are shown collected in Table 1.

TABLE 1.

λ	165 m	115 m	80 m	50 m
	ohm	ohm	ohm	ohm
R_1	0·153	0·18	0·285	0·344
R_2	0·213	0·266	0·373	0·444
$R_2 - R_1$	0·06	0·086	0·088	0·10

Now though these differences increase roughly as $\sqrt{f}$, yet they are much larger than the estimated resistances of the ammeter. For example, at $\lambda = 50$ m the apparent resistance is 100 milliohms instead of about 42 milliohms.

Measurements with the 1-μH coil are given in Table 2.

TABLE 2.

λ	80 m	50 m
	ohm	ohm
R_1	0·194	0·258
R_2	0·31	0·342
$R_2 - R_1$	0·116	0·084

The values by difference are in rough agreement with those found with the 2-μH coil, but consistency of repetition in the measurements showed that the agreement ought to be closer if the difference does represent the resistance of the ammeter.

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* *Proceedings of the Royal Society*, loc. cit., equation (15).

From a different set of experiments, to be described at some future time, there was very strong reason to suppose that the condenser had an effective resistance of 0·16 ohm and 0·12 ohm at wavelengths of 50 m and 80 m respectively, at the capacity in use, with the 1-μH coil, before adding the ammeter. After adding the ammeter the capacity had to be reduced to 82 per cent of its former value; if the condenser had a constant power factor its effective resistance would then be 0·19 ohm and 0·145 ohm respectively. On this assumption the ammeter resistance would be respectively 0·06 ohm and 0·09 ohm at 50-m and 80-m wavelengths. It is clear, therefore, that the condenser can make a large effect on the value deduced for the resistance. But probably we can say that the high-frequency resistance is certainly not more than twice the estimated value. The resistance of the small ammeter was measured at 50-m and at 80-m wavelengths, using the 2-μH coil, and found to be 0·187 ohm and 0·193 ohm respectively, showing an apparent increase of about 2·3 times the steady-current value.

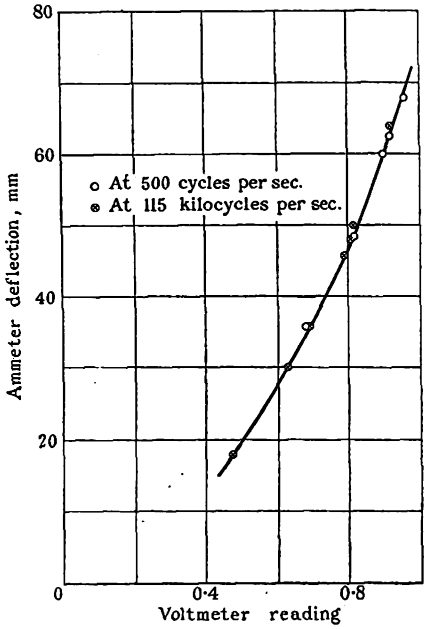

FIG. 8.

The inductance of both instruments has been measured by difference, using the same two coils. With a given coil the inductance values by difference are consistent over a wide range of wavelength, but depend slightly on the coil used. The large ammeter has an inductance of 0·18 μH when measured by difference with the 1-μH coil, and 0·22 μH when measured with the 2-μH coil; these values are about 20 per cent greater than the estimated value. The inductance of the small instrument appeared to be 0·2 μH.

The capacity of the system has not been measured, because to do so would entail opening the system at the far end. The terminal capacity of both forms of terminal system has been measured. When measuring the capacity of the axial terminal, as in Fig. 4, the movement had been removed, but 4 cm of lead protruded into the case from the terminal. The capacity was measured by noting the necessary decrease of a variable condenser required to compensate for joining a neighbouring wire to the axial terminal, the capacity formed between the terminal and its lead and the case then being in parallel with the variable condenser. With the case full of oil, this capacity was found to be 3·6 $\mu\mu$F over a range of wavelengths, and 2·9 $\mu\mu$F with the case empty of oil. The capacity of the lead, considered as a piece of concentric cylinder, is 0·6 $\mu\mu$F in air and 1·2 $\mu\mu$F in oil. Subtracting these values we find the true terminal capacity to be 2·4 or 2·3 $\mu\mu$F.

The capacity of the terminal system shown in Fig. 5 was measured when the terminal lead was just freed from the fixed cylinder. The capacity in oil was found to be 4·1 $\mu\mu$F and this includes the capacity of 6 cm of terminal lead whose capacity belongs to the system. Again estimating this capacity as for a concentric cylinder, we must subtract 1·8 $\mu\mu$F and again find a residue of 2·3 $\mu\mu$F due to the terminal proper. It therefore seems safe to assume that the true terminal capacity, shunting the system, is less than 3 $\mu\mu$F.

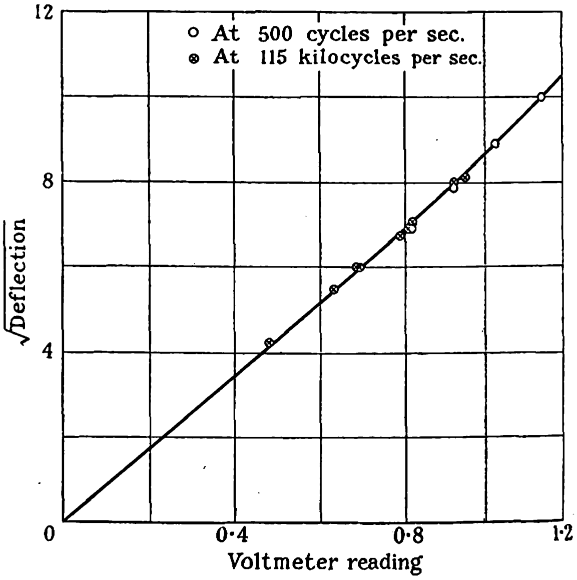

FIG. 9.

(6) TESTS AT HIGH FREQUENCY AND TEMPERATURE-RISE.

The smaller instrument has been checked very carefully at various frequencies up to 3×10^6 cycles per sec. Three 1-ampere hot-wire instruments (with 8-in. dials) were joined in parallel and then connected in series with the ammeter being tested. The relation between deflection and the sum of the three ammeter readings at 500 cycles per sec. was obtained with great care, and this has been compared with the relation obtained at radio frequencies. Also the voltage-drop across 0·39 ohm of No. 26 S.W.G. Eureka wire was measured by means of a thermionic voltmeter. The silk-covered Eureka wire was twisted on itself, making a very narrow loop 7 cm long, and the calculated inductance of this loop to steady currents is 0·03 μH. At 115 kilocycles per sec. the resistance will have increased by less than 1 part in 1 million and the reactance will increase the voltage-drop by 0·17 per cent. Tests were made with the voltmeter at 115 ($\lambda = 2\,600$ m), and with the hot-wire ammeters at 1 850 ($\lambda = 160$ m), 2 300 ($\lambda = 130$ m) and 2 830 ($\lambda = 106$ m) kilocycles per sec. Fig. 8 shows the comparison between voltmeter reading and deflection: the points marked with a circle were obtained at 500 cycles per sec. and the points marked with a cross in a circle were obtained at 115 kilocycles per sec. Fig. 9 shows the voltmeter reading plotted against the square root of the deflection, and the average agreement between the points obtained at 500 cycles per sec. and those at 115 kilocycles per sec. is certainly closer than 1 per cent. Fig. 10 shows the sum of the three ammeter readings plotted against the deflection: the points marked with a dot in a circle were obtained at 500 cycles per sec. These high-frequency observations could not be made in very ideal circumstances, both because conditions were not perfectly steady at the very high frequencies, and also because sufficient current for full-scale deflection could not be obtained. At the frequencies to which Fig. 10 relates the proximity of the cylinders should increase the deflection for a given current by 0·7 per cent. Fig. 10 is satisfactory in showing that a given deflection always corresponds to a larger reading of the hot-wire ammeters at very high frequencies than at low frequencies, and so shows that the hot-wire instruments are consistently reading high: their error is, however, small and is of the order of 3 per cent round about $\lambda = 100$ m.

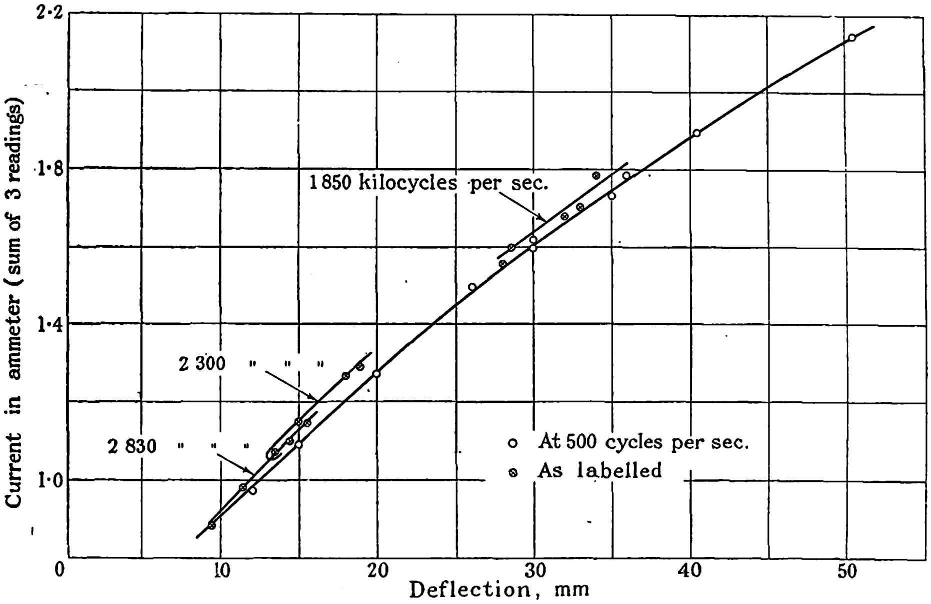

FIG. 10.

The large ammeter has been calibrated at 500 cycles per sec. against a Weston model 425 radio-frequency thermo-ammeter (0 to 20 amperes) and the two instruments again compared at 3 000 kilocycles per sec. ($\lambda = 100$ m). The result of the comparison is exhibited in Fig. 11, the points marked with a cross being obtained at 3 000 kilocycles per sec. Here again it was difficult to obtain perfectly steady conditions at the high frequency, and the current could be adjusted only in fixed steps which did not correspond to the most desirable parts of the scale. Since both instruments had a square-law scale, the four readings between 17 and 18 amperes should be the most reliable, and according to these a current at 3 000 kilocycles per sec. produces 5·6 per cent more deflection than it did at 500 cycles per sec. But now we have to allow for the proximity effect of two cylinders, 3·19 mm diam., placed 11·1 mm apart, and from formula (1) this will increase the deflection by 4·1 per cent. We have accordingly to account for a residue of only 1·5 per cent, and thus the scale reading of the Weston instrument is only 0·75 per cent high at a wavelength of 100 m—surely a very satisfactory performance for so small a thermal instrument of 20-ampere capacity.

Curves of temperature-rise for the large instrument are shown in Fig. 12, and by means of a cooling curve the thermal time-constant of the ammeter was found to be about 3 000 seconds. The heat capacity is about 4 600 joules and the cooling coefficient 1·5 watts per deg. C.

From the two heating curves of Fig. 12 we deduce that the resistance at $\lambda = 100$ m is 72 milliohms, and this value is in fair agreement with the values collected in Table 1.

(7) CALCULATED CORRECTION TABLES FOR THE LARGE AMMETER.

These factors are expressed as a correction to be applied after the proximity effect has attained its limiting value. Thus we suppose the calibration has been made at some convenient frequency such as 200 cycles per sec.

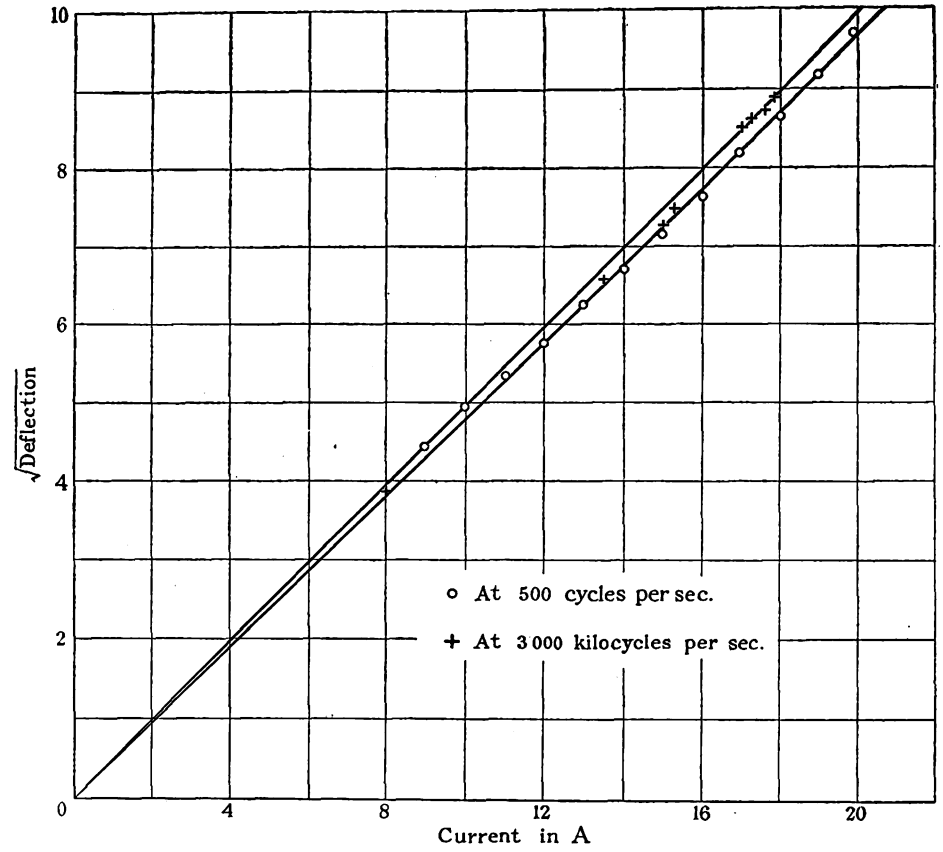

FIG. 11.

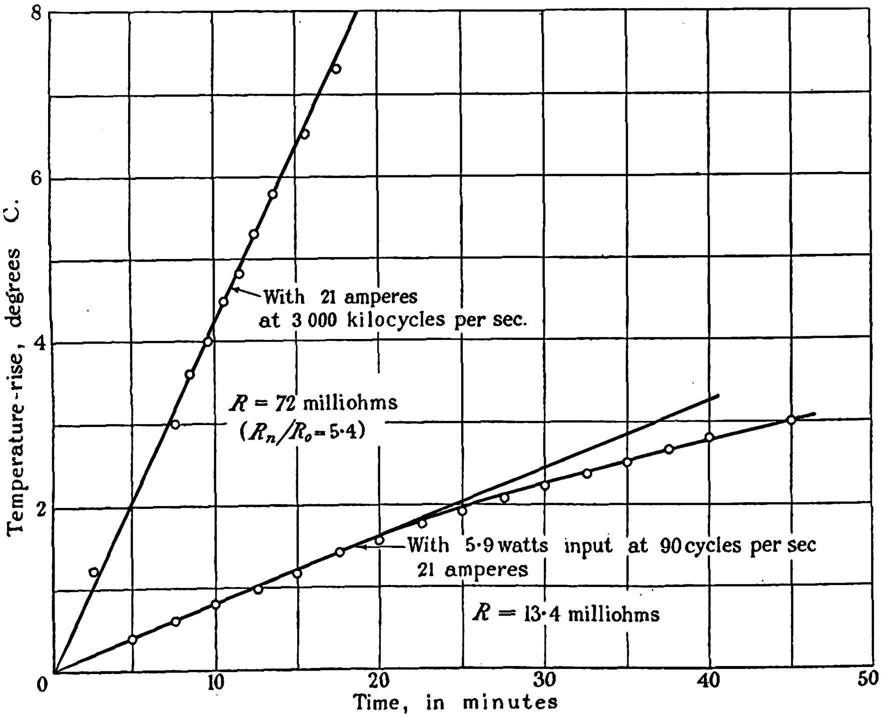

FIG. 12.—Heating curves of large ammeter.

and that the deflections then observed have been increased by 4·1 per cent to render the calibration valid for frequencies greater than 100 kilocycles per sec. (Note that at 40 kilocycles per sec. the addition is 3 per cent.) This calibration will then hold without further adjustment between 100 and 6 000 kilocycles per sec. ($\lambda = 3\,000$ m to 50 m). In calculating the factors collected in Table 3, the inductance has been taken as 0·2 μH and the terminal capacity as 3 $\mu\mu$F. The correction for longitudinal distribution of current has been calculated from formula (5) and in this k has been taken as 2 and l as 40 cm. The current corresponding to the observed deflection is to be read from the calibration curve, and then this current is to be reduced by the amount shown in the last column of Table 3.

TABLE 3.

λ	f (kilocycles per sec.)	Correction for current distribution	Correction for terminal capacity	Net reduction factor for current
m		per cent	per cent	per cent
50	6 000	0·085	0·02	0·1
20	15 000	0·504	0·5	1·0
10	30 000	2·15	2·0	4·1
5	60 000	8·2	8·5	16·7

It will be seen that the correction factor is small, and perhaps unimportant, until the wavelength is less than 15 m, but when it is less than 10 m the factor rapidly becomes large. The non-uniformity of the complete system may possibly make the factor slightly different from that calculated by equation (5), and perhaps that analysis should be interpreted as showing that the factor will not reach 1 per cent until the wavelength is less than about 15 m, and should thereafter be used for estimating roughly the correction for much shorter waves. Possibly future experience with instruments having systems of different lengths may substantiate the applicability of equation (5) to bent systems. Also the correction for terminal capacity becomes very appreciable, and this factor cannot well be more than an approximate estimate.

If and when it becomes necessary to make accurate current measurements at wavelengths shorter than 10 m it will be necessary to use an ammeter with a shorter system; in other words the ammeter must constitute a smaller fraction of the total length of the circuit in use.

(8) FUTURE DEVELOPMENTS.

The mechanical development and testing of these two instruments has shown up certain difficulties and drawbacks. The chief mechanical difficulty is to provide supports for the moving cylinder which are heavy enough to carry the current and yet do not impose too great a control. The convenience of calibrating at, say, 500 cycles per sec. has shown that a steady-current calibration is both unnecessary and troublesome. Accordingly it is proposed to abandon the possibility of steady-current calibration, for then the instrument can be built in a way which possesses very great advantages both in construction and use. In future it is proposed to use only one cylinder, which will be placed eccentrically within the screen tube, and to measure the repulsive force between the current in the cylinder and the eddy currents induced in the screen tube.* The cylinder will then be fixed and the screen tube will become the moving member. Since all the current in the screen tube is induced in it by the field of the cylinder, no means are required for leading this current in and out. This avoids the difficulty of carrying current through thin strips, and oil immersion is no longer required: the absence of the strips will reduce the resistance of the instrument at least 10-fold. It is proposed to carry the screen tube on knife edges and the whole control will be by gravity. The whole system is uniform as the right-angle bends, necessitated by the control springs, are no longer present; and the whole length is operative in producing repulsive force. Also the relevant value of l to be substituted in equation (5) is the length of the screen tube instead of the whole length of the complete loop. Thus had the 20-ampere instrument been made with one cylinder and a moving screen tube, its effective length would have been 10 cm instead of 40 cm. It may be calculated from (5) that the correction for current distribution would then have been only 1·7 per cent at $\lambda = 2$ m. With such an instrument we could therefore ignore the effect of current distribution entirely. In addition the inductance of the system would be halved, because now the screen tube is equivalent to placing a thick copper plate in the median plane of Fig. 1 and then obliterating one cylinder. It will further be reduced because the length of the system has been shortened by the length of the control springs. Probably the inductance would be reduced from 0·2 μH to 0·07 μH. The presence of the ammeter would then make less disturbance to the circuit, and the small inductance would render the terminal capacity much less effective. Assuming an inductance of 0·07 μH and a terminal capacity of 3 $\mu\mu$F, it may be calculated that the correction for terminal capacity would be 0·6 per cent at $\lambda = 10$ m and 2·4 per cent at $\lambda = 5$ m. The calibration of such an instrument would therefore be independent of frequency between 100 cycles and 30 000 kilocycles per sec.

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* *Proceedings of the Royal Society*, loc. cit., Fig. 13.

AN AMMETER FOR VERY HIGH FREQUENCIES.

By Professor C. L. **Fortescue**, O.B.E., M.A., Member, and L. A. **Moxon**.

(*Paper first received* 18*th September, and in final form* 20*th December*, 1929; *read before the* Wireless Section 5*th February*, 1930.)

Summary.

This paper describes the construction and theory of a simple form of hot-wire ammeter intended for use at any frequency up to 100 million cycles per sec. A cylindrical form is adopted in order that the correction factors for various frequencies may be calculated with certainty, and figures are given for an instrument as actually constructed.

(1) Introduction.

An ammeter for measuring currents up to about 1·2 amperes at frequencies between 10^7 and 10^8 cycles per sec. has been described by E. B. Moullin.[*] It consists of two parallel conductors mounted on elastic supports, the deflection of these supports under the electrodynamic forces arising from the mutual action of the currents being used to measure the magnitude of the current. The corrections for the capacity effects and the distribution of the current over the cross-sections of the conductors are somewhat difficult to calculate. The impedance would appear to be rather high and is to some extent dependent upon the magnitude of the current being measured. Finally, the measurement of the movement of the conductors is made by means of a microscope, with the result that the instrument is rather expensive, inconvenient to use and by no means robust.

Several alternative proposals have been made. P. R. Coursey and others have proposed to use capacity dividers and thermo-junctions. Hot-wire ammeters of the ordinary type are commonly used in practice without correction. The measurement of the voltage across either a single-turn loop of wire or other calculable form of inductance by means of a rectifying valve has also been suggested.

The ammeter described in this paper is a hot-wire instrument so arranged that the correction can be calculated easily. The impedance is relatively low and the R.M.S. value of the current is given directly by the movement of a pointer over a scale.

(2) The Difficulties of Measuring Very High-Frequency Currents.

These arise from:—

(*a*) The capacity effects in consequence of which the current in the measuring device is different from that entering the instrument.

(*b*) The high inductive reactance of even very short conductors, and the consequent difficulty of using parallel circuits.

(*c*) The disturbance of the circuit in which the measurement is being made, owing to the relatively high impedance of the measuring device.

With regard to (*a*), at a frequency of 10^8 the reactance of a capacity as low as 10 $\mu\mu$F is only 160 ohms, and where thorough screening is adopted—as it must always be—it is by no means easy to keep the parallel capacities down to so low a figure. Moreover, the distribution of the current along the conductors employed for its measurement is dependent upon the distributed inductance and capacity. It is not always permissible to assume that the distribution is uniform, and where a high degree of accuracy is necessary a correction must be made for this effect.

The high value of the inductive reactance makes it difficult to adjust any instrument depending upon the subdivision of the current in unequal arms. At a frequency of 10^8 the reactance of a lead having an inductance of only 0·1 μH is already 62·8 ohms. The circuits must either be so adjusted that the impedances are identical, or the inductive reactance must be swamped by resistance or capacity reactance. In the latter cases the resultant instrument would have far too high an impedance for general use.

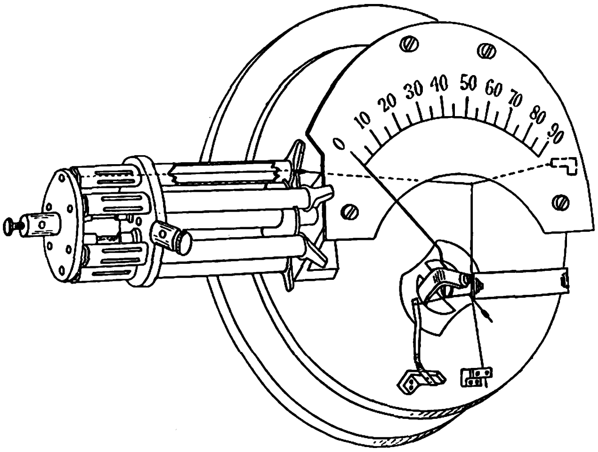

Fig. 1.

As to the permissible impedance, this depends upon the current for which the instrument is designed. The admittance should, if possible, be not less than 1 reciprocal ohm per ampere to be measured, since the total inductive reactance of resonant circuits at these high frequencies is usually low.

(3) Principle of the New Hot-Wire Instrument.

The simplest case for which all corrections can be applied with certainty is that of a wire of small diameter mounted co-axially with a cylindrical screen. Russell[*] has given a full treatment of this case. The high-frequency resistance of the wire and cylinder are easily calculable; the varying distribution of the current is easily found from the dimensions and a correction for the capacity of the terminal blocks can easily be made.

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[*] See page 544; also *Proceedings of the Royal Society*, A, 1928, vol. 121, p. 41.

[*] *Philosophical Magazine*, 1909, vol. 17, p. 524.

The passage of the current heats the wire and causes it to expand, and this expansion is used to measure the currents. The instrument is calibrated by direct current and the corrections for the high-frequency currents are calculated and applied either by reference to correction curves or by the use of curved scale divisions.

(4) The Construction of the Instrument.

This is shown in Figs. 1 and 2, where provision is made for six parallel wires each carrying a maximum direct current of about 1·2 amperes at full scale deflection.

Each current-carrying wire is kept in its central position on the axis of a screening tube by means of a flat spring at the end. One of these wires is directly attached to what is normally the heated wire of an ordinary hot-wire ammeter. As the wire in the tube expands and contracts, the pointer of the instrument moves to and fro over the scale and this movement thus becomes a measure of the current in the heating wires within the screening tubes.

A symmetrical arrangement of the terminal connections ensures uniform distribution of current between the heated wires.

For some experimental work this first instrument has been used with only one screened heating wire. This is quite satisfactory for the experiments, but the terminal capacity is much greater than need be the case with a simple wire, and consequently the corrections are abnormally large.

A second heating unit having only a single wire is now under construction. The terminal capacity is estimated to be only about one-fifth of that of the 6-wire heater, with the result that the corrections will be more normal.

(5) Calibration and Correction.

The initial calibration is by direct current in the ordinary way, and the scale is marked from this calibration.

The capacity between the terminal blocks and the screening tubes is measured before the wires are inserted. This and the dimensions enable the corrections to be made, the actual value of the alternating current entering the input terminal for each scale division being thus found and plotted for use as a correction curve. Alternatively, curved scale divisions as shown in Fig. 3 may be used.

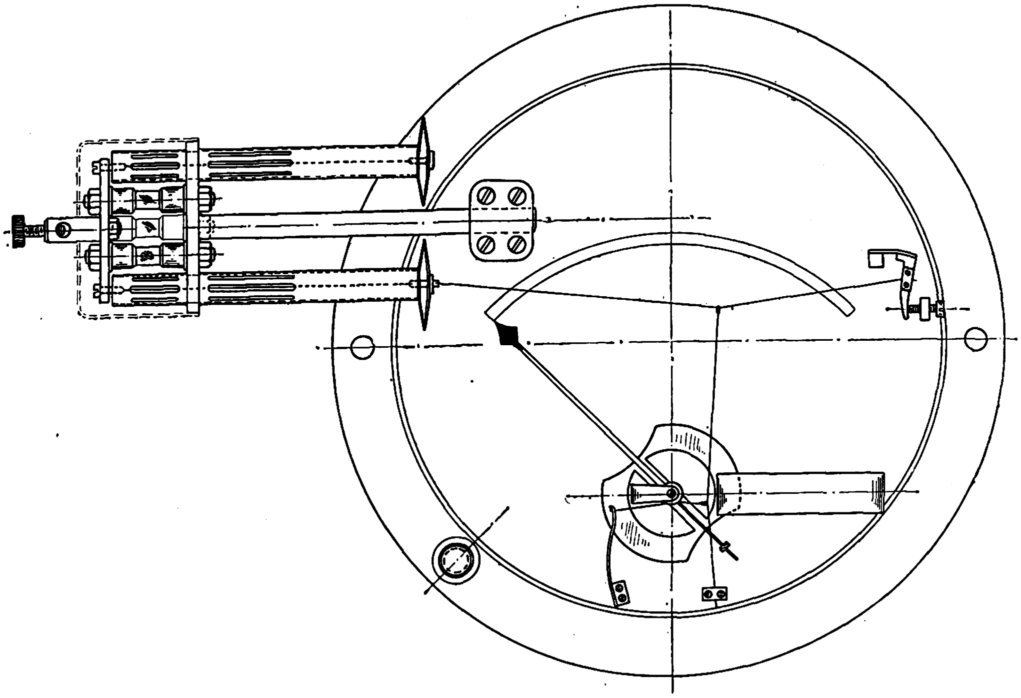

Fig. 2.—High-frequency hot-wire ammeter

Scale: $\frac{3}{5}$ full size.

(6) Calculations of the Corrections.

Notation :—Terminal block capacity	C_t
Capacity per cm length of heating wire	C
Inductance per cm length of heating wire	L
High-frequency resistance per cm length of heating wire	R
Total current (R.M.S. amperes) entering input terminal	I_0
Current (R.M.S. amperes) in the terminal capacity	I_t
Current (instantaneous or vector amperes) in wire at distance x cm from input terminal	i
Ditto (maximum value)	$\mathfrak{I}$
Ditto (R.M.S. value)	I
Current (instantaneous, maximum and R.M.S. amperes) in wire at input-terminal end	i_w, $\mathfrak{I}_w$, I_w

Voltage (instantaneous or vector volts) between wire and cylinder at distance x from input terminal	v
Ditto (at input terminal)	v_w
Number of parallel heating wires	N
Length (cm) of each wire	l

Considering firstly the distribution of current along the wire, the conditions are as usual; viz.

$$\left.\begin{aligned} -\frac{\partial i}{\partial x} &= C\frac{\partial v}{\partial t} \\ -\frac{\partial v}{\partial x} &= iR + L\frac{\partial i}{\partial t} \end{aligned}\right\} \quad . \ . \ . \ . \ . \quad (1)$$

The terminal conditions are that when $x = 0$, $i = i_w$, and when $x = l$, $v = 0$, it being assumed that the screening tube is equivalent to a short-circuit. The methods given by Russell * must be adopted if this is not the case.

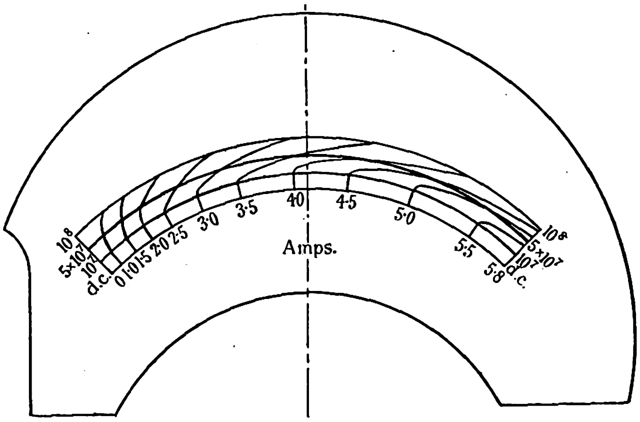

Fig. 3.—Scale for high-frequency ammeter.

Equation (1) and the terminal conditions give:—

$$i = i_w\,(\cosh mx - \tanh ml \sinh mx) \quad . \ . \quad (2)$$

$$v_w = i_w\frac{m}{j\omega C}\tanh ml \quad . \ . \ . \ . \quad (3)$$

where $\quad m = a + j\beta = (-\omega^2LC + j\omega CR)^{\frac{1}{2}} \quad . \ . \quad (4)$

The mean power input is equal to the real component of the multiplier of i_w in (3) multiplied by I_w^2. If $I_{d.c.}$ is the calibrating direct current for the whole N wires, the current in one wire is $I_{d.c.}/N$ and the power expended is $(I_{d.c.}/N)^2lR_{d.c.}$, where $R_{d.c.}$ is the d.c. resistance per cm length of the wire.

If this power expenditure causes the same deflection as the alternating current, then

$$\frac{I_{d.c.}^2}{N^2}lR_{d.c.} = I_w^2\left(\text{Real component of } \frac{m \tanh ml}{j\omega C}\right) \quad (5)$$

Turning now to the current in the terminal capacity, this will be

$$i_t = i_w m\frac{C_t}{C}\tanh ml \quad . \ . \ . \ . \ . \quad (6)$$

The input current to the input terminal will be the sum of the capacity current given by (6) and N times the current in each wire; viz.

$$i_w\left(N + m\frac{C_t}{C}\tanh ml\right)$$

whence the value of the mean-square input current, I_0^2, can be found. Then, with the aid of (5), I_0^2 is connected with $I_{d.c.}^2$ and the correction factor determined.

From (4),

$$a = \omega\sqrt{(LC)}\left[\frac{1}{2}\left\{\sqrt{\left(1 + \frac{R^2}{\omega^2L^2}\right)} - 1\right\}\right]^{\frac{1}{2}}$$

and

$$\beta = \omega\sqrt{(LC)}\left[\frac{1}{2}\left\{\sqrt{\left(1 + \frac{R^2}{\omega^2L^2}\right)} + 1\right\}\right]^{\frac{1}{2}}$$

When $\omega\sqrt{(LC)}$ is small, both a and β are small and

$$m \tanh ml = m^2l = (-\omega^2LC + j\omega CR)l$$

Also the real component of $m \tanh ml/(j\omega C)$ is then lR and, from (5),

$$I_w^2 = \frac{I_{d.c.}^2}{N^2}\cdot\frac{R_{d.c.}}{R} \quad . \ . \ . \ . \ . \quad (7)$$

With the same approximations, the input current is

$$i_0 = i_w\{(N - l\omega^2LC_t) + jlR\omega C_t\}$$

and $\quad I_0^2 = I_w^2\{(N - l\omega^2LC_t)^2 + l^2R^2\omega^2C_t^2\}$

$$= I_w^2(N - l\omega^2LC_t)^2$$

in most cases.

Substituting for I_w^2 in (7) gives

$$I_0^2 = I_{d.c.}^2\frac{R_{d.c.}}{R}\left(1 - \frac{l\omega^2LC_t}{N}\right)^2$$

or $\quad I_0 = I_{d.c.}\left(1 - \frac{\omega^2lLC_t}{N}\right)\sqrt{\left(\frac{R_{d.c.}}{R}\right)} \quad . \ . \quad (8)$

The effective impedance of the instrument is

$$Z_0 = \frac{v_w}{i_0} = \frac{m \tanh ml}{j\omega(NC + mC_t \tanh ml)}$$

With small values of a and β this becomes

$$Z_0 = \frac{l(R + j\omega L)}{(N - l\omega^2LC_t) + jlR\omega C_t} \quad . \ . \ . \quad (9)$$

which at relatively low frequencies becomes

$$Z_0 = lR/N$$

as it should be for steady currents.

(7) CALCULATIONS FOR THE FIRST INSTRUMENT MADE.

Number of heating wires	6
Length of each wire	9·5 cm
Internal diameter of screening cylinder	0·80 cm
Diameter of wire	0·0140 cm
D.C. resistance of wire per cm length at 15° C.	0·1562 ohm
Specific resistance of wire at 15° C.	24·2 × 10⁻⁶ ohm per cm per cm²
Observed terminal capacity	14·6 μμF

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* *Loc. cit.*

The capacity per cm length of wire is

$$\tfrac{1}{2}\log_\epsilon \frac{0\cdot 80}{0\cdot 0140} \text{ electrostatic units}$$
$$= 0\cdot 1373 \times 10^{-12} \text{ farad.}$$

The inductance per cm length of wire is

$$2\log_\epsilon \frac{0\cdot 80}{0\cdot 0140} \text{ electromagnetic units}$$
$$= 8\cdot 093 \times 10^{-9} \text{ henry.}$$

The ratio $R/R_{d.c.}$ when computed from the usual tables is as follows:—

Frequency ..	10^6	10^7	5×10^7	10^8
$R/R_{d.c.}$ ..	1·000	1·015	1·268	1·678

The approximations made in the previous section are permissible for all except the last case, which must be calculated from the complete formulæ.

The results are:—

Frequency	10^6	10^7	5×10^7	10^8
$\frac{I_0}{I_{d.c.}}$	1·000	0·992	0·874	0·706
Impedance of instrument, in ohms ..	0·261	0·840	4·11	8·84

(8) Comments on These Results.

(*a*) The corrections are very small for frequencies below 10^7, and from this frequency downwards the direct-current calibration can be used with errors not greater than 1 per cent. Above that frequency, however, the correction increases rapidly owing to the relatively quick increase of the resistance, and also because of the increasing current in the terminal capacity.

(*b*) The impedance of the instrument increases with the frequency, and the reactance is inductive up to frequencies considerably above 10^8.

(*c*) The magnitude of the correction due to the capacity is mainly dependent upon the term $\omega\sqrt{(LC)}$, which in this case is ω/c^2, where c is the ratio of the electromagnetic to the electrostatic absolute units of quantity. With the cylindrical construction, therefore, the dimensions will have little influence on this correction. There is consequently a fairly free choice of dimensions, which enables the design to be adapted to the other requirements of the hot-wire instrument.

(*d*) The results given in the previous section are only calculated to a moderate degree of accuracy because sufficient experience of either the construction or use of these instruments has not yet been obtained to justify more exact computations. These will be made later if it is found desirable.

(9) Programme of Further Work.

There is now in progress a lengthy research which includes both the design of the instrument, and the method of comparing the results with other similar ammeters or indirect methods of measuring current. This research is being carried out under the auspices of the Department of Scientific and Industrial Research, by whose permission this paper is now published.

The authors wish to thank Mr. D. W. Hopkin for assistance in preparing drawings for the illustrations.

A METHOD OF MEASURING MECHANICAL IMPEDANCE.

By Professor E. MALLETT, D.Sc. (Eng.), Member, and R. C. G. WILLIAMS, B.Sc. (Eng.), Graduate.

(*Paper first received 2nd December, and in final form 20th December,* 1929; *read before the* WIRELESS SECTION *5th February,* 1930.)

SUMMARY.

The device the mechanical impedance of which at a given frequency is to be measured is driven by one prong of an electrically-driven tuning fork, and the other prong is loaded to restore balance, the load required being the mechanical impedance to be determined. The balance condition is indicated by the absence of vibration of the fork support.

An improvement depends upon the experimentally determined fact that mechanical resistance out-of-balance does not appreciably affect the support vibration. If the prongs are balanced for mass, the total resistance can be found from a decay-factor determination or by a single measurement of amplitude with a known current, and the resistance of the device estimated.

A measurement is made of the mechanical impedance at 100 cycles per sec. of a certain gramophone pick-up.

LIST OF SYMBOLS.

m = equivalent mass of each prong of a tuning fork (grammes).

s = equivalent stiffness of each prong of a tuning fork (dynes/cm).

r = equivalent mechanical resistance of each prong of a tuning fork (dynes/cm/sec.).

a = decay factor of each prong $\left\{= r/(2m)\right\}$.

m' = mass added to one prong of tuning fork (grammes).

r' = total mechanical resistance added to two prongs (dynes/cm/sec.).

r_1 = resultant mechanical resistance of each prong when loaded $(= r + \frac{1}{2}r')$.

f_0 = resonant frequency of tuning fork (cycles/sec.).

$\omega_0 = 2\pi f_0$ (radians/sec.).

C_0 = capacity (μF) in oscillatory circuit of valve oscillator to produce a frequency f_0.

x = amplitude of displacement of prong from mean position (cm).

u_m = maximum value of velocity of prong (cm/sec.).

$\left.\begin{matrix} x_0 \\ u_0 \end{matrix}\right\}$ values of x and u_m at resonance.

i = R.M.S. value of alternating current in driving coil of fork (mA).

i_m = maximum value of alternating current in driving coil of fork (absolute electromagnetic units, called " abamps ").

A = force factor of driving system (dynes/abamp) $(= NB/S)$.

N = number of turns on driving coil.

B = flux density of permanent magnetism in the air-gaps (lines/cm^2).

S = total reluctance of the magnetic circuit of the driving system.

SECTION (1).

The resonant frequency of an electrically-driven tuning fork depends upon the length and thickness of the prongs and upon the material of which they are made, but referred to the point of drive an equivalent mass m and an equivalent stiffness s can be found for each prong, so that the resonant frequency is given by

$$f_0 = \frac{1}{2\pi}\sqrt{\left(\frac{s}{m}\right)} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

This applies accurately for small amplitudes only. At large amplitudes the frequency of maximum response decreases as the amplitude is increased, according to a square law.*

The decay factor of each prong of the tuning fork can also be expressed in terms of an equivalent mechanical resistance r, as

$$a = \frac{r}{2m} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Here again only small amplitudes are intended, as the decay factor increases with amplitude.

If a mass m' is added to each prong at the point of drive the resonant frequency will be lowered to

$$f_0 = \frac{1}{2\pi}\sqrt{\left[\frac{s}{m + m'}\right]} \quad . \quad . \quad . \quad . \quad (3)$$

and if a mechanical resistance r' is added to each prong at the point of drive the decay factor will be altered to

$$a = \frac{r + r'}{2(m + m')} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

If the two prongs of the fork are perfectly balanced there will be little or no tendency for the support to vibrate, but if they are not balanced the support will tend to vibrate in order that the centre line of the mass of the two prongs may remain stationary. Suppose now that one prong is made to drive a gramophone pick-up. Its constants will on that account be altered to $(m + m')$ and $(r + r')$, and the fork will be thrown out of balance and the support caused to vibrate. But if the other prong can be loaded with a known mass and a known resistance to restore the balance, the effective mass and resistance of the pick-up are determined. The case where the pick-up reactance is effectively a stiffness can be dealt with by loading each prong initially with a known mass m' sufficient to cause a greater reduction of frequency than the increase caused by the pick-up stiffness.

SECTION (2).

The obvious indication that balance has been obtained is the absence of vibration in the support, and many experiments were made in this direction.

The fork used was a laboratory model consisting of two bars of hard steel mounted on a bracket to form a tuning fork. The effective length of the prongs could be varied by altering the position of a massive steel clamping block, the frequency range being from 80 to 500 cycles per sec. The fork was magnetized and between its prongs was mounted a small low-resistance coil with a core of a bundle of soft-iron wires to complete the magnetic circuit of the prongs.

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* *Proceedings of the Physical Society of London*, 1926–7, vol. 39, p. 338.

In order to leave the support fairly free to vibrate, the bracket at the stationary end of the prongs was removed, the only support being a long bolt clamping the steel block to the base. The unused portion of the prongs was then available for mounting the vibration detector as in Fig. 1.

After trying several types of detectors the one found to be most useful was a set of 22 single reeds rigidly clamped into two brass blocks and of various lengths covering a frequency range of about 80 to 100 cycles per sec., the free ends being viewed from above through a low-power microscope. A button microphone and vibration galvanometer was much more sensitive but somewhat unstable, and the tuning of the galvanometer had to be adjusted with every alteration of balancing load, making the measurement very laborious.

The oscillator used had an L.S.6A output valve working from the 400-volt d.c. mains through a filter circuit, this large power output being necessary to drive the heavily loaded fork through a high-value swamping resistance necessary for stability.*

The balancing impedances used were (*a*) reactive, and (*b*) resistive, as follows:—

(*a*) A set of weights each shaped to clamp on to the prongs by means of a small set-screw.

(*b*) A 3-bladed copper paddle dipping into a bath of thick machine oil. The direction of motion of the paddles was in their own plane, this scheme allowing rigid construction consistent with lightness to be used.

The pick-up was driven from the fork by fixing a small piece of gramophone record to the top of the prongs by means of hot shellac and resting on this the needle of the pick-up. This coupling has the advantage of simplicity and, moreover, very nearly reproduces the forces between needle and record under actual playing conditions. Back-coupling due to vibrations passing along the pick-up arm and hence to the fork support was prevented by mounting the arm on a massive cast-iron base independent of the fork mounting.

The practical difficulties encountered with this apparatus are summarized below:—

(1) Resistance could not be added without also adding effective mass.

(2) Resistance out-of-balance produced an inappreciable vibration of the support.

(3) An out-of-balance of mass produced a considerable increase of effective resistance, which caused a decrease in the prong and support vibrations although balance conditions were being departed from.*

(4) Every change of added mass necessitated a change of frequency of drive. Unless the fork were driven at the resonant frequency corresponding to the load of the moment, it was impossible to say whether balance conditions were being approached.

It then appeared to be possible [from (2)] that with the order of resistances encountered the additional effective resistance of each prong would be one-half the total added resistance, irrespective of whether it was added to one prong only or divided between the two. In other words, a determination of the decay factor of the fork by any method,† provided of course that the mass of each prong was balanced, would give the resistance of the pick-up. In Appendix 2 it is shown that this idea is justified. The use of the support vibration as an indication in balancing the mass was possible but tedious for the reasons given above. A simpler method was found to be as follows: A curve of resonant frequency/added mass (equal mass to each prong) was drawn. Then the pick-up was added to one prong and mass added to the other prong until the resonant frequency of the fork for the mass added agreed with the value read from the curve. The effective mass of the pick-up was then equal to the mass added. Alternatively, equal known masses (greater than the pick-up mass) were added to each prong, and one of these was subsequently replaced by the pick-up and a variable mass, the latter being adjusted to bring the resonant frequency back to its previous value.

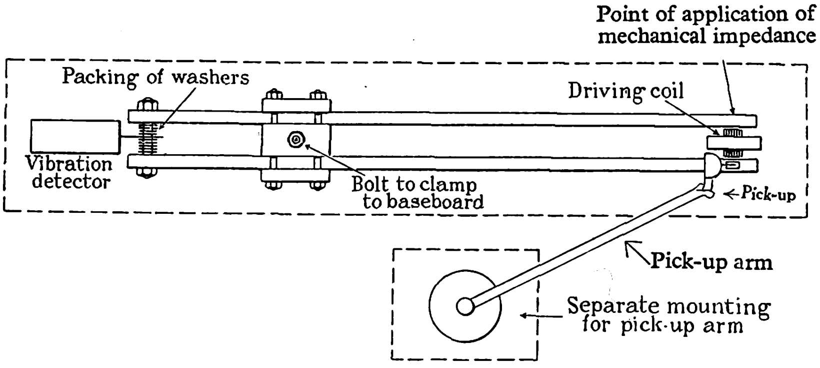
Point of application of mechanical impedance
Packing of washers
Driving coil
Vibration detector
Bolt to clamp to baseboard
Pick-up
Pick-up arm
Separate mounting for pick-up arm

FIG. 1.

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* *Proceedings of the Physical Society of London*, 1926–7, vol. 39, p. 337.

* See Appendix 1.

† *Journal I.E.E.*, 1924, vol. 62, p. 517.

SECTION (3).

Details will now be given of an experimental determination of the impedance of a certain gramophone pick-up.

The skeleton circuit used is given in Fig. 2. The fork amplitudes were measured by viewing some illuminated mercury globules on the prong tips through a high-power travelling microscope with a scale in the eye-piece, and the current was determined by the valve voltmeter and known resistance R_1, using a Weston relay as a critically damped reflecting galvanometer.* R_2 was a series controlling resistance for keeping the current constant while taking the resonance curve, the smallest value to which R_2 was reduced being sufficiently large to prevent unstable effects.

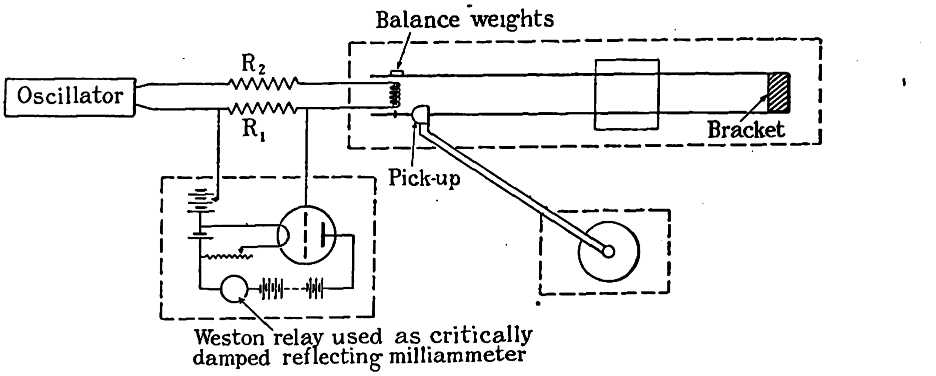
Balance weights
Oscillator
R2
R1
Bracket
Pick-up
Weston relay used as critically damped reflecting milliammeter

FIG. 2.

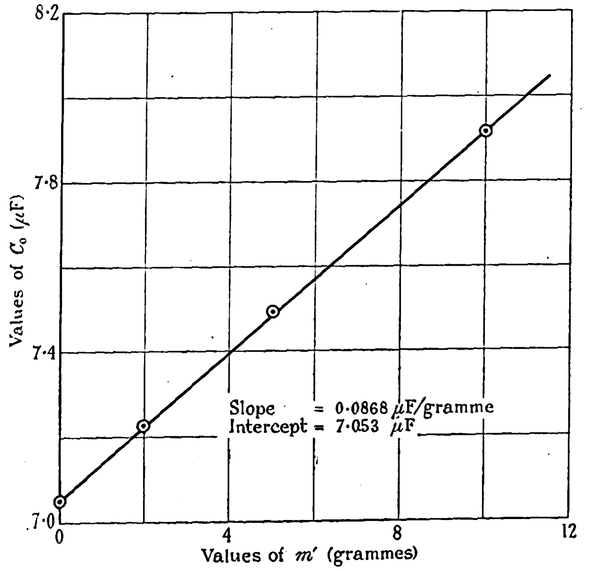

FIG. 3.

The equivalent mass and resistance of the fork prong required in equations (3) and (4) were found by the following method:—

$$\text{From (3)} \qquad \frac{1}{f_0^2} = 4\pi^2\frac{m}{s} + 4\pi^2\frac{m'}{s} \quad . \quad . \quad . \quad . \quad (5)$$

and if C_0 is the capacity in the oscillatory circuit of the oscillator corresponding to a frequency f_0

$$f_0^2 C_0 = K$$

where K is some constant determined from the oscillator calibration.

$$\text{Hence} \qquad C_0 = 4\pi^2K\frac{m}{s} + 4\pi^2K\frac{m'}{s} \quad . \quad . \quad . \quad . \quad (6)$$

If, therefore, equal masses m' are added to the prongs at the point of drive, C_0 found for resonance, and m' plotted against C_0, the graph should be a straight line of slope $4\pi^2K/s$ and intercept $4\pi^2Km/s$, and from these two quantities m and s are determined.

This experiment was carried out, the graph obtained being shown in Fig. 3. This checks the theory and provides a rapid method of finding m and s for any fork.

K, from the oscillator calibration, was

$$10^5 \text{ (cycles/sec.}^2)^2 \ \mu\text{F}$$

and from the graph the slope is 0·0868 μF/gramme and the intercept is 7·053 μF.

$$\text{Hence} \qquad m = 81 \cdot 3 \text{ grammes, and}$$
$$s = 45 \cdot 5 \times 10^6 \text{ dynes/cm}$$

A resonance curve of the unloaded fork at constant current was taken and by the circle construction the decay factor was found to be 0·096, giving

$$r = 2ma = 15 \cdot 6 \text{ dynes per cm per sec.}$$

where r is the mechanical resistance of one prong of the fork.

The pick-up was now coupled to one prong and at a frequency of 117 cycles per sec. it was found that the reactive load of the pick-up and 16 grammes was balanced by 4·3 grammes on the other prong.

Thus the pick-up has an apparent negative mass of 16 − 4·3 = 11·7 grammes, corresponding to a stiffness, at this frequency, of

$$s_0 = \omega_0^2 m_0 = 4\pi^2 \times 117^2 \times 11 \cdot 7 \text{ dynes per cm}$$
$$= 6 \cdot 36 \times 10^6 \text{ dynes per cm}$$

A resonance curve taken of this balanced system gave

$$a = \frac{r + \frac{1}{2}r'}{2(m + m')} = 14 \cdot 3$$

$$\text{hence} \qquad r + \tfrac{1}{2}r' = 2\,450$$

$$\text{giving} \qquad r' = 4\,870 \text{ dynes per cm per sec.}$$

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* *Journal I.E.E.*, 1925, vol. 63, p. 401; also *Proceedings of the Physical Society of London*, 1927-8, vol. 40, p. 14.

In order to test the sensitivity of the method for the balancing of mechanical reactance, a graph was taken showing resonant capacity C_0 plotted against mass added to one prong only (Fig. 4). The steepness of the curve for small values of mass out-of-balance is very apparent, and a measurement can be obtained without any difficulty with an accuracy of 2 or 3 per cent.

The determination of the decay factor from the graphical construction, however, is laborious and not so accurate, and the advantages of a single-reading method for determining the resistance from the points of view of increased accuracy and rapidity of measurement are apparent.

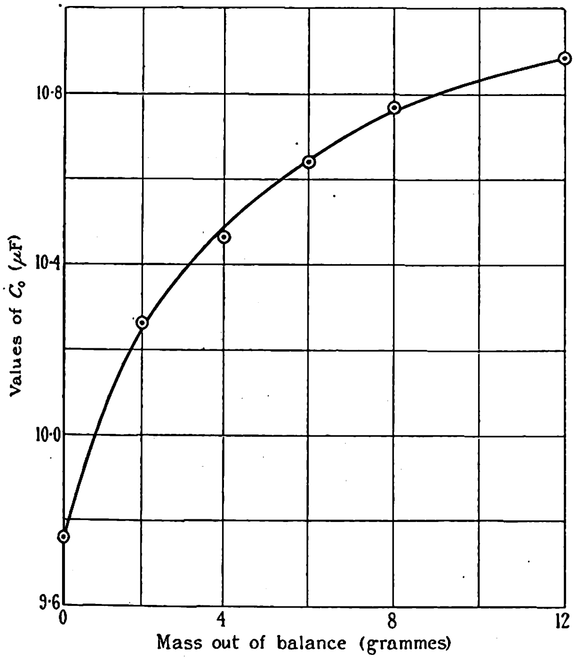

FIG. 4.

Such a method can be obtained by making use of the equation

$$u_0 = \frac{Ai_m}{r_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where x_0 = amplitude at resonance,
u_0 = max. velocity at resonance,
$= \omega_0 x_0$,
i_m = current in abamps (max. value),
A = force factor of driving system in dynes per abamp, and
r_1 = total mechanical resistance of one prong.

Hence if A is known, measurement of x_0, C_0 and i_m will determine the mechanical resistance $\frac{1}{2}r' + r$.

It is well known that

$$A = NB/S \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where N = number of turns on driving coil,
B = flux density, in lines per cm^2, of permanent magnetism in the air-gaps, and
S = reluctance of magnetic circuit,

so that from theoretical considerations A should be independent of the external load on the fork. The accuracy of this assumption is discussed in Appendix 4.

The experimental details for determining the force factor are given in Appendix 3, the result being $A = 5{\cdot}06 \times 10^6$ dynes per abamp.

The resonance curve giving the pick-up impedance was taken at a constant current of 26·0 mA and the maximum deflection at resonance was 0·0102 cm, so that, using the shorter method,

$$\tfrac{1}{2}r' + r = \frac{Ai_m}{\omega_0 x} = \frac{5{\cdot}06 \times 10^6 \times 26 \times 10^{-4} \times \sqrt{2}}{2\pi \times 117 \times 0{\cdot}0102}$$
$$= 2\,470 \text{ dynes per cm per sec.}$$

This gives

$$r' = 4\,910 \text{ dynes per cm per sec.}$$

which agrees with the result obtained by the graphical construction.

CONCLUSION.

The method has so far been tried only at the low frequency of about 100 cycles per sec., but no difficulty is anticipated in obtaining results at frequencies up to, say, 500 cycles per sec. with forks of higher pitch. It is hoped to extend the frequency range still further by employing the higher modes of vibration of the fork.

The experimental work described in this paper was carried out in the Telegraphy and Telephony Laboratories of the City and Guilds (Engineering) College, and the thanks of the authors are due to Mr. F. W. Andrews and the staff of the departmental workshop for assistance in the construction of the special apparatus used.

APPENDIX 1.

INCREASE OF EFFECTIVE MECHANICAL RESISTANCE OF FORK WITH A MASS OUT OF BALANCE.

In the first attempt made to measure mechanical impedance by a tuning-fork method,* the pick-up was driven by one prong of the fork, and the influence on the decay factor and frequency of the fork was used to estimate the mass and resistance of the pick-up. The mass was determined from a curve such as Fig. 4. To estimate the resistance, resonance curves were drawn with various masses added to one prong only of the fork and the decay factor as determined from these curves was plotted against the mass added, to obtain a curve such as Fig. 5. From this curve the increase in the effective mechanical resistance of the fork itself resulting from out-of-balance of mass can be estimated and subtracted from the total increase obtained with the fork driving the pick-up. To obtain an idea of the correction involved, reference may be made to Section (3). With the mass balanced the pick-up introduces a decay factor of 14·3, whereas the reactive load of the pick-up, being 11·7 grammes, would itself introduce, if unbalanced, a decay factor of 10·1.

This correction is of the same order as the resistance to be measured, and the scheme was therefore abandoned in favour of a balance method.

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* The first experiments in which were carried out by Mr. R. Toombs.

APPENDIX 2.

CONSTANCY OF FORK RESISTANCE WITH AN UNBALANCED RESISTIVE LOAD, AND MEASUREMENT OF POWER FACTOR OF OIL DAMPING.

For this experiment, matched, 3-bladed copper paddles could be attached to each prong at equal distances from the support, and glass containers so arranged that either or both paddles could be immersed to the same level in thick machine oil. By this means oil damping could be applied to either or both prongs while leaving balanced the reactive load due to the mass of the paddles.

The equivalent mass and stiffness of each prong with paddle attached was found as described in Section (3), and the decay factors under the various resistive loads were found by plotting resonance curves. With only one paddle immersed there was an out-of-balance of reactive load due to the oil carried along with the paddle. This was indicated by a change in the resonant frequency, and was corrected as described above by the addition of a small mass to the prong carrying the free paddle.

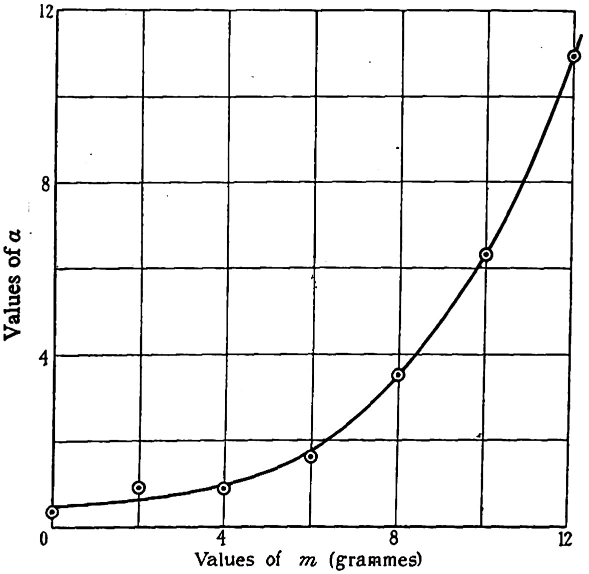

FIG. 5.

The results, giving the total mechanical resistance of the two prongs (as determined from the resonance curve multiplied by 2) under different loads, are given below, the resonant frequency being constant at $103\cdot 2$ cycles per sec.

	Resistance, in dynes/cm/sec.
(1) Thick oil round left-hand paddle with right-hand paddle free	2 776
(2) Thick oil round right-hand paddle with left-hand paddle free	3 320
Sum	6 096
(3) Thick oil round both paddles	5 980
(4) Both paddles free	136
Sum	6 116

Assuming no increase of prong resistance with unbalanced resistive load, the two sums should agree as they are each equal to the mechanical resistance of 4 prongs plus 2 immersed paddles plus 2 free paddles, and from the results it is clear that the assumption is justified.

From the balancing mass required with only one paddle immersed, a figure may be obtained expressing the " mechanical power factor " of the damping. With the right-hand paddle immersed, $1\cdot 0$ gramme had to be added to the left-hand paddle to restore the mass balance.

The mechanical resistance of the oil damping with the right-hand paddle

$$= 3\,320 - 136 = 3\,184 \text{ dynes/cm/sec.}$$

Hence " power factor " of the oil damping

$$= \frac{r'}{\sqrt{[(r')^2+\omega_0^2(m')^2]}} = \frac{3\,184}{\sqrt{[3\,184^2+(2\pi\times 103\cdot 2\times 1)^2]}}$$
$$= 0\cdot 98$$

This result shows that oil damping, at any rate under the conditions used, acts practically as a pure resistance.

APPENDIX 3.

DETERMINATION OF THE FORCE FACTOR A.

The force factor was determined in the first instance in the well-known manner by drawing curves of vibration amplitude against frequency and of coil impedance against frequency. The decay factor a is determined from either; the former gives, in addition, the amplitude x_0 at resonance and the latter the diameter OD in ohms of the motional impedance circle.

From (7), $$\omega_0 x_0 = \frac{A i_m}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

and $$\text{OD} = \frac{2A^2}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

whence $$A = \frac{\text{OD}}{2\omega_0 x_0} i_m \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Subsequently, however, the determination of m and s from a curve such as Fig. 3, and a from a resonance curve of amplitude against frequency, enabled r to be found as

$$r = 2ma$$

and a quicker determination of A from equation (9) as

$$A = \frac{\omega_0 x_0 r}{i_m} \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

For the experiments described in Section (3),

$$\omega_0 = 2\pi \times 119 \text{ radians per sec.}$$
$$x_0 = 0\cdot 0108 \text{ cm}$$
$$r = 15\cdot 6 \text{ dynes per cm per sec.}$$
$$i = 0\cdot 176 \text{ mA (R.M.S. value)}$$

giving $A = 5\cdot 06 \times 10^6$ dynes per abamp.

APPENDIX 4.

CHECK ON CONSTANCY OF FORCE FACTOR WITH UNBALANCED RESISTIVE LOADS.

Using the equation (12) derived above, the force factor A was determined for the unbalanced resistive loads used in Appendix 3, giving the results tabulated below.

From the figures in the last column of the table it is clear that A is sensibly independent of the load on the fork, provided that there is mass balance.

	ω_0	x_0	r_1	i(R.M.S.)	A
	radians/sec.	cm	dynes/cm/sec.	mA	dynes/abamp.
(1) Thick oil round left-hand paddle with right-hand paddle free	650	0·00794	1 388	10·1	$5{\cdot}00 \times 10^6$
(2) Thick oil round right-hand paddle with left-hand paddle free	650	0·0081	1 660	12·5	$4{\cdot}94 \times 10^6$
(3) Thick oil round both paddles	650	0·00685	2 990	19	$4{\cdot}91 \times 10^6$
(4) Both prongs free (from Appendix 3) ..	—	—	—	—	$5{\cdot}06 \times 10^6$

SOME NOTES ON THE DESIGN OF A GRAMOPHONE PICK-UP.

By G. W. Sutton, B.Sc.

(Paper first received 29th November, and in final form 20th December, 1929; *read before the* Wireless Section *5th February,* 1930.)

Summary.

It is a matter of common experience that the performance of the large majority of commercial pick-ups leaves much to be desired. The following notes describe an experimental investigation of the performance of certain types.

Further experiments are then described on the mode of vibration of a pick-up armature and on other factors affecting the performance of the instrument.

A theoretical treatment based on the results of these experiments is given and finally a new design is evolved.

Table of Contents.

(1) Classification of types of pick-up.
(2) Results of preliminary tests.
(3) Experiments on mode of vibration of a pick-up armature.
(4) Parasitic vibrations in the pick-up support.
(5) Lamination of armature and pole-shoes.
(6) Distribution of alternating component of the magnetic field at different frequencies.
(7) Effect of annealing armature and pole-shoes.
(8) Damping the vibrating system.
(9) Acoustical damping.
(10) Résumé of theory of operation.
(11) Method of design.
(12) Regulation of voltage output.
Appendix 1. Measurement of voltage output over a wide range of frequency.
Appendix 2. Theory of the pick-up.
Appendix 3. Tendency of the pick-up needle to leave the record groove.

(1) Classification of Types of Pick-up.

It would appear that there is a demand for three types of pick-up:—

(1) A type, frequently called a "play-back," which is used to reproduce directly from the "wax" immediately after an impression has been made, in order to ascertain whether the recording is satisfactory. In this device voltage output is of relatively little importance compared with the necessity for an absolute minimum of wear by the needle.

(2) An instrument which is intended to be used with its own special amplifier, where again the voltage output is of minor importance since it can be so readily augmented in the amplifier.

(3) A type which can be used with a standard broadcast receiving set. This should provide an output of the order of 0·15 volt/mm/cycle/sec.* in order to comply with the present tendency in receiver design.

It is with type (3) that the present paper is primarily concerned.

It may be accepted at the outset that the technique of recording has advanced to a very high standard. The frequency range covered is such as to call for reproducing apparatus capable of dealing properly with frequencies down at least to 50 cycles per sec., and up to the region of 8 000 cycles per sec. In the author's opinion the importance of the lower frequency limit is still not fully appreciated.

Not only has the useful frequency band been very considerably widened, but the amplitude of the groove has been increased, at least in the better-class records. This means that the ratio of recorded note amplitude to that of those unavoidable irregularities which give rise to surface noise or "scratch" has been increased. Full advantage of this can only be taken by the use of electrical pick-ups, since some control of volume of the output becomes necessary. In fact there have been many protests from musically inclined listeners who use mechanical sound-boxes, at the excessive volume given by good modern records.

Considerations of voltage output and of cost of production led the author to conclude that the moving-iron electromagnetic type of generator was the only one likely to prove satisfactory in class (3). In designing this type we have to choose between the methods of construction which are generally known as the "attracted reed" and the "balanced armature." Of these the latter appears to possess two distinct advantages. Firstly, the resultant forces of magnetic attraction on the armature are smaller, and therefore do not necessitate the use of such a high order of stiffness in the armature suspension. Secondly, a comparatively much larger amplitude of armature vibration can be allowed without introducing "rectification" effects in the voltage output. These two points allow a very useful margin of freedom in deciding the dimensions of the armature and pole-pieces and of the constants of the principal vibrating system.

(2) Results of Preliminary Tests.

The results of some preliminary tests, using the method outlined in Appendix 1, on various commercial pick-ups, brought out the following points:—

(1) The existence, in every case, of one or more "resonant" points in the voltage characteristics. The prominence of these peaks varied considerably, and in some cases so affected the output that when the instrument was used for the reproduction of speech and music a clearly noticeable distortion resulted. It appeared probable that corresponding damage was

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* Measured from + peak to − peak of the amplitude of needle-point displacement.

caused to the record. Such a case is illustrated in Fig. 1.

(2) A tendency, with some pick-ups, for the needle to jump out of the groove at frequencies below about 100 cycles per sec. In all cases a distinct vibration of the tone-arm or supporting lever could be felt at low frequencies.

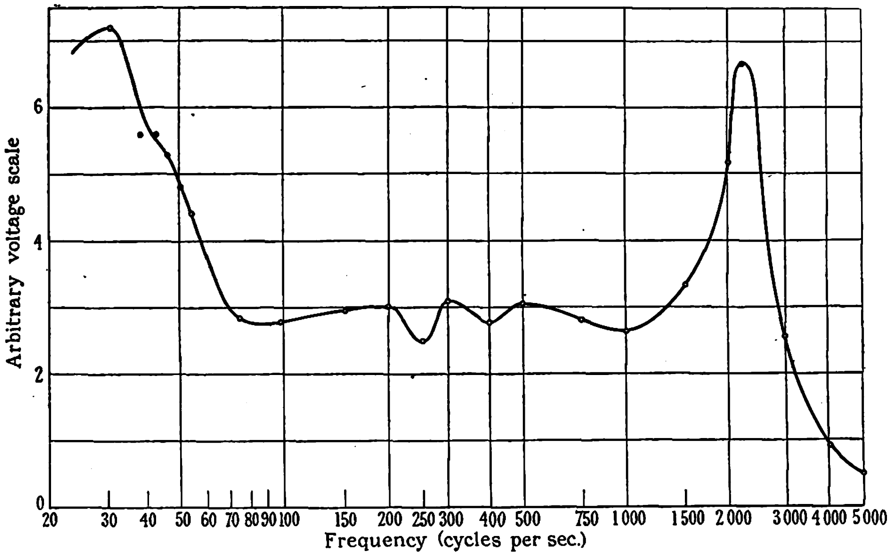

Fig. 1.—Voltage output characteristic of commercial pick-up using "loud" tone H.M.V. needle, showing two principal resonances.

(3) A comparatively poor voltage output at frequencies of 5 000, 4 000 and sometimes even 3 000 cycles per sec. This leads to a distinct lack of "brilliance" in speech and music reproduction.

(3) Experiments on Mode of Vibration of a Pick-up Armature.

The reason for the peak in the characteristic in Fig. 1 at 2 200 cycles is not at first clear. It is true that at a certain frequency the reaction force due to the moment of inertia of the vibrating armature is balanced by that due to its method of suspension, leaving only frictional or damping forces at play. This, however, should only increase the amplitude of vibration at that frequency *for a constant deflecting force*. When the needle-point rests in the groove of a record the amplitude of excursion of the point is governed, however, by the record, and the deflecting force adjusts itself accordingly. Consequently, providing the armature is rigid and the needle-point does not leave the groove there is no reason why there should be a peak in the voltage characteristic at this frequency. To explain the existence of the peak, therefore, it is necessary to assume either that the armature is not rigid or that the needle itself bends very considerably. It was thought worth while to investigate this point experimentally, and the following simple test was devised. The commercial pick-up of Fig. 1 was mounted in an inverted position in a heavy clamp. A certain measure of flexibility (to simulate that existing when the instrument is fitted to a tone-arm) was provided by blocks of rubber (R in Fig. 2). A mirror, about 2 mm square, stuck to the armature as close to the air-gap as possible, reflected a clearly defined spot of light on to a scale at a distance of about 3 m. By this means vibrations of so small a total amplitude as 0·00005 radian could be observed, and 0·0001 radian and upwards could be fairly accurately measured. A constant-amplitude variable-frequency current was passed through the pick-up windings by placing it in the anode circuit of a power valve excited by a heterodyne oscillator. The valve was of the "pentode" class, having a differential resistance of 30 000 ohms. This ensured a sufficient degree of constancy of the current with frequency (for constant voltage input to the grid) up to about 3 000 cycles per sec. Curve A in Fig. 3 shows the result of a test carried out under these conditions. One clearly defined resonance is noticed at 715 cycles per sec. The armature of this generator was of simple shape and its moment of inertia could readily be calculated. The value was $1 \cdot 52$ gramme-cm^2. The stiffness of the suspension was measured by hanging weights on a short length of steel wire clamped in the needle holder and observing the deflection. The mean value obtained was 23×10^6 dyne-cm per radian. From this and the moment of

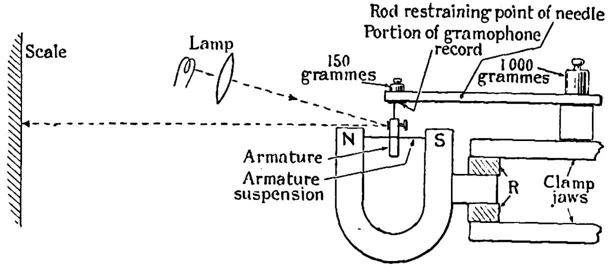

Fig. 2.—Method used for examining the mode of vibration of the armature.

inertia the resonant frequency is found to be 620 cycles per sec.; a result in fair agreement * with the value obtained from Fig. 3.

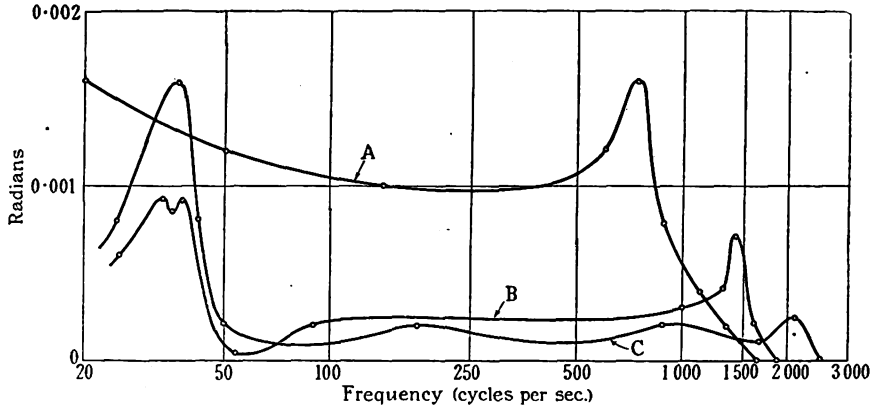

FIG. 3.—Amplitude of armature vibration of commercial pick-up. Vibrations produced electrically; constant input current.
A.—Armature free. B.—Needle-point restrained, "soft" needle. C.—Needle-point restrained, "loud" needle.

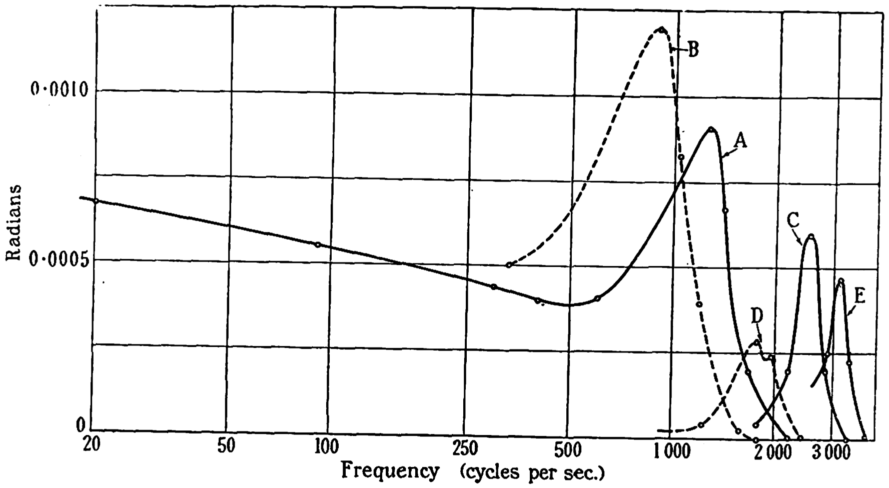

FIG. 4.—Amplitude of armature vibration of experimental pick-up.
A.—Armature free. B.—Armature free, moment of inertia artificially increased. C.—Needle-point restrained, "soft" needle. D.—Needle-point restrained, "soft" needle. E.—Needle-point restrained, "loud" needle.

It will be noted that there is no appreciable peak in the voltage characteristic (Fig. 1) at this frequency.

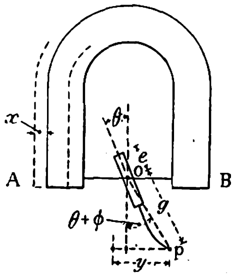

FIG. 5.

The test illustrated in Fig. 2 was than extended by restraining the point of the needle in a manner which reproduced, as closely as possible, the conditions under which the pick-up normally operates. A small portion of gramophone record was firmly stuck to a square-section rod which was then placed in position as illustrated in Fig. 2. The 150-gramme weight corresponded to the weight of the pick-up when in its normal operating position. The readings obtained with the same operating current as before are shown in Fig. 3, curves B and C.

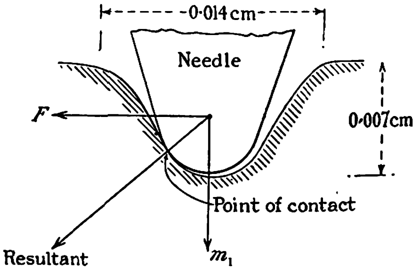

FIG. 6.

It will be seen that the general level of amplitude is

* Compare similar calculation on page 574.

much reduced in curves B and C and that there is no sign of the peak at 620 cycles per sec. Instead, prominent peaks are introduced at 40 cycles and at 1 450 and 2 100 cycles for the "soft" and "loud" needles respectively. The two peaks in curve C correspond almost exactly to those in Fig. 1, and the test demonstrates fairly conclusively that the bending of the needle plays an important part in the performance of the amplifier, particularly at the higher frequencies.

(4) Parasitic Vibrations in the Pick-up Support.

With a simple and rigid construction no complications will arise from parasitic vibrations in the armature itself, except at quite high frequencies, i.e. above 5 000 cycles per sec. On the other hand, trouble may readily arise at lower and more important frequencies from vibrations of the pick-up support or of some part of it. Evidence of this was apparent in several of the output characteristics taken in the course of the work, and the most striking example is illustrated in Fig. 7. In the characteristic A a peculiar irregularity occurs between 200 and 500 cycles per sec. The shape resembles that of the impedance/frequency curve of a coil to which a tuned circuit is coupled, in the neighbourhood of the resonant frequency of the latter. It suggests, therefore, that energy is being absorbed by some system coupled to the pick-up. It was noticed also that the counterbalance weight vibrated appreciably at about 300 cycles per sec. When damping oil was put into the pick-up the effect was very considerably intensified (see curve B).

The counterbalance weight was a sliding fit on the supporting lever and was held in position by a clamping screw. It was thought that by insulating this weight from the rod instead of clamping it rigidly to it the vibrations transmitted by the pick-up along the lever would be absorbed instead of being reflected. The hole through the weight was therefore bored out to a larger diameter and the space so formed between it and the rod was packed with felt. This was sufficient to reduce the irregularity in the characteristic to the negligible proportions illustrated in curve C.

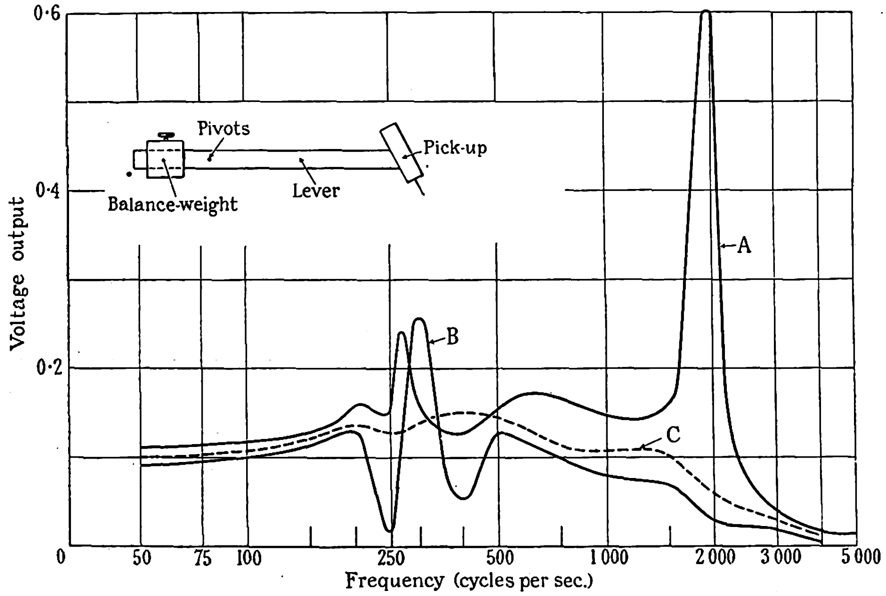

Fig. 7.—Effect of vibration in supporting lever. Balanced-armature pick-up; armature mounted on 0·0085 in. disc.

A.—No added damping. B.—Heavy oil damping. C.—Medium oil damping; balance-weight insulated from lever with felt.

(5) Lamination of Armature and Pole-Shoes.

In all apparatus designed for alternating fields, particularly of high frequency, care is taken to laminate the iron core. It is a matter of some difficulty to do this in the present case owing to the limitations of size.

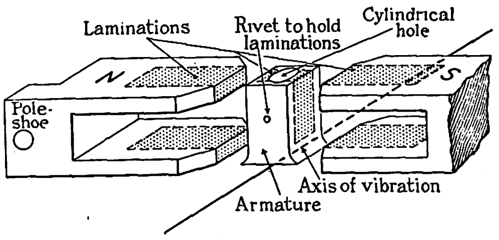

Fig. 8.

Experiments were, however, made to ascertain whether improved performance at 3 000, 4 000 and 5 000 cycles per sec. could be obtained by this means.

The shape of the armature and pole-shoes of the model upon which the experiment was conducted is shown in Fig. 8. The armature consisted in the first place of a short length of annealed mild-steel rod, hollowed out by drilling as shown. A voltage characteristic of this instrument was taken, after which it was disassembled and the portions shown dotted were cut away and replaced by thin stalloy laminations. After reassembling a fresh characteristic was taken. It was found that only slight improvements in voltage and output resulted and that this was more pronounced for frequencies *below* 200 cycles than for those above it. In any case it was not sufficient to justify the complications of construction, and it appeared that improvements at the higher frequencies were more likely to be obtained from reduction in the inertia of the armature. The apparent anomaly of a greater improvement at lower than at higher frequencies may indicate insufficient insulation between laminations; in the author's opinion, however, it is more likely to be due to the difficulty of reassembling such a small instrument to exactly the same gap dimensions and motional constants of the armature as it previously possessed.

TABLE 1.

Cycles per sec.	50	100	250	500	1 000	5 000
V_a volts	0·061	0·071	0·094	0·091	0·075	0·029
V_b volts	0·061	0·066	0·085	0·082	0·065	0·023
V_c volts	0·056	0·064	0·083	0·082	0·065	0·016

TABLE 2.

Cycles per sec.	50	150	500	3 000	4 000	5 000
Output before annealing, volts ..	0·140	0·137	0·164	1·50*	0·101	0·055
Output after annealing	0·167	0·207	0·220	3·0*	0·155	0·084
Percentage increase	19	51	34	100	55	53

* No additional damping was introduced for this experiment, and 3 000 cycles was the principal resonant frequency.

(6) DISTRIBUTION OF ALTERNATING COMPONENT OF THE MAGNETIC FIELD AT DIFFERENT FREQUENCIES.

The experiment just mentioned suggested that the falling off at high frequencies was not due in such large measure as had previously been supposed to the effect of eddy currents on the alternating flux distribution. A further experiment to check this point was carried out.

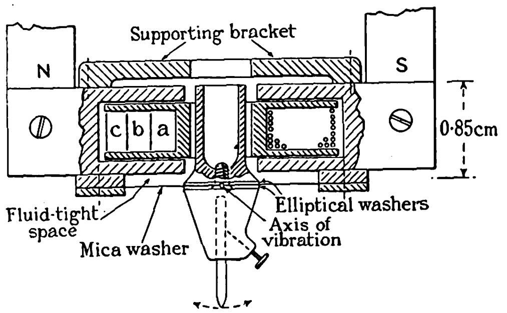

FIG. 9.—Calculated moment of inertia of vibrating system:

Armature (above axis)	0·08	(mass 0·55 gramme)
Needle-clamp	0·08	(mass 0·87 gramme)
Clamping screw	0·17	(mass 0·35 gramme)
Needle	0·12	(mass 0·19 gramme)
	0·45 gramme-cm	

A coil was wound in three sections (a, b and c, Fig. 9) of 2 000 turns each, and the voltage outputs from the three sections were measured and compared. As will be seen from the diagram, the changes in flux distribution due to the motion of the armature will be greatest at the pole-tips. Consequently a given amplitude of vibration will induce a larger voltage in "a" than in "c"; and the higher the frequency the greater will be the ratio of V_a to V_c. In fact it had previously occurred to the author to make use of this by backing-off V_c against V_a and V_b in series, with the object of levelling up the voltage characteristic of the pick-up. Measurement showed, however, that the difference was not actually as great as was anticipated. The figures in Table 1 illustrate the point.

(7) EFFECT OF ANNEALING ARMATURE AND POLE-SHOES.

The opportunity was taken when constructing one model to ascertain the extent of the improvement in output which might be expected from annealing the mild-steel portions of the magnetic circuit. The difficulty in making the experiment was to reconstruct the instrument after annealing to the same dimensions as it possessed originally. In order to reduce as much as possible the uncertainty due to this, the model selected was one which had been constructed with comparatively long air-gaps.

The armature was a short length of mild-steel rod and the pole-shoes were machined from a sheet of the same material. The annealing process consisted of heating the portions in a gas flame to a pale yellow colour and then allowing them to cool slowly by gradually reducing the flame. The operation was spread over a period of about ½ hour.

The results are given in Table 2.

(8) DAMPING THE VIBRATING SYSTEM.

When the reaction force due to the inertia of the armature is balanced by that due to the stiffness of the needle and the armature suspension, the damping alone controls the extent of the vibration. As the frictional forces are ordinarily much smaller than the reaction forces, both voltage output and record wear become excessive at this resonant frequency. Some method of increasing the damping is therefore essential. The means available may be classed as follows:—

(1) To raise the resonant frequency to the neighbourhood of 4 000 or 5 000 cycles.

(2) To couple to the armature a second vibrating system which absorbs energy, either electrically or mechanically.

(3) To increase artificially the damping factor by mechanical means.

(1) If this can be achieved by a reduction of the moment of inertia of the armature it is the most satisfactory way of dealing with the problem. Both the damping "constant" itself, for a given construction, and the force corresponding to a given damping constant, increase with frequency. Consequently, if the resonant frequency is raised to, say, 5 000 cycles per sec., additional damping becomes unnecessary, that inherent in the suspension being sufficient. A sufficient reduction in the inertia of the armature can only be achieved, however, at such a sacrifice of voltage output as to remove the pick-up from the present class as regards sensitivity.

It is much more common to attempt to get the same result by inserting small pieces of rubber between the armature and pole-faces. This is usually spoken of as "damping" the system with rubber. Actually, however, the stiffness of the system is increased to a far greater extent than the damping factor, and this has an undesirable effect on the performance of the pick-up at low frequencies (see equations 8 and 11).

(2) Unfortunately, the degree of coupling between the mechanical vibrating system of the pick-up and the electrical circuit is not sufficiently close to make it feasible to damp the former with a tuned-circuit shunt. It is necessary, therefore, to employ a second mechanical system and to couple it mechanically with the first. A form of construction which makes this possible is described later. Preliminary experiments with the method have given promising results.

(3) It is most commonly attempted to employ rubber for this purpose, as mentioned above. The difficulty of devising a satisfactory construction to this end is considerable. In the case of an electromechanical recorder* it was found necessary to use a rod of gum rubber 25 cm long to provide a non-reactive load sufficient to swamp the reactive forces set up in the vibrating system during operation. The rod was attached to the armature in such a manner that torsional vibrations were set up in it. These were transmitted axially from end to end, and were absorbed by the time they had travelled along the rod and back again. It is apparent, therefore, that if vulcanized rubber, which is presumably far less viscous in nature than gum rubber, is to be employed, its dimensions and disposal must be exceedingly carefully worked out.

The use of viscous liquid, such as a heavy oil, offers a simpler solution to the problem. The difficulty which immediately arises, however, is to design a suitable liquid-tight container.

At least one good commercial pick-up has been constructed on these lines and one of the designs described later employs the same method.

The author has also used the friction set up between two small oily mica surfaces, one carried by the armature and one attached to the pole-shoes. This has proved satisfactory, but suffers from the drawback of needing very careful and frequent adjustment.

"Book" damping has also been tried. This consists of a number of small sheets of tissue paper which are alternatively compressed and released by the motion of the armature. In the author's experience this method also needs frequent adjustment owing to the liability of the paper to become "packed."

(9) Damping Due to Acoustical Output from a Mechanical Sound-Box.

It is well known that the performance, as judged by ear, of a modern mechanical sound-box connected to a well designed tone-arm and horn is remarkably good, despite the somewhat complicated nature of the lever system by which the needle operates the diaphragm, and the fact that the only damping incorporated is that due to the acoustic load. It was thought worth while, therefore, to study the vibration of the operating lever of a sound-box with and without its acoustic load.

The method employed was to mount the permanent magnet, pole-tips and coils of a telephone ear-piece on the outer face of the sound-box. A very small piece of annealed mild steel was firmly attached to the sound-box lever close to the centre of the diaphragm, and the ear-piece was clamped in such a position that the piece of steel formed its armature. Thus the vibration of the lever produced proportional voltages in the ear-piece coils, and these were measured on the valve voltmeter as before. The instrument became, in fact, a combined sound-box and pick-up. As such it was useful for the comparison by ear or microphone of the acoustical output from the gramophone itself with that from the amplifier and moving-coil loud-speaker. By means of a switch in the pick-up circuit, the loud-speaker reproduction from a record could be superimposed on the direct gramophone reproduction, or removed, at will.

In Fig. 10, curve A shows the voltage generated by the sound-box pick-up when operating under normal conditions. Over the frequency range employed it will represent fairly closely the amplitude of vibration of the centre of the sound-box diaphragm. Curve B was taken after the narrow end of the tone-arm had been tightly plugged with cotton-wool, thus preventing sound output through the horn. A prominent resonance point is apparent, under these conditions, at about 1 300 cycles per sec. The effect of the acoustical load in obliterating this resonance is apparent from comparison of the curves. If impedance/frequency characteristics of a horn-type moving-iron loud-speaker are plotted with and without the horn in place, it is seen that the resonance effect of the armature is smothered by the acoustical damping in just the same way.

The curves of Fig. 10 also indicate how closely the mechanical and acoustical systems of a well designed gramophone are coupled, since the numerous horn resonance points impress themselves upon the vibrations of the lever system. When the same tone-arm and horn were used in conjunction with a different sound-box, the cavities in which were not so well adjusted to the aperture in the tone-arm, this effect was not nearly so pronounced, although a useful degree of damping was provided by the acoustical load. The results of a measurement under these conditions are given in Fig. 11.

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* *Bell Telephone Laboratories Reprint*, B—377, 3, p. 5.

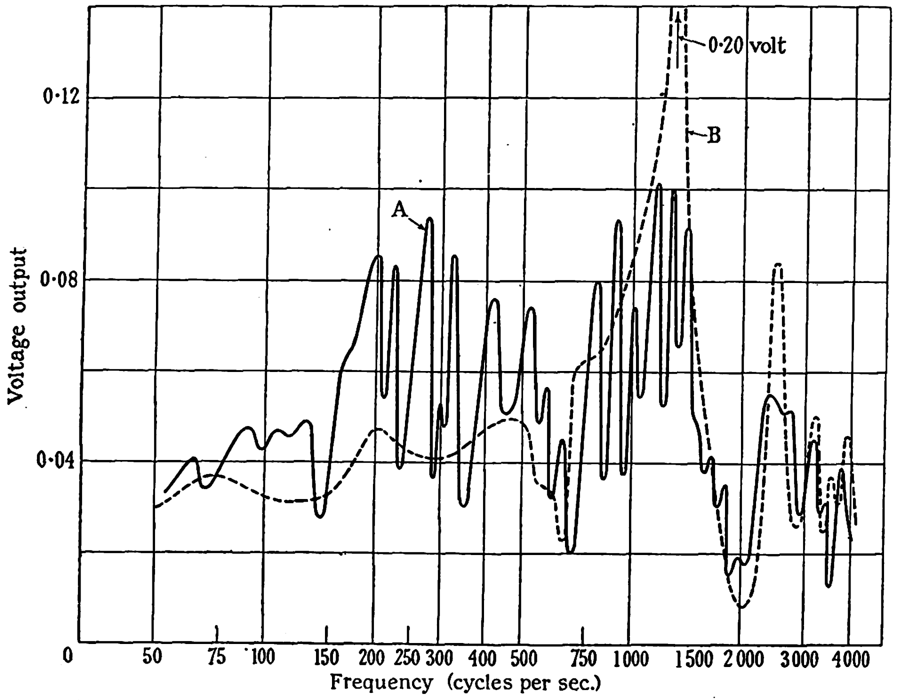

FIG. 10.—Sound-box lever as armature of electromagnetic generator.

A.—Sound-box, tone-arm and horn in normal operation. B.—Acoustic output prevented by plugging tone-arm with cotton-wool.

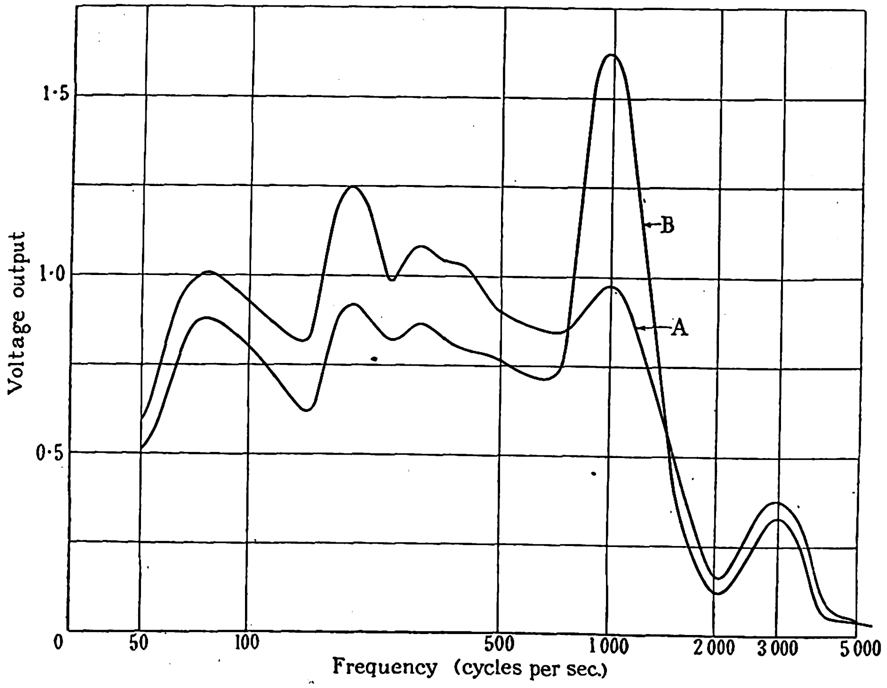

FIG. 11.—Voltage output of sound-box pick-up.

A.—When loaded acoustically. B.—With tone-arm closed, preventing the full acoustic output.

In comparing the curves of Fig. 10 with those of Fig. 11 it is noticeable that the output falls off above 2 000 cycles much more in the latter case than in the former. This was doubtless due to the greater rigidity of the lever system in the former. An appreciable lack of brilliance in the reproduction from the second sound-box, both in the case of the electrical and the mechanical methods, was very apparent.

These curves show clearly, when compared with Fig. 12, the advantage to be gained by the use of the simple rigid vibrating system of the electrical pick-up as compared with the more complicated one necessary in the case of the sound-box.

(10) RÉSUMÉ OF THE THEORY OF OPERATION.

In Appendix 2 the equations of motion of the vibrating armature of a pick-up are examined and it is found that the position on the scale of frequency of the principal resonance is governed by the inertia of the armature and the sum of the stiffnesses of the armature suspension and of the needle. In a well designed instrument the stiffness of the suspension will be small compared with that of the needle (of the order of one-tenth), so that the latter is virtually the governing factor. In fact the only means available to the designer to raise the principal resonance to a high figure (as suggested in Section 8) is to reduce the armature inertia.

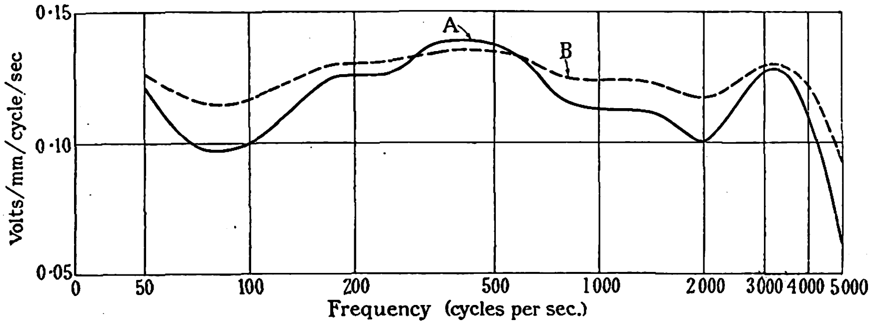

FIG. 12.—Voltage characteristic of experimental model used with a 6 : 1 step-up transformer.

A.—To a scale of volts (measured at secondary of transformer). B.—To a scale of log (volts).

It is also seen that a state of resonance arises at a very low frequency, the pick-up vibrating as a whole about the point of the needle and the pivot of the tone-arm or lever. This frequency is governed by the stiffness of the suspension and the inertia of the body of the pick-up about the axis of suspension of the armature. It is not a difficult matter, therefore, to reduce it to so low a figure that its effect is of no importance, by increasing the mass of the pick-up and its support. Except for the two resonant conditions just mentioned, there appears to be no reason why the amplitude/frequency characteristic of the armature of a pick-up should not be a horizontal straight line up to the point at which it is no longer justifiable to assume it to be a rigid structure.

An attempt is made in Appendix 3 to deduce the conditions under which the needle is liable to leave the groove.

It is seen from equation (11) that the inertia of the pick-up about the support pivots should be large, so that $1/(\omega^2 m)$ may be small compared with $g^2/\mathbf{T}$. Also that **T**, the suspension control constant, should be as small as possible so that $m_1 g$, the bearing pressure on the needle, may be reduced to a minimum.

It is a common experience to find that in a commercial pick-up which has been "damped" by inserting small rubber blocks in the air-gap, the value of **T** has been raised to such a value that the needle will not follow the groove of a test record at 100 or even 150 cycles per sec. without holding it down (i.e. raising $m_1 g$ considerably).

(11) METHOD OF DESIGN.

The reasons for adopting the balanced armature system have already been given in Section (1). It remains to deduce from the foregoing data and those in Appendices 2 and 3 the best dimensions and constants for the vibrating system.

The most important single property of this system is its moment of inertia, and every effort must be made to reduce it to a minimum. The system must consist of the needle itself, needle-clamp and armature. In the case of types (1) and (2) (see page 566) it is possible to dispense with a separate portion for the armature and to use either the needle or the clamp for the purpose. An attempt was made to use the clamp in this double role in the first model which the author constructed to fulfil the conditions of type (3), but it was then found difficult to incorporate a damping device within the limited space involved, and the attempt was abandoned.

It is an advantage to suspend the system at its mid-point, since for a given mass this leads to the lowest moment of inertia and also facilitates the application of additional damping.

Analysis of the performance of the commercial instrument of Fig. 1 leads to the conclusion that its inertia constant is much too high (1·5 gramme-cm^2). The experimental armature was therefore designed so that **I** should be not more than 0·5 gramme-cm^2. This was achieved by making the armature portion hollow (see Fig. 9). It is well known that a given mass distributed in the form of a hollow cylinder or rectangular block will possess much greater rigidity than the same mass in the form of a rod. Two further advantages accrue from this construction. Skin effect would in any case restrict the flux to the surface of the armature at the higher frequencies. Hollowing it out will therefore tend to produce a more uniform characteristic; while the greater diameter of armature involved lengthens the magnetic paths straight from pole-face to pole-face for a given length of air-gap between armature and pole-face.

The hollow in the armature has also been used for coupling the system with rubber or oil (i.e. "capacity" or "resistance" coupling) to a second vibrating system mounted above the first, to provide increased damping.

The armatures in the experimental models subsequently built were mounted on mica discs as shown in Fig. 9. Mica was used since it is non-magnetic and has a high stiffness/mass ratio. Moreover, having decided on a suitable thickness (0·010 in. was employed finally) the discs are easily made to specification and are very uniform in their properties.

In order to prevent motion of the armature in a plane parallel to the pole-faces due to irregularities in the record groove, two elliptical washers were clamped into the positions shown in Fig. 9. The minor axes of these were made equal to the armature diameter, and the major axes were made about twice as long. Measurement showed that this rendered the stiffness of the support in the plane parallel to the pole-faces nearly twice that in the plane of normal armature vibration.

The mica disc was clamped at its outer edge between two heavy rings, with carefully turned flat faces, and these in their turn were bolted to the pole-pieces (Fig. 9).

The thickness of the disc was adjusted by experiment until it was just sufficient to prevent the armature sticking to the poles by magnetic attraction. The value of **T** was then found to be $13 \cdot 8 \times 10^6$ dyne-cm per radian, which is little more than half the value for the commercial instrument previously tested. The above value was determined by deflecting the armature by a known torque in the usual manner. It appears probable that at high frequencies the effective value of **T** increases due to the mode of vibration of the disc and the resilience of the air in the cavities around the armature, since the values obtained from the tests illustrated in Fig. 4 are considerably higher than this. Thus the resonant frequency shown in curve A would be 890 cycles per sec. from $\mathbf{T} = 13 \cdot 8 \times 10^6$ dyne-cm per sec. and $\mathbf{I} = 0 \cdot 45$ gramme-cm^2, whereas it is actually 1 250 cycles per sec., indicating either an increase in the effective value of **T** at these frequencies, or an error in calculating **I**.

The values of **I** calculated from these curves, in terms of a known increment of moment of inertia (attaching a known weight at a measured distance from the axis), were 0·42 and 0·51 gramme-cm^2 (0·45 gramme-cm^2 calculated from dimensions). It was difficult to measure accurately the effective radius of gyration of the added mass, owing to the small dimensions of the armature and the irregularity of its contour. The value of **T** calculated from the curves, using $\mathbf{I} = 0 \cdot 45$ gramme-cm^2, is 30×10^6.

It has been seen (equation 11) that **T** should have as small a value as possible to reduce the tendency for the needle to leave the groove and the consequent wear and tear on the record, at frequencies of the order of 100 cycles per sec. At these low frequencies it is safe to assume that the effective value of **T** approximates much more closely to the value $13 \cdot 8 \times 10^6$ (obtained statically) than 30×10^6 (obtained dynamically at 1 000 cycles per sec. and over). This is confirmed by the comparative freedom of this model from tone-arm vibration at 100 cycles per sec.

That the value of **T** (measured statically) was sufficient to prevent amplitude distortion is indicated by the linear relationship found to exist between deflecting torque and angular displacement for the armature, up to values far in excess of the amplitudes obtained in operation, even at low frequencies.

The air-gap length was about 0·3 mm, whereas the maximum amplitude of displacement of the armature in the gap was about 0·05 mm.

Having thus determined **I** and **T**, the remaining important quantities are the mass of the pick-up itself and the bearing pressure on the needle. From consideration of equation (11) it is seen that the former should be as large as possible *—of the order of 300 or 400 grammes—while the latter should be no more than is sufficient to prevent the needle leaving the groove at the lowest frequencies and the largest amplitudes of vibration. These conditions may be fulfilled by connecting the pick-up very rigidly to a massive and rigid supporting lever. The weight of the lever should be so disposed about its pivots that the bearing pressure on the needle is about 100 grammes. This, assuming the given values of g and **T**, provides a sufficient margin of safety.

It will be seen from Fig. 9 that the construction of this model leaves a space above the mica disc and around the armature which may be rendered liquid-tight by varnishing, and may then be filled with oil of suitable viscosity to provide the necessary additional damping.

The voltage characteristic for this instrument is given in Fig. 12, both to a scale of volts/mm/cycle/sec. and also to the logarithm of this quantity.

(12) Regulation of Voltage Output.

It is usual to employ a simple resistance potential-divider for this purpose. Unless its ohmic resistance is very high, however, this will cause considerable falling off of output in the upper part of the frequency scale.

The coil of the experimental instrument just described had 6 000 turns and an inductance, measured at 500 cycles per sec., of 2·25 H. Neglecting its resistance, this corresponds to an impedance of about 700 ohms at 50 cycles and 70 000 ohms at 5 000 cycles. Consequently even a 70 000-ohm potential divider would lead to a 50 per cent loss of output voltage at 5 000 as compared with 50 cycles per sec. A tapped choke, having a liberal iron core in order to prevent excessive voltage-drop at low frequencies, and an inductance of at least 10 H, would be preferable for the purpose.

It is even better to use a transformer with a tapped secondary. The pick-up can then be wound with a few hundred turns of heavier-gauge wire, thus reducing the tendency to oscillation of the amplifier when long leads are used to connect the two.

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* Thus making the term $1/(\omega^2 m)$ in equation (11) negligible compared with $g^2/\mathbf{T}$ at 100 cycles per sec.

ACKNOWLEDGMENT.

The work was carried out at the Telegraphy and Telephony Laboratories of the City and Guilds (Engineering) College, and the author is indebted to Prof. C. L. Fortescue, O.B.E., Member, and to Prof. E. Mallett, Member, for facilities placed at his disposal and for helpful suggestions made.

APPENDIX 1.

PRELIMINARY EXPERIMENTS. THE MEASUREMENT OF VOLTAGE OUTPUT.

A set of sine-wave "constant power" records covering a range of frequencies from 50 to 5 000 cycles per sec. was employed to drive the pick-up. The amplifier and valve voltmeter for measuring the output presented little difficulty. The voltmeter was of a type previously described by the author.* The rapidity of indication of this type enables readings to be obtained in very rapid succession and with a minimum of wear on the record—an important point when a large number of comparative tests are carried out.

TABLE 1.

Lever setting	0	1	2	3	4	5	6	7
Speed (r.p.m.)	46·5	58·8	67·4	74·0	79·4	84·3	88·3	92·3
Speed (r.p.m.) taken at a different time	47·4	58·5	67·4	73·9	79·6	84·2	88·2	92·0

TABLE 2.

Frequency (cycles per sec.)	50	75	100	150	200	250	300	400	500	750	1 000	1 500	2 000	3 000	4 000	5 000
	1·0	0·91	0·78	0·80	0·47	0·42	0·66	0·50	0·40	0·53	0·53	0·56	0·67	0·56	0·48	0·32

To obtain readings intermediate between the fixed frequencies (50, 75, 100 and 150 cycles per sec. and so on) provided by the records, the speed of the mechanical motor driving the record turn-table was varied by means of the mechanical governor. A range of speed of from 46 to 88 r.p.m. was thus rendered available. The speed at any given setting of the control lever was found to be remarkably constant. This is illustrated by the readings set out in Table 1.

The range of speed variation was of the greatest use in taking the characteristics, as it enabled points of inflexion in the curve to be accurately ascertained. For speeds other than that at which the record is intended to be run, correction of the voltage reading has, of course, to be made.

Although the product of amplitude and frequency was supposed to be constant over the whole of the records, it was soon suspected that this was only approximately the case. To ascertain the extent to which the product varied from one frequency to the next, the voltage output from a good pick-up on the 50-cycle groove when running at, say, 90 r.p.m. was compared with that from the 75-cycle groove running at 60 r.p.m. The frequency is the same in both cases and, provided the amplitude characteristic of the pick-up used is reasonably good, the ratio of the voltages is the ratio of the groove amplitudes. By a succession of such measurements each groove may be compared with the next in the series. The results of this test are shown in Table 2.

The figures given express the actual amplitude as a decimal of that which would render the product with frequency equal to the corresponding product for the 50-cycle groove.

The test was found to be difficult to carry out with accuracy as the groove for any one frequency varied in amplitude slightly from point to point, and accidental irregularities were troublesome. Moreover, the errors are obviously cumulative in ascending the frequency scale, and no simple method of check from, say, the 500-cycle to the 50-cycle groove suggests itself. The departures from the ideal in the matter of amplitude are so serious, however, that even an approximate correction is valuable.

The measurement of absolute amplitude of the grooves was carried out by driving the pick-up from a tuning fork which was excited by a valve oscillator. The vibration of the tip of the fork was observed and measured by a microscope whilst the needle of the generator was allowed to rest on a small piece of broken gramophone record firmly attached to the prong close to the tip. The amplitude of vibration of the fork was adjusted by controlling the current from the maintaining valve until the voltage generated by the pick-up was the same as that produced when it was driven by a record of the same frequency.

APPENDIX 2.

THEORY OF THE PICK-UP.

We may consider the generator to have a total mass of m grammes, and to be mounted on a tone-arm which exerts negligible control and frictional forces. The armature is assumed to have a moment of inertia of $\mathbf{I}$ gramme-cm^2, and its suspension to exert a control torque of $\mathbf{T}$ dyne-cm per radian, together with a frictional force A dyne-cm per radian per sec. In addition, the armature itself is assumed to be rigid, whilst the needle is not rigid, i.e. it is capable of bending when its point is deflected. The effect of the stiffness of the needle on the armature may be represented by an additional control torque $\mathbf{T}_n$ dyne-cm per radian, the angle considered being that subtended by the point of the needle when bent, and its mean position, at the axis of vibration.

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* *Proceedings of the Physical Society of London*, 1927–8, vol. 40, p. 14.

Let y be the instantaneous displacement of the point p (Fig. 5) by the action of the record groove. This will result in a bodily displacement x of the generator, an angular displacement θ of the armature, and an angular displacement $(\theta + \phi)$ of p about the axis 0.

Let the horizontal component of the forces exerted by the groove at this instant be F dynes. This is equivalent to an equal force acting horizontally through 0 and a couple Fg acting on the armature.

The reaction couple acting on the armature

$$\begin{aligned} &= \mathbf{T}\theta + Ad\theta/dt + \mathbf{I}d^2\theta/dt^2 \quad . \quad . \quad . \quad (1) \\ &= Fg \end{aligned}$$

Also, along the axis AB we have

$$F = md^2x/dt^2 \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and, for the bending of the needle,

$$Fg = \mathbf{T}_n\phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

If the displacement of p varies harmonically and the resultant reaction forces are as given in the above equations, the force exerted by the groove will be harmonic and so also will the displacement x, θ and ϕ.

Therefore we may write

$$\begin{aligned} F'g &= \mathbf{T}\theta' + jA\omega\theta' - \omega^2\mathbf{I}\theta' \quad . \quad . \quad . \quad (4) \\ &= \alpha\theta' \end{aligned}$$

and $$F' = -\,\omega^2 mx' = -\,\beta x' \quad . \quad . \quad . \quad (5)$$

Where F' and θ' are vectors representing harmonically varying quantities.

The alteration in gap length due to the above displacement is $= e\theta$, and the movement of the needle-point is

$$x + g(\theta + \phi)$$

$e\theta/[x + g(\theta + \phi)]$ may be called the "output factor" of the pick-up, and would have a value e/g, independent of frequency, in the ideal instrument.

Taking R.M.S. values we have

$$\begin{aligned} \frac{e\theta'}{x' + g(\theta' + \phi')} &= \frac{e(g/\alpha)F'}{F'/\beta + g(F'g/\alpha + F'g/\mathbf{T}_n)} \\ &= \frac{eg/\alpha}{1/\beta + g^2(1/\alpha + 1/\mathbf{T}_n)} \\ &= \frac{eg}{\left\{(g^2/\mathbf{T}_n - 1/\omega^2 m)\right\}(\mathbf{T} - \omega^2\mathbf{I} + jA\omega) + g^2} \end{aligned}$$

Simplifying by putting $e = g$ and re-arranging, we have

$$\begin{aligned} \frac{e\theta'}{x' + g(\theta' + \phi')} &= \frac{\mathbf{T}_n\omega^2 mg^2}{[(\omega^2 mg^2 - \mathbf{T}_n)(\mathbf{T} - \omega^2\mathbf{I}) + \mathbf{T}_n\omega^2 mg^2] + jA\omega(\omega^2 mg^2 - \mathbf{T}_n)} \quad . \quad . \quad . \quad . \quad (6) \\ &= \frac{\mathbf{T}_n\omega^2 mg^2}{y + j\delta} \end{aligned}$$

the amplitude of which is

$$\frac{\mathbf{T}_n\omega^2 mg^2}{\sqrt{[y^2 + \delta^2]}}$$

The values of the quantities involved, in the case of the generator of Fig. 1, are as follows:—

$m = 135$ grammes, $\mathbf{I} = 1{\cdot}52$ gramme-cm^2, $g = 2$ cm,
$\mathbf{T} = 23 \times 10^6$ dyne-cm per radian

At 3 000 cycles per sec, $\omega^2\mathbf{I} = 5{\cdot}4 \times 10^8$ and $\omega^2 mg^2 = 19{\cdot}2 \times 10^{10}$.

It is assumed, and is confirmed later, that at this and neighbouring frequencies $\mathbf{T}_n$ is negligible in comparison with $\omega^2 mg^2$, and y (equation 6) then reduces to

$$\omega^2 mg^2(\mathbf{T} - \omega^2\mathbf{I}) + \mathbf{T}_n\omega^2 mg^2$$

This indicates a state of resonance when

$$\mathbf{T}_n + \mathbf{T} - \omega^2\mathbf{I} = 0 \quad . \quad . \quad . \quad . \quad (7)$$

made possible by the bending of the needle. This is seen to occur for a "loud" needle at 2 100 cycles per sec. in both Figs. 1 and 3. Substitution of the known values for $\mathbf{T}$, $\mathbf{I}$ and ω in equation (7) gives $\mathbf{T}_n$ the value 240×10^6 dyne-cm per radian.

At 30 cycles per sec. $\omega^2\mathbf{I} = 5{\cdot}4 \times 10^4$ and $\omega^2 mg^2 = 19{\cdot}2 \times 10^6$.

At this and lower frequencies we may neglect $\omega^2\mathbf{I}$ in comparison with $\mathbf{T}$, when y becomes

$$(\omega^2 mg^2 - \mathbf{T}_n)\mathbf{T} + \mathbf{T}_n\omega^2 mg^2 \quad \text{or} \quad (\mathbf{T} + \mathbf{T}_n)\omega^2 mg^2 - \mathbf{T}_n\mathbf{T}$$

When $$\omega^2 mg^2 = \frac{\mathbf{T}_n\mathbf{T}}{\mathbf{T} + \mathbf{T}_n} \simeq \mathbf{T}_n \quad . \quad . \quad . \quad . \quad (8)$$

$y = 0$, indicating a state of resonance in the operation of the pick-up, the instrument vibrating as a whole about the point of the needle as axis. Such a state of vibration is known to exist at low frequencies, being made apparent by feeling the instrument with the tips of the fingers.

Substituting numerical values in the above expression, the resonant frequency is found to be 32 cycles per sec., which agrees with the value indicated in Figs. 1 and 3. This peak may readily be removed to a still lower frequency, if necessary, by increasing the mass of the pick-up or by attaching it rigidly to a massive supporting lever. The mass of the lever should, of course, be distributed in such a manner as to prevent excessive bearing pressure on the needle point.

At frequencies above about 3 000 cycles per sec. it is inadmissible to assume rigidity of the armature. The voltage output will fall off, moreover, owing to eddy-current effects in the magnetic circuit. The high-frequency peak may therefore serve the useful purpose of maintaining the voltage output at frequencies at which this would otherwise decrease. To achieve this it should occur at at least 3 000 cycles per sec.

APPENDIX 3.

Tendency of the Pick-up Needle to Leave the Record Groove.

The profile of the groove in a record is approximately as shown in Fig. 6, and the forces exerted by the needle on the groove are illustrated there. If F becomes greater than mg the direction of the resultant force will subtend an angle of more than 45° with the vertical and the needle point will leave the groove. The tendency for this to happen is greatest at the lowest frequencies, when the amplitude of vibration is greatest. At such frequencies $\mathbf{I}d^2\theta/dt^2$ is small compared with $\mathbf{T}\theta$, so that the reaction force exerted by the needle point becomes

$$F = md^2x/dt^2 = \frac{\mathbf{T}\theta + Ad\theta/dt + \mathbf{T}_n\phi}{g}$$

or

$$F' = -\,\omega^2 mx' = \frac{\mathbf{T}\theta' + jwA\theta' + \mathbf{T}_n\phi'}{g}$$

At low frequencies the amplitudes of x and θ are high compared with ϕ, so that

$$F' \simeq \frac{\mathbf{T}\theta' + j\omega A\theta'}{g}$$

As previously shown, $y = x + g\theta$, hence

$$y' = -\,F'/(\omega^2 m) + g^2F'/(\mathbf{T} + j\omega A)$$

$$= F'\left(\frac{g^2\mathbf{T}}{\mathbf{T}^2 + \omega^2A^2} - \frac{1}{\omega^2 m} - \frac{g^2 jA\omega}{\mathbf{T}^2 + \omega^2A^2}\right) = F'(a - jb) \quad (9)$$

It has been seen that if $F_{max.}$ exceeds m_1g* the needle will leave the groove, i.e.

$$y_{max.} \ngtr m_1g\sqrt{[a^2 + b^2]} \quad . \quad . \quad . \quad (10)$$

The tendency to leave the groove first becomes apparent, when using constant-power test-records, when the frequency is reduced to 100 cycles per sec. or lower. At this frequency we may neglect ω^2A^2 in comparison with $\mathbf{T}^2$ in equation (9), which reduces equation (10) to

$$y_{max.} \ngtr m_1g\left(\frac{g^2}{\mathbf{T}} - \frac{1}{\omega^2 m}\right) \quad . \quad . \quad . \quad (11)$$

Inserting numerical values, $y_{max.} = 0{\cdot}0205$ cm. The amplitude of the constant-power record of this frequency was 0·0037 cm, which is less than a fifth of the permissible value. At 50 cycles per sec. $y_{max.} = 0{\cdot}0131$ cm, while the groove amplitude was 0·0075 cm, or more than one-half of the permissible value. As might be expected from this, this particular pick-up followed the 50-cycle groove without jumping, although with considerable tone-arm vibration. Unfortunately, the values of g, $\mathbf{T}$ and m were not determined for the instruments which left the low-frequency grooves when under voltage test.

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* It should be noted that the mass which provides the vertical force m_1g will not be the same as that which provides the horizontal force ω^2mx' in the case of a pick-up which is rigidly attached to a lever and counterbalance weight. m_1 will then be considerably less than m, owing to the effect of the counterbalance weight.

FREQUENCY STABILIZATION OF VALVE OSCILLATORS.

By Professor E. MALLETT, D.Sc., Member.

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SUMMARY.

The addition of a series inductance of suitable value to the anode circuit of a valve oscillator results in the frequency of the oscillations generated being independent of fluctuations in the valve constants.

There is no need to stress the importance of definitely fixing the frequency of transmitting stations, and the general practice to-day is towards using master oscillators of quite small power output to provide, through a series of amplifiers if necessary, the necessary grid swing of the power valves. Valve-maintained tuning-forks with frequency multipliers, and valve-maintained quartz crystals, are often used as the master oscillators on account of the great degree of frequency stability secured. The ordinary valve oscillator, however, has advantages, such as ease of frequency adjustment and simplicity of apparatus, not possessed by the mechanical oscillators, and, were it not for the frequency drift commonly encountered, it would undoubedly be far more used.

(1) THEORETICAL.

Considering the common type of oscillator in which an oscillatory circuit LRC is connected to the anode and a grid coil is coupled with L by a mutual inductance M, the frequency departures from the value $f = 1/\{2\pi\sqrt{(LC)}\}$ may conveniently be divided into two groups, primary and secondary. In the first group may be placed changes in the LC value itself, such as alteration of the effective value of L by a load coupled with L, and by grid currents flowing in the grid coil. The first of these is minimized by using the oscillator as a master, that is, by coupling to a second valve in which no grid current flows, and the second by using a bright-emitter valve showing definite saturation and having sufficiently high anode and grid biasing voltages, under which circumstances oscillations may be maintained without grid current flowing. These devices do not entirely avoid departures of this kind as there remain the grid-filament capacities through which currents flow, and the anode-filament capacity which shunts the condenser; but these are not likely to change.

The second group comprises the frequency departure imposed by the constants of the valve itself, and includes alterations due to change of anode- and filament-battery voltages, and of filament emission. The main effect of these changes on the frequency is through their alteration of the internal resistance R_a of the valve.

For an oscillator such as the one under consideration, neglecting the effects of valve capacities, the text-books find

$$\omega = \sqrt{\left[\frac{1}{CL}\left(1 + \frac{R}{R_a}\right)\right]} \quad . \quad . \quad . \quad (1)$$

for determining the frequency of the oscillations. Thus any change in R_a definitely affects the frequency. Suppose now that a series impedance Z' (inductance L', resistance R') is placed in the anode circuit as indicated in Fig. 1. Writing the parallel impedance of the LRC circuit Z_p and the series impedance Z, calling the anode current I_a and the current through L, I_1 (I_a and I_1 being vector currents), and supposing for a moment that a voltage E of frequency $\omega/(2\pi)$ is induced in the grid coil from an external source, then

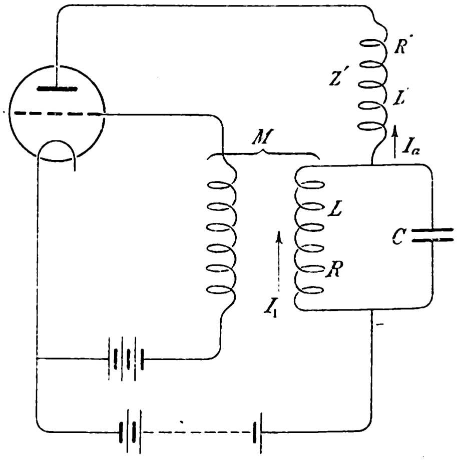

FIG. 1.

$$I_a = \mu E/(R_a + Z' + Z_p) \quad . \quad . \quad . \quad (2)$$

and

$$I_1 = -\frac{j}{\omega CZ} I_a \quad . \quad . \quad . \quad . \quad (3)$$

and the grid voltage induced by I_1 is $V_g = j\omega MI_1 = MI_a/(CZ)$. Hence E in (2) must be replaced by $E + V_g$, giving

$$I_a = \frac{\mu}{R_a + Z' + Z_p}\left(E + \frac{M}{CZ} I_a\right)$$

i.e.

$$I_a\left(R_a + Z' + Z_p - \frac{\mu M}{CZ}\right) = \mu E$$

In order that oscillations may persist when E is made zero, the left-hand side of this expression must also be zero, whence

$$R_a + Z' + Z_p - \frac{\mu M}{CZ} = 0 \quad . \quad . \quad . \quad (4)$$

Writing for Z, Z_p, and Z', their values, viz.

$$Z = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

$$Z_p = (R + j\omega L)\left(-\frac{j}{\omega C}\right)\Big/\left\{R + j\left(\omega L - \frac{1}{\omega C}\right)\right\}$$

and $Z' = R' + j\omega L$

equation (4) gives

$$CR(R_a + R') - \omega CL'\left(\omega L - \frac{1}{\omega C}\right) + L - \mu M$$
$$+ j(R_a + R')\left(\omega L - \frac{1}{\omega C}\right)C + j\omega L'RC - j\frac{R}{\omega} = 0$$

Equating the imaginary terms to zero yields

$$\omega^2 = \frac{1}{LC} \cdot \frac{R_a + R + R'}{R_a + R' + (L'/L)R} \quad . \quad . \quad (5)$$

for the frequency.

Note that if $R' = L' = 0$, (5) becomes (1). Note also that if $L' = L$, (5) becomes

$$\omega^2 = 1/(LC) \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and the frequency is quite independent of the valve constants.

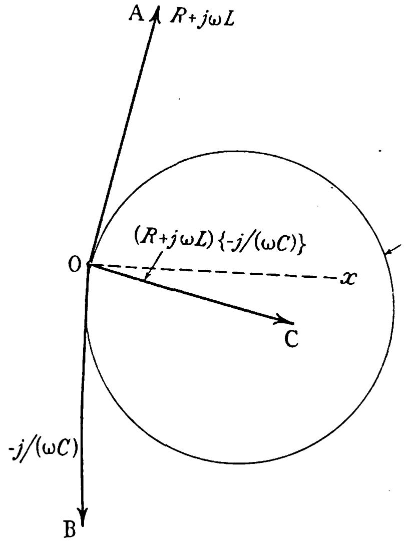

FIG. 2.

Equating the real terms to zero gives for the condition of maintenance

$$CR(R_a + R') - \omega CL'\{\omega L - 1/(\omega C)\} + L = \mu M$$

If $L' = R' = 0$ this becomes the well-known expression

$$CRR_a + L = \mu M$$

whereas if $L' = L$, so that $\omega = 1/(LC)$, it becomes

$$CR(R_a + R') + L = \mu M \quad . \quad . \quad . \quad (7)$$

These conclusions can be arrived at graphically in an illuminating manner. The condition for oscillations is, from (4),

$$R_a + Z' + Z_p - \frac{\mu M}{CZ} = 0 \quad . \quad . \quad . \quad (8)$$

The locus of $1/Z$ is a circle with a horizontal diameter of length R, and the complex quantity $(R + j\omega L)\{-j/(\omega C)\}$ is found in Fig. 2, where OA = $(R + j\omega L)$, OB = $-j/(\omega C)$, and OC is the product of these two and varies very little with the frequency-changes involved.

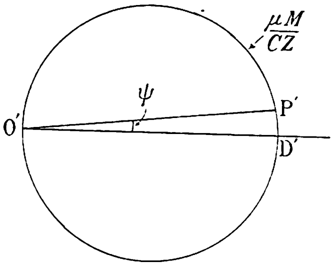

FIG. 3.

Thus the locus of Z_p is very nearly a circle drawn with its diameter in the direction OC; the diameter is the complex quantity $(R + j\omega L)\{-(\omega C)\}/R$.

Fig. 3 shows the locus of $\mu M/(CZ)$ — a circle with a horizontal diameter O′D′ of length $\mu M/(CR)$.

The vector diagram corresponding to (8) is drawn in Fig. 4. OA is made equal to R_a, AA′ to R', and $A'B$ to $j\omega L'$. From B the Z_p circle is drawn as in Fig. 2. To complete the diagram the subtraction of $\mu M/(CZ)$ must bring the point back to O, i.e. a point P must be found on the Z_p circle, such that OP = $\mu M/(CZ)$.

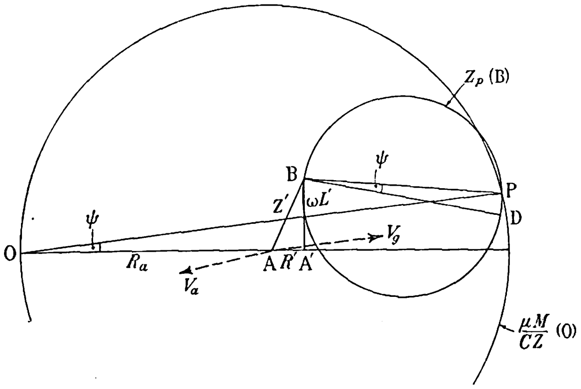

FIG. 4.

It is necessary therefore that O′P′ in Fig. 3 drawn parallel to OP in Fig. 4 shall make the same angle ψ with the diameter O′D′ that BP makes with BD in Fig. 4. The angle ψ determines the frequency, and the extent to which the circle of Fig. 3 must be enlarged to make O′P′ = OP determines M. In the diagram the frequency is below resonance. If A′B (i.e. $\omega L'$) is so adjusted that D falls on OA produced, then the point P must fall on D, P′ falls on D′ and the frequency is that of resonance of the circuit, i.e. $\omega^2 = 1/(LC)$.

Since $\mathrm{BD} = (R + j\omega L)\left(-\frac{j}{\omega C}\right)/R = \frac{L}{CR} - j \cdot \frac{1}{\omega C}$ it is clear that D will fall on the axis when $\mathrm{A'B} = 1/(\omega C)$; i.e. $\omega L' = 1/(\omega C)$ or $L' = 1/(\omega^2 C) = L$, and that then

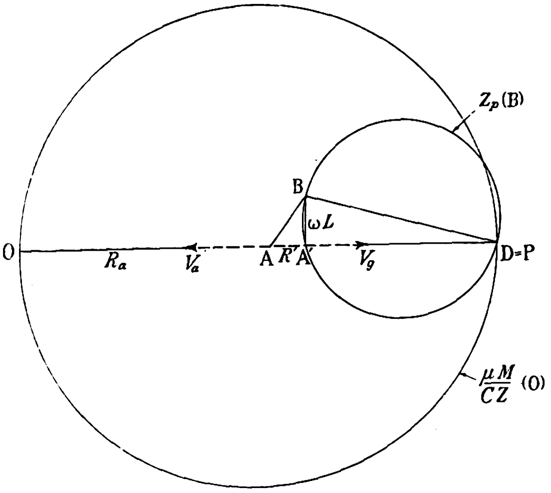

FIG. 5.

$\mathrm{O'D'} = \mathrm{OD}$, or $\mu M/(CR) = R_a + R' + L/(CR)$ in agreement with (7). The diagram is now as drawn in Fig. 5.

$$\text{Since} \quad V_a = -I_a(Z' + Z_p)$$
$$= -I_a(\mathrm{AB} + \mathrm{BD}) = -I_a \times \mathrm{AD}$$

V_a is drawn horizontally to the left from A.

$$\text{And since} \quad V_g = \frac{M}{CZ} I_a$$
$$= \frac{M}{CR} I_a.$$

V_g is drawn horizontally to the right from A. V_a and

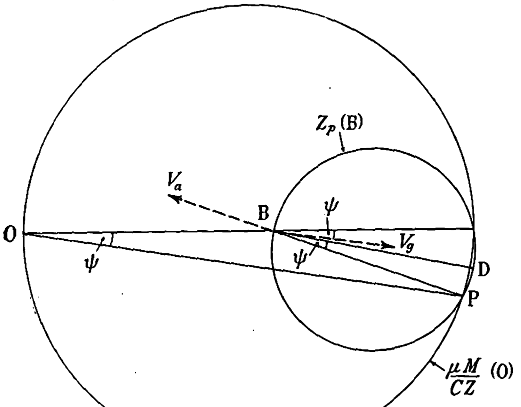

FIG. 6.

V_g are thus in exact phase opposition. With Z' omitted, that is in the usual circuit, the vector diagram is as drawn in Fig. 6, and the resonant frequency is higher than resonance. V_a is drawn in extension of PB and V_g is parallel to OP; there is not exact phase opposition. Similarly, in Fig. 4, V_a is drawn in the direction PA produced, and V_g is drawn parallel to OP. Here again there is not exact phase opposition.

The effect of adding the inductance L' of suitable value to the circuit is thus to bring the grid and anode voltages into exact phase opposition, which results—according to the simple theory given—in the frequency of the maintained oscillations being that of the free undamped oscillations of the oscillatory circuit.

(2) EXPERIMENTAL.

Some preliminary experiments, made with the assistance first of Mr. C. R. Urwin, and later of Mr. W. J. E. Tobin, have indicated that the possibility of frequency stabilization in the manner described does exist. The valve chosen was a Mullard ORA which, with an anode battery voltage of 300 volts and a grid-bias voltage of 34 volts, maintained oscillations in a circuit of inductance 350 μH and capacity 556 $\mu\mu$F without grid current flowing and without alteration of mean anode current. The characteristic curve with these adjustments is given in Fig. 7. The frequency was thus about 360 000 cycles per sec. (wavelength 835 m).

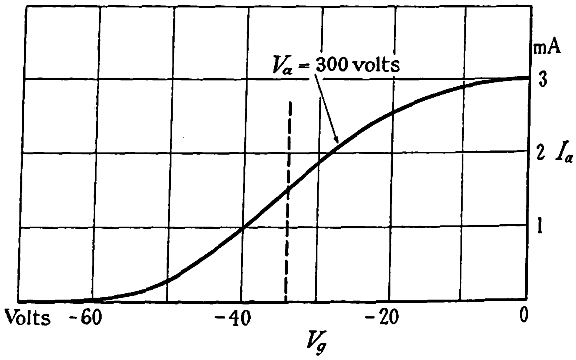

FIG. 7.

A second oscillator was set up some distance away to "receive" the oscillations of the first by heterodyne, and a third (low-frequency) oscillator enabled the heterodyne note to be adjusted by beats to a fixed value by alteration of the frequency of the second oscillator. The small alterations of frequency required were made (and estimated) by alteration of the capacity of a standard 200-$\mu\mu$F condenser with vernier adjustment in series with a fixed 10-$\mu\mu$F condenser, the combination being in parallel with the main oscillatory condenser. If C_1 is the capacity of the standard condenser and C_2 that of the fixed condenser (= 10 $\mu\mu$F) then the additional capacity across the oscillatory condenser is $C_1C_2/(C_1 + C_2)$, and if the change of this is δC, then $\delta f = \frac{f_0}{2C_0} \delta C$, where f_0 in the experiments was 360 000 cycles per sec., and C_0 was 556 $\mu\mu$F.

It appeared that the insertion of resistance in the oscillatory circuit lowered the frequency, instead of raising it as is indicated by equation (1). This was ascribed to alteration, by stray capacity effects, of the effective LC value, i.e. a primary alteration not due to the valve. This effect was great enough to mask any improvement due to the insertion of an inductance. It was, however, found that the insertion of the inductance L' did lower the frequency.

Changing the anode battery voltage yielded more promising results. It was found to be necessary to avoid cutting off the battery when changing over, and a quadruplex increment key was used (as indicated in Fig. 8), in which contact with the front stop is made before contact with the back stop is broken, the resistances "r" preventing excessive currents flowing while contact is made with both stops.

The results of one preliminary experiment are given in the table. The added inductance L' is given in the first column. In the second and third columns are given the readings of the condenser C_1, A for an anode voltage of 270 volts and B for an anode voltage of 300 volts. In the fourth and fifth columns the corresponding values of $C_1C_2/(C_1 + C_2)$ are entered. These were read off from a chart prepared from the calibration curve of C_1. δC in the sixth column is the difference of these, and δf in the last column is the frequency change, reckoned positive if an increase of anode battery voltage causes an increase of frequency.

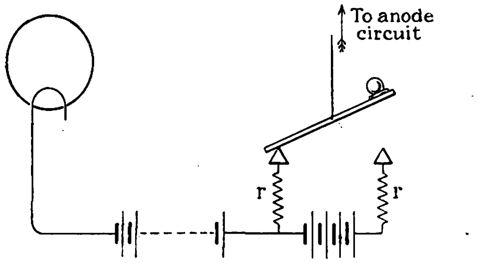

FIG. 8.

The frequency change produced by the 30-volt change in anode battery is plotted against the added inductance L' in Fig. 9, and from the curve obtained it would appear that with an added inductance of 63 μH no frequency-change would have been produced.

Altering the filament current by short-circuiting a small resistance in series yielded no positive result; the frequency alteration due to the change made was very small, and was not made any smaller by the insertion of inductances.

The fact that a smaller value of inserted inductance was found experimentally than is required by the theory is of interest. It may be due to the effect of the capacity between the anode and the grid, and the anode coil and the grid coil,* or to the effect of resistance in the capacity arm of the oscillatory circuit.† Other capacities may also be expected to modify the vector diagram; Appendix 1 is merely illustrative.

Other experiments at different frequencies have shown that the correct value for the inductance does depend upon the frequency and that the stray capacities may be such that the value of L' required is negative, i.e. a capacity must be added. Intermediately it may just happen that the circuit is already stabilized at the particular frequency in use.

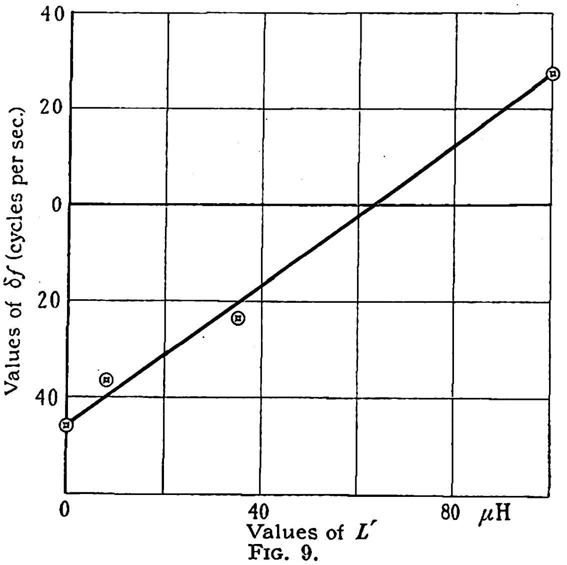

FIG. 9.

Experiments are being continued with a view to ascertaining whether the triode circuit modified in this way can take the place of the tuning fork or quartz crystal. The mechanical vibrator is always placed in a thermostatic chamber to avoid frequency-changes due to temperature-changes; it would equally be necessary to place the whole of the oscillatory circuit of the electrical oscillator in a constant-temperature chamber.

While only one of many valve oscillator circuits (including those with mechanical vibrators) has been examined, it may be said in conclusion that the same principle would appear to apply to all—frequency stabilization is carried out by a circuit adjustment which eliminates the influence of the valve constants on the frequency —and that this adjustment will be found to ensure

Added inductance L'	Reading of C_1		$C_1C_2/(C_1 + C_2)$		δC	δf
	A	B	A	B		
μH			μμF	μμF	μμF	Cycles/sec.
0	94·8	119·0	9·20	9·34	0·14	— 45
8	69·2	78·3	8·98	9·09	0·11	— 36
35	89·2	98·0	9·16	9·23	0·07	— 23
100	61·5	56·7	8·90	8·82	— 0·08	26

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* See Appendix 1.

† See Appendix 2.

that the grid and anode potentials are in exact phase opposition.

The experimental work has been done in the Telegraph and Telephone Laboratories of the City and Guilds (Engineering) College, and the author wishes to thank Professor C. L. Fortescue, O.B.E., Member, for the interest that he has taken in the work.

APPENDIX 1.

Effect of Anode-Grid Capacity.

In Fig. 10 the condenser C_g represents the combined effect of the anode-grid capacity and the capacity between the anode and grid coils.

Let I' be the current through the grid coil and the capacity C_g, and R_g be the resistance and L_g the inductance of the grid coil. The current I' is small compared with I_a, and is due mainly to the voltage V_a established across the points A and B, and only to a smaller degree to the voltage induced from the anode coil.

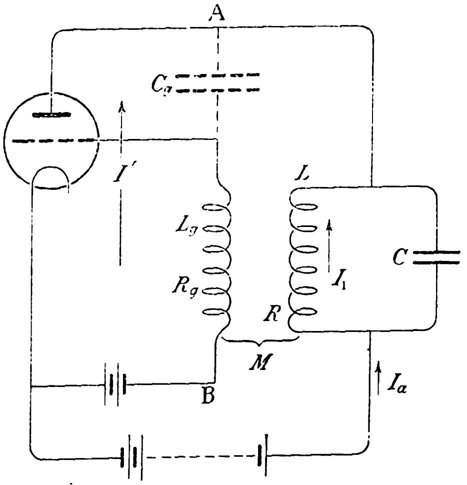

FIG. 10.

Thus, approximately,

$$I' = \frac{V_a}{R_g + j\omega L_g - j/(\omega C_g)} \doteqdot j\omega C_g V_a$$

$$V_a = -Z_p I_a$$

$$\therefore V_g = j\omega M I_1 + (R_g + j\omega L_g)I'$$

$$= \left\{\frac{M}{CZ} - j\omega C_g Z_p (R_g + j\omega L_g)\right\} I_a$$

and the condition for oscillations becomes

$$R_a + Z_p + j\mu\omega C_g Z_p (R_g + j\omega L_g) - \frac{\mu M}{CZ} = 0$$

or

$$R_a + Z_p(1 - \mu\omega^2 L_g C_g + j\mu\omega C_g R_g) - \frac{\mu M}{CZ} = 0$$

The general effect on Fig. 6 is a reduction of the diameter BD and a decrease of the angle of depression. Thus a smaller inserted inductance L' is required to bring D on to the axis.

It might therefore be possible to effect the adjustment for stability by adding to the anode-grid capacity instead of by the insertion of the inductance L'.

APPENDIX 2.

Effect of Resistance in Capacity Arm of the Oscillatory Circuit.

Let the resistance of the capacity arm be R_c and of the inductance arm be R_l, and let $R = R_c + R_l$.

Equation (3) becomes

$$I_1 = \frac{R_c - j/(\omega C)}{Z} I_a$$

and equation (4)

$$R_a + Z' + Z_p - \frac{\mu M}{CZ} - \frac{j\omega\mu M R_c}{Z} = 0$$

with

$$Z_p = (R_l + j\omega L)\{R_c - j/(\omega C)\}/Z$$

This yields for the frequency of the oscillations

$$\omega^2 = \frac{R_a + R' + R_l}{LC\{R_a + R' + (L'/L)R + R_c - \mu M R_c/L\}}$$

and in order that this may be $1/(LC)$,

$$L' = L\left(\frac{R_l}{R} - \frac{R_c}{R} + \frac{\mu M R_c}{RL}\right)$$

For maintenance with greatest output power

$$CRR_a = L \text{ (nearly)} \quad \text{and} \quad \mu M = 2L.$$

The expression then becomes $L' = L$, as before. If, however, the inductance is too great (i.e. if an anode tap is required for largest output, which generally happens at high frequencies), the value of L' required is less than L, whereas if the inductance is too small, L' must be greater than L.

AN INSTRUMENT FOR PROJECTING AND RECORDING THE RESPONSE CURVES OF ELECTRICAL CIRCUITS.

By Professor C. L. FORTESCUE, O.B.E., M.A., Member, and F. RALPH.

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SUMMARY.

The paper describes a combination of a projection oscillograph, a special amplifier, and a variable condenser coupled to the rocking mirror of the oscillograph, by means of which response curves can be thrown on to a screen for observation or may be recorded photographically.

The amplifier may also be used with the oscillograph in the ordinary way for low-frequency observations, the amplifier then functioning as a special form of valve voltmeter giving an output suitable for operating the oscillograph.

(1) INTRODUCTION.

There are many occasions when it is desirable to observe with a minimum of trouble the response curves of electrical circuit arrangements, such, for example, as those of an ordinary wireless receiver, over some predetermined range of frequency. This can, of course, always be done by taking the necessary observations and plotting the curves, but where there are a large number of variables this becomes too long a process for the proper investigation of the properties of the circuits. The instrument described in this paper is an attempt to overcome this difficulty by a combination of a specially designed amplifier and a projection-type Duddell oscillograph. The horizontal deflection of the spot is made dependent upon the frequency change, and the vertical deflection is dependent upon the amplitude of the output of the circuits under test. The curve is repeated some 10 or 15 times per second, just sufficiently rapidly for the normal persistence of vision to give the impression of a continuous curve. This curve is projected on to a small screen in view of the operator adjusting the circuits. The effects of changing any particular variable are thus immediately seen. Photographic apparatus of the usual type can also be used for recording all response curves of sufficient interest to justify the time and expense involved.

In addition to this, the terminals are so arranged that the low-frequency parts of the instrument can be used for converting small voltages into currents large enough to operate the oscillograph. This is useful in such cases as the measurement of leakage fluxes where even an oscillograph current would cause appreciable changes in the flux being measured.

(2) THE SOURCE OF THE HIGH-FREQUENCY CURRENTS.

A variable-frequency screened oscillator is used in which the frequency is dependent upon the inductance and capacity in the oscillatory circuit. Both inductance and capacity are varied to give the necessary ranges of frequency change. The circuit arrangements are such that the wave-form is reasonably good over the whole range of frequency change, but at the same time the voltage amplitude in the oscillatory circuit remains constant. This adjustment is easily obtainable with any simple magnetically-coupled circuit, if the grid bias is so arranged that the change of anode current at the onset of oscillations is comparatively small. The coupling should be a little greater than the minimum value for which the oscillations will start.

The capacity in the oscillating circuit is in two parts. One part consists of a variable condenser adjusted by hand in order to give the correct mean value of the frequency—the appropriate inductance having been decided upon beforehand. The second part consists of a motor-driven variable condenser made up of two sets of fixed vanes and two sets of moving vanes, the latter being mounted on a long extension of the shaft of the driving motor. The two parts of the double condenser are in series and, as the vanes rotate, the capacity varies from maximum to minimum and back again during one revolution. This arrangement has the advantage that there are no sliding contacts in the high-frequency circuit. It has the disadvantage, however, that the moving vanes are not at earth potential, and consequently an insulating coupling must be used to connect the condenser spindle to the motor shaft.

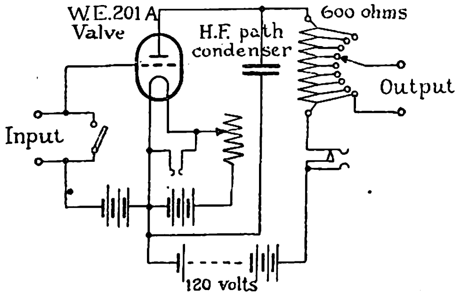

FIG. 1.

This motor-driven condenser is arranged to give a capacity of from about 50 to 200 $\mu\mu$F. By choosing various values of the inductance and hand-adjusted capacity, it is usually possible to arrange for this change of capacity to give the desired range of frequency. The only difficulty experienced occurred when a very large range of frequency was required.

In some cases it is more convenient to keep the frequency of the oscillator constant and to vary the tuning of the receiving circuit. This can be done, where the receiver consists of only a single resonant circuit, by connecting the motor-driven condenser in parallel with the capacity of this resonant circuit.

An extension of the condenser spindle carries a cam operating the usual rocking mirror of the oscillograph. By this means the spot of light is deflected horizontally in proportion to the change of capacity above and below the mean value. If this change is small compared with the total capacity, the horizontal scale is then practically a frequency scale. When desired, the frequency scale can be checked at several points by means of a wavemeter.

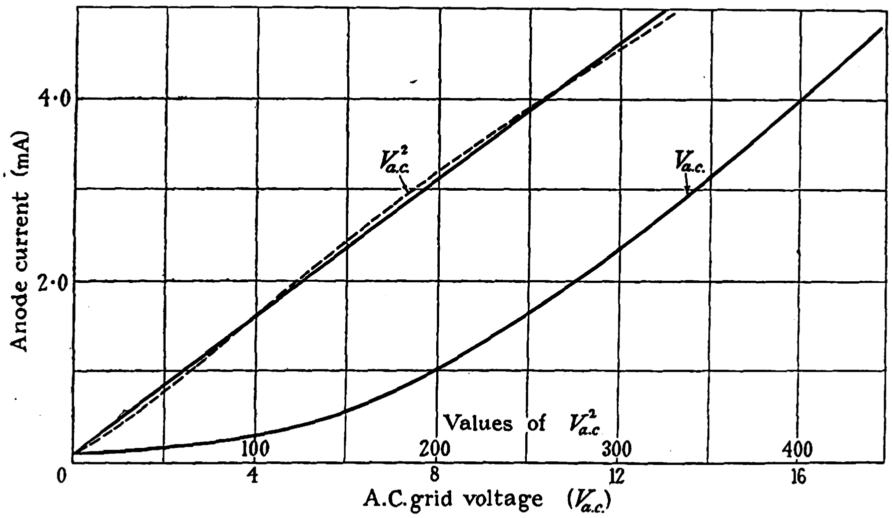

FIG. 2.

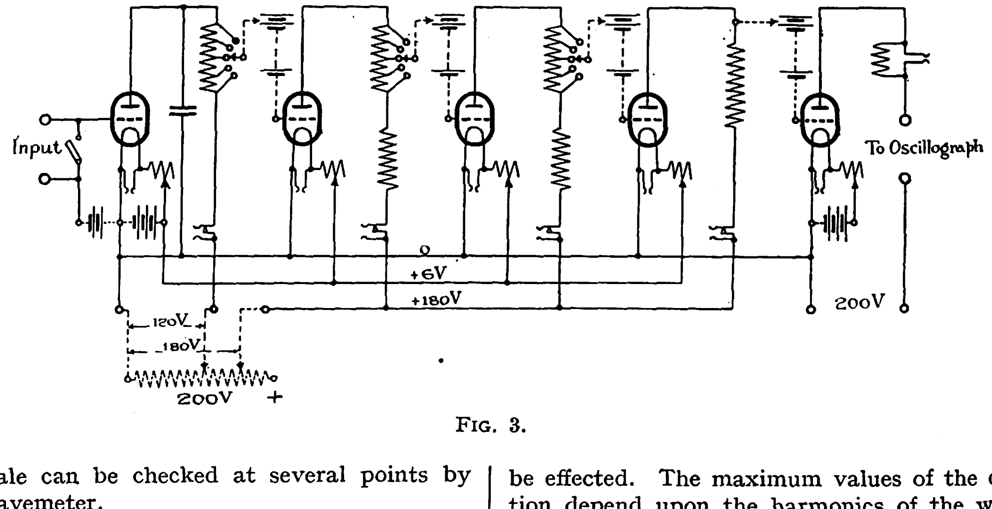

FIG. 3.

The motor shaft also carries a shutter which cuts off the light for one half-revolution. This is necessary as the rotary condenser plates may not be exactly symmetrical.

(3) THE RECTIFYING UNIT.

This consists of a single Western Electric 201A valve connected as shown in Fig. 1. The output voltage from the circuit is applied directly to the grid, superimposed upon a steady grid-bias voltage of about 6 volts. The anode circuit consists of a resistance with a capacity across it so proportioned that no more than 1 per cent of the high-frequency component passes through the resistance, and no more than 1 per cent of the rectified current passes through the capacity.

If a condenser were not used in this way the high-frequency components would go through all stages of the amplifier and upset the proportionality of the response to the rectified component. This necessity imposes certain limits on the frequencies, since the oscillation frequency must be sufficiently above the frequency of the cyclic variation for this separation to be effected. The maximum values of the cyclic variation depend upon the harmonics of the wave-form of the response curve, and include all those that can be recorded by the oscillograph. Any harmonics higher than this need not be provided for as they will be lost in any case owing to the moving strips and mirror being unable to follow them. The maximum cyclic frequency may therefore be put at about 1 000. The minimum oscillation frequency is then in the neighbourhood of 100 000, depending upon the degree of accuracy which is required.

The Western Electric 201A valve was chosen as experience has shown that the rectification follows the square law over a considerable range. Fig. 2 gives the result of an actual test with one of these valves.

(4) The Amplifier.

The output voltage of the rectifying unit may be as much as 1 volt. The R.M.S. current required by the projection-type oscillograph is about 0·15 ampere. Thus with a variation of input voltage of, say, ± 1·4 volts, the variation of the output current is to be about ± 0·2 ampere, and these two should be proportional to one another to within an accuracy of a few per cent.

When the amplifier is used without the rectifying unit for flux measurement, the voltages are often as low as 0·1 volt (R.M.S.). The amplifier is therefore designed to deal with only this small input if necessary, and to be used with larger inputs with a reduced amplification per stage.

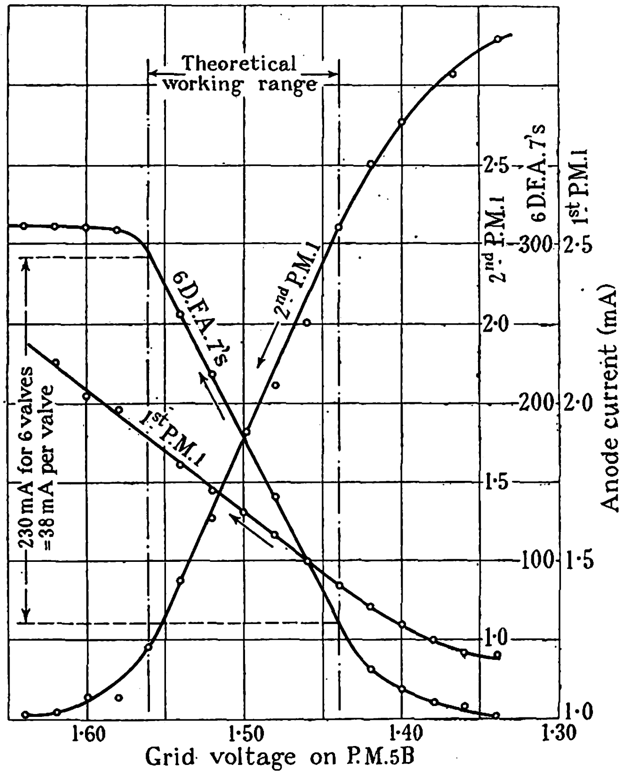

Fig. 4.

A further special requirement in this case is that the amplifier should perform equally well at zero cyclic frequency, i.e. with step-by-step changes of input voltage. This is necessary for calibration purposes and immediately determines one point in the design of the instrument, viz. that it must be resistance-coupled with separate grid batteries for each stage.

The output stage was determined by the variation of the current required for the oscillograph. Eight Mullard D.F.A.7 valves working with an anode voltage of 200 and a mean anode current of about 175 mA were found satisfactory.

Three intermediate stages were employed as follows:—

1st stage: Mullard P.M.5B valve ($V_a = 180$ volts).

2nd and 3rd stages: One Mullard P.M.1 L.F. valve ($V_a = 180$ volts).

The resistances in the anode circuits were 84 000, 26 000 and 50 000 ohms respectively. Some variation of resistance was provided in the first two intermediate stages. Fig. 3 gives the connections for the complete amplifier. Other combinations of valves and resistances have also been used, with similar results.

With careful adjustment it was found possible to compensate for the curvature of the characteristics of the output valves by that of the valves in the intermediate stages. This is possible because each stage reverses the phase and a current limitation on one valve leads to a voltage limitation on the next in the direction in which the current would normally be too large.

The final result for the whole amplifier, but with only six valves in the output stage, is shown in Fig. 4, where the current in the output circuit is shown plotted against the voltage applied to the grid of the first amplifier valve.

Very similar curves are obtained with eight valves in the output stage.

Where the maximum amplification is not required it is generally convenient to cut out the second amplifying valve by taking the grid connection of the third valve to the anode of the first valve instead of the second. The straight-line amplification is still preserved within the limits of accuracy required.

(5) The Oscillograph.

This was a standard Duddell instrument constructed by the Cambridge Instrument Co. The strips were larger than those fitted to the ordinary instruments, in order to provide for the larger mirrors necessary for projection purposes. The large strips were capable of carrying a considerable current, but actually the mean current is usually diverted by a battery and resistance in parallel with the strip. For this purpose the parallel resistance is made about 10 times the strip resistance so that about 90 per cent of the current change passes through the strips themselves.

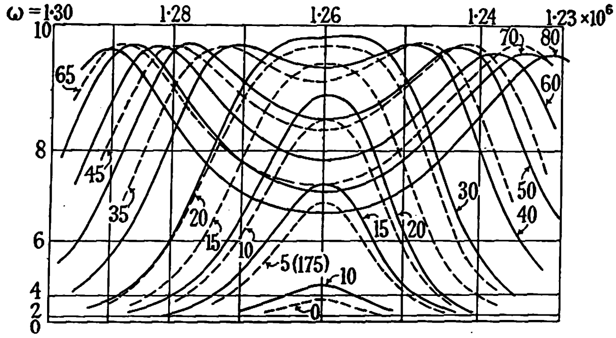

Fig. 5.—Test No. 3. Mutual only. Secondary current.

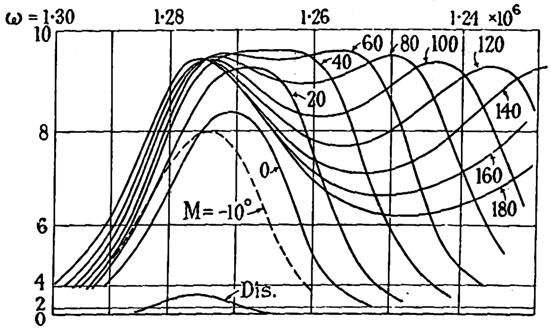

Fig. 6.—Test No. 9. Capacity coupling; $M = 0$. Secondary current.

(6) CIRCUIT ADJUSTMENTS.

The mean anode currents for all the stages were found by preliminary experiments and kept constant throughout. The amplifier was fitted with a voltmeter and a milliammeter, which could be connected in turn to each stage to verify the conditions. Once adjusted, the only changes called for were those due to batteries running down. This is perhaps the most serious difficulty in using the instrument, and it can only be overcome by using good batteries throughout and keeping them in good condition.

(7) EXAMPLES OF THE APPLICATION OF THE AMPLIFIER.

(*a*) *Response curves.*—The curves of Figs. 5 and 6 are reproduced directly from records obtained from coupled circuits, magnetic and capacity coupling respectively.

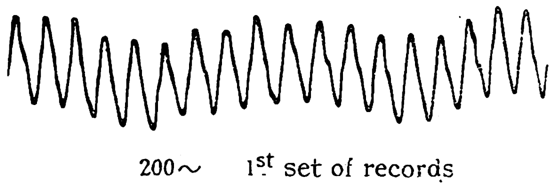

Fig. 7.

(*b*) *Other applications.*—Fig. 7 is reproduced from a record of the output of an electrical gramophone pick-up when working from a "sine wave" record. The output is not sinusoidal and the question arose as to whether this was attributable to the amplifier, the pick-up or the record. On driving the pick-up by means of a maintained fork the curves of Fig. 8 were obtained; they are obviously much more nearly sinusoidal, thus showing that the irregularities of Fig. 7 are due to the record itself.

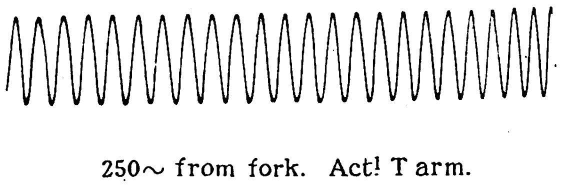

Fig. 8.

SUMMARY (TO 1925) OF EUROPEAN AND AMERICAN DATA ON INTERFERENCE BETWEEN POWER AND COMMUNICATION CIRCUITS.*†

TECHNICAL REPORT (REF. M/T3) OF THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION.

(*Paper received 5th September, 1929.*)

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Appendices.
1. List of articles, etc., on which the summary is based.
2. Calculation of inductive effects.
3. Table 1, showing the value of exponents for use in formula expressing variation of coefficients of induction with separation of the two circuits.
   Table 2, giving the characteristic residual voltages of conductors in parallel single-circuit and twin-circuit lines.
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11. Telephone transposition schemes.
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14. Legal aspects.

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[*] Further information, bringing the subject up to date, will probably be available during the year 1930.

[†] The Papers Committee invite written communications, with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (excepting those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

INTRODUCTION.

In 1922 a Committee on telephone interference was formed by the Association. Before considering experimental work it was decided to make an exhaustive survey of what had already been done in this field; and for that purpose Professor C. Parker Smith, D.Sc., with Mr. S. A. Knight, B.Sc., as his assistant, was appointed to make a critical résumé of all the available information on the subject. In March 1928 Professor Parker Smith presented a report which covered information published prior to the middle of 1925.

The present résumé consists of a brief summary of the material included in the report mentioned above, and the Association desires to express its appreciation to Mr. S. A. Pollock and Mr. W. G. Radley of the Post Office for its preparation.

Later work is under consideration by the Association, and a supplementary report will be issued shortly.

SYNOPSIS.

A general review of the subject and a statement of the physical principles underlying remedial measures are included in Section 1 (pages 589 to 591).

The methods of CALCULATING THE VOLTAGE induced in a telephone or telegraph circuit due to the disturbing influences of heavy current or high-tension open-wire power lines are indicated in Section 2 (pages 591 to 593).

The design of POWER transmission and TRACTION circuits is considered in Sections 3 and 4 (pages 593 to 597), from the point of view of causing least interference, and the design of TELEGRAPH and TELEPHONE circuits is dealt with in Sections 5 and 6 (pages 598 to 599), from the point of view of suffering least interference. An endeavour has been made to collect into each of these sections a brief mention of the whole of the information regarding the particular type of circuit under discussion.

Inductive effects from both current and voltage under normal operating conditions of the power circuit may be very greatly reduced by transposing individual conductors of both power and communication circuits at definite intervals. In Section 7 (pages 599 to 601) the various TRANSPOSITION schemes which have been tried are outlined and the most suitable pointed out, together with the best arrangement of the conductors in the case of both single and twin-circuit power lines. In order that any transposition scheme may be fully effective there must be close co-operation between the power and communication authorities.

Disturbances to the normal telephone working are generally due to the presence of high-frequency HARMONICS in the power circuit. Section 8 (pages 601 to 603) deals with the generation of harmonics by machinery or apparatus connected to the power lines. Certain modifications in the design of rotating machinery enable these harmonics to be reduced or eliminated; and the technical devices whereby this may be done are mentioned. The importance of the disturbing effects of triple-frequency harmonics manifests itself especially in power systems where the neutral point is earthed.

The mathematical work, together with a detailed discussion of many of the points which arise, is contained in a series of appendices attached herewith. References to them are given in the report. In addition the original digests prepared by Professor Parker Smith, together with more detailed data from the articles digested, have been filed away at the offices of the Association and are available to interested parties on application. Appendix 1 to this résumé gives a list of the articles from which the original digests were prepared.

A summary of the points which have been regarded by the various investigating authorities as important, and on which there is some measure of agreement, are presented in the form of a series of conclusions (Section 9). Based on the conclusions a code of guiding rules might be drawn up for the purpose of directing authorities in designing their systems. The outstanding problems on which further research work was required are also mentioned in this section.

From a general study of the available information, it would seem to be possible with the experience gained to suppress satisfactorily all inductive interference from all sources whatsoever, with the exception of shocks on short circuit, in which case the evidence is not conclusive. The elimination of interference, however, may not only entail capital cost, but also a high degree of maintenance on the part of both power and communication authorities.

DEFINITIONS.

1. *Communication circuit.*

Any type of signalling circuit arranged in cable or open wire. Communication circuits are sub-divided under—

- (*a*) Telephone circuits comprising—
  - Public long-distance trunk lines.
  - Public inter-exchange local lines.
  - Public subscribers' lines.
  - Railway despatching lines.
  - Private power companies' lines.
- (*b*) Telegraph circuits.
- (*c*) Signal circuits.

2. *Line.*

Circuit or aggregation of circuits carried on a single series of poles.

3. *Power circuit.*

Constant-potential circuits supplying energy, excluding traction circuits and communication circuits.

4. *Traction circuit.*

Constant-potential circuit used for traction and utilizing the earth as a part of the circuit.

5. *Interference.*

Disturbance and danger occurring on communication circuits due to inductive effects of power and traction circuits.

6. *Disturbance.*

Dislocation of traffic and impairment of transmission on communication circuits.

7. *Danger.*

Risk of damage to plant and of shock to personnel and the public.

8. *Parallel.*

Where a power or traction circuit and a communication circuit follow routes likely to cause interference.

9. *Normal parallel.*

Where interference may occur on a parallel due to normal operating conditions.

10. *Abnormal parallel.*

Where interference may occur on a parallel due to abnormal conditions.

11. *Separation.*

Distance between lines forming a parallel measured as a perpendicular from the power or traction circuit.

12. *Constant separation parallel.*

Part of a parallel in which discontinuities occur, but the separation remains constant.

13. *Converging parallel.*

Part of a parallel in which the separation decreases uniformly.

14. *Configuration.*

Geometrical arrangement of a circuit or circuits including size of wires and their relative positions with respect to one another and to earth.

15. *Uniform parallel.*

Part of a parallel in which there are no discontinuities.

16. *Balanced voltages and currents.*

Components of voltages and currents in the conductors whose algebraic sum equals zero at any instant.

17. *Residual voltages and currents.*

Components of voltages and currents in the conductors whose algebraic sum does not equal zero at any instant.

18. *Longitudinal voltage.*

Voltage induced along the conductors of a communication circuit or between the conductors and earth.

19. *Transverse voltage.*

Voltage induced between the two conductors of a communication circuit.

20. *Magnetic induction.*

Interference due to electro-magnetic effects of the currents in the power or traction circuits.

21. *Electric induction.*

Interference due to electrostatic effects of the voltages in the power or traction circuits.

22. *Transposition.*

Interchange of conductor positions of a circuit between successive lengths.

23. *Discontinuity.*

Any abrupt change on either circuit of the physical dimensions, electrical characteristics, apparatus or load which materially affects magnitude or phase of induced voltages or currents per unit length.

24. *Barrel.*

Section of a power circuit in which each conductor occupies each of the conductor positions for such distances to give best balance.

25. *Co-ordination.*

Transposition of both power and communication circuits efficiently located with regard to each other and to discontinuities in order to reduce induction.

26. *Protector.*

Over-voltage protective device consisting of some form of spark-gap which may be connected between each wire of a telephone circuit and earth.

27. *Characteristic residual voltage.*

Residual voltage of a short uniform non-transposed power circuit when insulated from earth and energized with balanced three-phase voltages between conductors.

28. *Unbalanced exposure.*

That length of parallel of the same cross-sectional dimensions as the given parallel and between a telephone and power circuit neither of which is transposed, which will produce inductive effects of the same magnitude as those produced in the given parallel with the given transpositions in the power and telephone circuits.

29. *Coefficient of induction.*

Ratio of the induced voltages in the communication circuit to the inducing factors (components of voltage or current) of the parallel power circuit.

30. *Reduction factor.*

The value by which the calculated values of the induced voltage or current requires to be multiplied to take into account the shielding effect due to earthed bodies near the power lines or communication lines.

(1) CIHEF FEATURES OF THE PROBLEM.*

Inductive effects are produced in communication circuits whenever they lie in the electrostatic or electromagnetic fields of power circuits.

In general, both magnetic and electric induction are present, although their effects on a communication circuit may be such that one effect may be negligible relative to the other.

ELECTRIC INDUCTION.

Due to the alternating electric field surrounding a power line having a difference of potential between itself and earth, any neighbouring line will have induced on it an electric charge. This charge varies directly with the potential of the disturbing line and depends on the capacities of the neighbouring line to the disturbing line and to earth. The charging current which flows is proportional to the frequency of the inducing voltage and to the length of the line.

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* The references given are numbered in accordance with list of articles digested given in Appendix 1.

MAGNETIC INDUCTION.

Due to the alternating magnetic field surrounding a power conductor and produced by the current flowing in it, an e.m.f. is induced by mutual induction on any neighbouring line. This induced e.m.f. is dependent on the current, frequency, length of parallelism and the mutual inductance.

EFFECT OF INDUCTION ON A TELEPHONE OR OTHER COMMUNICATION CIRCUIT.

Due to the varying magnetic and electric fields in which it is situated a conductor located near to a power or traction line will have a *longitudinal voltage* induced along it, or between it and earth. If one conductor of a telephone circuit is nearer than the other to the power line the longitudinal voltage induced in the two will be different. The difference between these longitudinal voltages is the *transverse voltage*. This is produced between the two sides of a circuit and causes a disturbing current to flow through the receivers at the ends of the circuit. Even in the event of both wires of the telephone circuit being uniformly exposed to the disturbing line, disturbing currents may be caused to flow unless both wires are perfectly balanced as regards series impedance, capacity and leakage to earth.

The effects of interference may be considered under the headings of disturbance and danger.

DISTURBANCE.

To telegraph circuits.—Since telegraph systems work under conditions such that the frequencies of the main components of the current transmitted are less than 300 cycles per second, only the fundamental and lower harmonics of the extraneous current disturb reception by distorting or mutilating the signals or causing relays to chatter. Telegraph instruments are not sensitive to higher harmonics. Signal circuits, other than telephone circuits, resemble, in general, telegraph circuits and are most affected by the fundamental.

A number of tests have been carried out by various investigators in order to determine the permitted amount of disturbing current which will not cause trouble to telegraphic communication.

To telephone circuits.—According to Helmholtz, the physiological limits of audition are about 25 to 30 cycles per second for the lower limit, and about 30 000 cycles per second for the upper limit. Transmission of speech over telephone circuits is carried out by currents, the frequencies of which lie between limits of about 100 to 4 000 cycles per second, the mean frequency being approximately 800 cycles per second. This figure is used in telephone transmission calculations. Although this point is not definitely stated to be the case in any published paper, noise due to fundamental frequencies (60 cycles or less) of power and traction circuits is not heard in a telephone receiver; and induction due to these frequencies causes very little interference.

The effect of higher harmonics is to produce noise in the telephone receiver, which reduces the transmission value of the circuit and may interfere with speech or render it impossible. The amount of noise that can be tolerated on a telephone circuit without undue interference with speech has not been specially investigated by the Post Office.*

Increasing importance is being given to this aspect of the subject of interference by the use of land lines for the purpose of simultaneous broadcasting.

DANGER.

High interfering voltages due to the fundamental components of the voltage or current in the power line render apparatus generally liable to damage and risk of fire, and personnel to electric shock.

Metallic telephone circuits are protected by carbon-block protector gaps between each wire and earth, these gaps being arranged to break down if the voltage to earth exceeds approximately 300 volts. When, due to the longitudinal voltage exceeding this critical figure, a protector breaks down, a sudden rush of current discharges from the other wire of the circuit through the receiver and gives an acoustic shock to the listener. In addition signalling devices, such as the subscriber's bell or the calling device at the telephone exchange, may be operated. Loading coils in trunk lines may be permanently damaged by the out-of-balance current. Similar effects are produced when abnormal conditions occur on the power circuit, such as a short-circuit or a switching operation.

Table 1 is shown, giving these effects in skeleton form.

BALANCED AND RESIDUAL COMPONENTS OF CURRENT AND VOLTAGE.

In analysing inductive effects it is convenient to classify the currents and voltages on power circuits into two classes:—

(i) Balanced currents and voltages.
(ii) Residual current and voltage.

Balanced currents and voltages.—Components of current or voltage in the several conductors of a power circuit such that at every instant their algebraic sum is zero. As an example, the currents in a three-phase line with no earth connection and with its three conductors symmetrically arranged with respect to the earth's surface are balanced currents. In power circuits generally part of the currents and voltages are usually balanced.

Residual current and voltage.—The algebraic sum of the currents or voltages in the conductors of a power circuit, when this is not equal to zero at every instant. Thus an overhead traction circuit with a return through the rails and earth is completely unbalanced with respect to earth; its total voltage and current being residual.

The necessity for this division arises since their inductive effects have little in common and the remedies are often fundamentally different. The inductive effects of residual components (residuals) are much greater comparatively than those of balanced components. Current or voltage residuals in the conductors of a power circuit are in phase with each other and act as if the power circuit were single-phase with all the line conductors in parallel, earth being utilized as a return. The inductive effects of the conductors are, therefore, cumulative, and the neutralizing effect of the earth return is small. On the other hand, the balanced components in the power conductors are mutually out of phase and the inductive effects are neutralized considerably.

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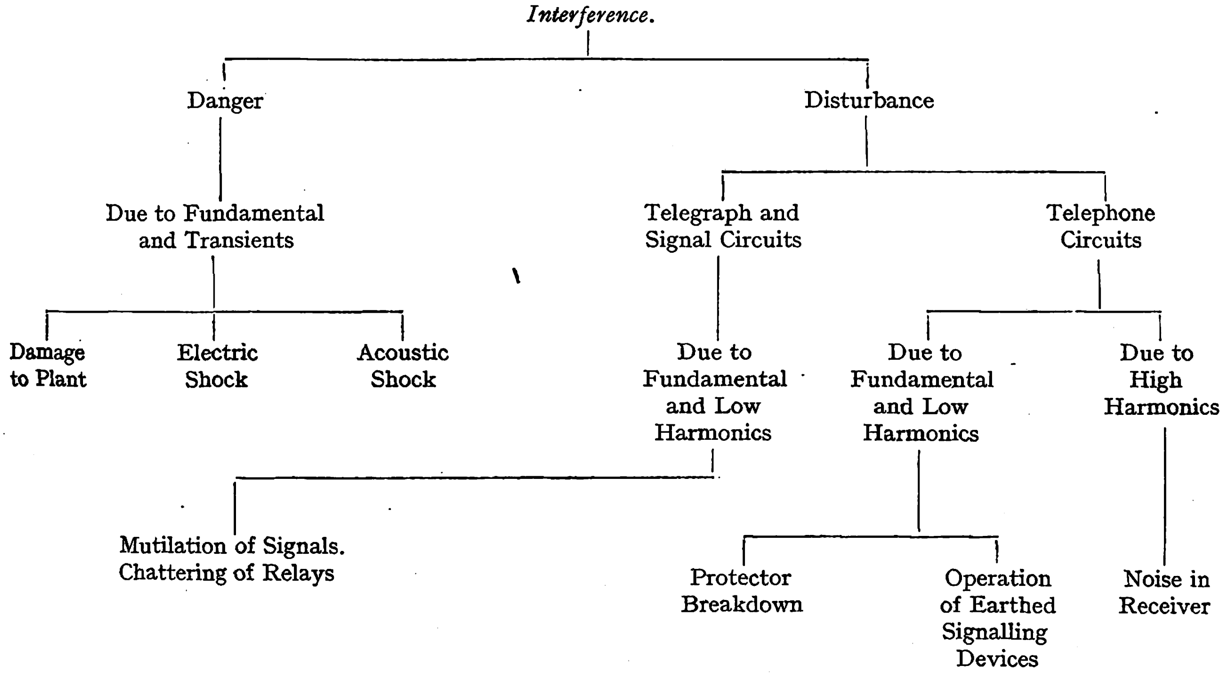
* See footnote to Conclusions, page 603.

TABLE 1.


Interference.
Danger
Disturbance
Due to Fundamental and Transients
Telegraph and Signal Circuits
Telephone Circuits
Damage to Plant
Electric Shock
Acoustic Shock
Due to Fundamental and Low Harmonics
Due to Fundamental and Low Harmonics
Due to High Harmonics
Mutilation of Signals. Chattering of Relays
Protector Breakdown
Operation of Earthed Signalling Devices
Noise in Receiver

NOTE.—D.C. ripples are considered as harmonics.

Both the balanced and residual components contain harmonics, but these form a greater proportion of the residual components than of the balanced components.

During abnormal and transient conditions on power or traction circuits, the residual components are greatly increased. These conditions can be produced by switching operations and faults.

(2) METHODS OF CALCULATION.

Before limitations can be fixed regarding the permissible length and separation of a parallel it is necessary to be able to estimate the inductive effects which may be present.

The methods of calculation for both electric and magnetic induction which have been investigated are given in full in Appendix 2.

ELECTRIC INDUCTION.

Formulæ giving the electric induction for a number of practical cases involving one, two and three power lines, paralleled by a communication circuit, will be found in Table 1, Appendix 2. This table also gives the value of the electric induction when the power circuit is unbalanced by an earth fault on one of the phases. The formulæ in this table have been corrected from certain formulæ given originally by Brauns (111). During their examination of the data the investigators found that there was a difference of the order of 250 per cent between the value of the induced current flowing through the apparatus obtained by Brauns and as calculated from the formulæ given with the French rules (102). As the limits of separation given by the Comité Consultatif International are based on the latter formulæ, this discrepancy was very carefully investigated. No error was found in the formulæ given by the C.C.I.

In the above methods the results are expressed in terms of potential coefficients, which in turn may be evaluated when the numerical dimensions of the spacing and height of the two circuits are known. Similar methods were used by the Californian Railroad Commission in their Technical Report No. 64 (30). This contains a theoretical study of the variation of the electric induction in communication circuits paralleled by three-phase power circuits, with the relative position and configuration of the two classes of circuit. Open-circuit induced voltages are determined both for single conductors and metallic circuits, and serve as criteria for comparing various configurations of power and communication circuits, and for judging the relative severity of the inductive effects of parallels. The necessary calculations in this study were made with the help of several types of calculation form, which enabled the determination of the induced voltages to be carried out with the aid of a calculating machine. Technical training was, for the most part, not required.

The investigators have also examined a number of approximate formulæ given by Lienemann (109), which enable the interference effects to be expressed directly in terms of the separation and other dimensions.

For a single interfering line, such as the overhead contact line of an a.c. railway, the induced voltage to earth in a parallel communication circuit is

$$\frac{1}{4} \times \frac{Vbc}{a^2 + b^2 + c^2}$$

where V is the working voltage of the h.t. line.

In this formula:—

a is the separation between the two lines,
b is the height of the h.t. line, and
c is the height of the telephone or telegraph wire above the earth.

A number of these simplified forms are given in the Appendix. They can be employed when 10 per cent inaccuracy is permissible.

MAGNETIC INDUCTION.

Formulæ are given in the Appendix by means of which the magnetic induction may be calculated. These formulæ are given in a form involving physical dimensions and apply both to the induction from residual and balanced currents. They were used by the C.R.R.C. in their calculations in Technical Report No. 64. The calculations necessary to determine the interference effects by means of these formulæ are, in principle, simpler and less laborious than those outlined for electric induction, but the results are less rigid, since it becomes necessary to modify in an empirical manner the terms expressing the height of the conductors above the ground, in order to take account of the effect of earth currents.

Owing to the fact that the earth possesses considerable conductivity, it will in itself provide a path for eddy currents which will be induced in it by the magnetic field from the power circuit. The effect of these eddy currents will be to reduce the magnetic flux entering the earth and consequently the induction. The formulæ given in Appendix 2 simulate the effect of the earth by replacing the earth by images of the conductors at a suitable distance below the earth's surface. If the earth were a perfect conductor the magnetic neutral zone would exist at the earth's surface; so that the correct position of the image conductors would be at a distance below the earth's surface equal to the height of the conductors above it, as in the case of electric induction.*

According to Californian Railroad Commission (30):—

" Experience has shown that this is not permissible. . . . Since the earth is not a perfect conductor the locus of earth currents is a considerable distance below the earth's surface. This distance varies with the frequency of the current and the character of the country."

" The results of tests made by the Joint Committee at three different localities show that the image conductors for computations of magnetic induction should be taken with respect to an 'equivalent earth plane' from 300 to 500 ft. below the actual surface. The figures given are for 60 cycles. For higher frequencies the equivalent earth plane is nearer the surface."

The special case of induction to phantom telephone circuits is referred to in the Appendix, as is also the induction arising from twin-circuit power lines.

Magnetic induction between lines with an earth return.—In the case where one or both of the circuits has an earth return the solution is more difficult and is not rigid, since the path of the earth currents is not exactly known and varies with the geological characteristics of the locality.

A number of specific cases is dealt with in the Appendix. These include:—

(i) Communication line with earth return.
(ii) Power line with earth return.
(iii) Both power and communication circuits with earth return.

The first case does not appear to enter into practice from the evidence collected, although telegraph circuits paralleling metallic single-phase power lines would fulfil the conditions.

The second case corresponds to parallels formed by metallic telephone circuits and a single-phase railway, but in general little consideration has been given to it by writers.

Breisig has obtained an approximate formula giving the mutual inductance, M, between two lines of equal length, l, with a common earth return; but it becomes necessary to modify this formula in an empirical manner in order to take account of the fact that the earth is not an ideal uniformly conducting medium. The formula then becomes:—

$$M = 2l\left(\log_e \frac{2l}{a} - q\right)10^{-4} \text{ henry per kilometre,}$$

where q is a number which varies from about 0·5 to 5, depending on the length of the line, according to experiments carried out by Brauns (111), and a is the separation of the two lines.

L. Truxa (107) gives a formula for lines of unequal length, but the derivation of this formula has not been rigidly investigated at the moment.

In the case of a single-phase railway the calculations are complicated by the fact that currents are induced in the earth by the magnetic field, and these form a circuit along the rails returning through the earth. From a theoretical consideration of this particular case, Pleijel (108) draws the conclusion that the induction is independent of the leakage coefficient of the rail lines and also of the conductivity of the earth.

Although many tests have been carried out in order to investigate the value of the mutual inductance between earth-return lines, the data on which the various authors base their conclusions is still not clear. The distribution of earth currents cannot be stated with certainty.

---

* The application of the formula used by the Californian Railroad Commission to the calculation of the induction from the residual currents in the case of an earth fault on the power system leads to results which differ very materially from those obtained by the formulæ developed by Breisig, Pollaczek or Rüdenberg. The conditions under which the C.C.I. allow proximity between telephone lines and power lines with an earthed neutral point are based on the latter formulæ.

(3) POWER CIRCUITS.

OPEN-WIRE TRANSMISSION LINES.*

DIMENSIONAL ASPECTS.

HORIZONTAL SEPARATION OF THE TWO CIRCUITS.

In general, as the horizontal separation between power and communication circuits is increased, the electric induction decreases. The rate of decrease varies from near direct proportionality to about the third power of the separation, and depends on the type of circuit. Due to the relatively great depth of the return current in the earth the magnetic induction due to load currents decreases much more slowly than the electric induction.

The Californian Railroad Commission has made a very thorough study of the dimensional aspects in connection with three-phase lines, and in their Technical Report No. 65 give a large number of curves plotted from calculations based on formulæ obtained as indicated in the preceding section. These curves apply to both electric and magnetic induction. In each case studied the induction was calculated for a range of separation of from five to one hundred times the unit of power-conductor spacing. From the discussion of the results the following statements are drawn concerning *both magnetic and electric induction.*

The decrease of the coefficients of induction with increase of horizontal separation is expressed approximately by the formula

$$V = K\left(\frac{a}{\delta}\right)^{-n}$$

where a is the separation between the two circuits and δ the spacing of the power circuit conductors.

Table 1, Appendix 3, presents average values of the exponent, n, for the several configurations and classes of coefficients. It is clear that the value of n is greater for induction into metallic communication circuits than into earthed circuits, the difference being about 0·9 with the one exception for induction from residual current, where the difference is only 0·4.

HEIGHT OF POWER LINE ABOVE GROUND.

"Increase in the height of the conductors of *both* power and disturbed circuits, is, in general, accompanied by an increase in the coefficients of induction, the rate of variation of the coefficients becoming greater as the horizontal separation of circuits is increased. This effect is somewhat greater on the induction from the residual than on induction from the balanced components of both voltages and currents." The effects of variation in height are much less pronounced on the coefficients of induction due to the currents than on the coefficients of induction due to voltages.

"Increase in the height of power conductors, height of disturbed conductors remaining constant, may cause either an increase or a decrease in the coefficients of induction depending upon particular conditions."

The effect of variation of height of the conductors on the capacity unbalance of the power line is small for vertical and horizontal configurations. For triangular configurations the unbalance decreases approximately as the height of the conductors above the earth is increased.

VERTICAL SEPARATION OF THE TWO CIRCUITS.

"With disturbed conductors below the power conductors, the coefficients of induction decrease with increase in vertical separation, measured from the plane of the lowest power conductors."

"This relation is approximately linear except at the smaller horizontal separations. The practical variations of vertical separation have much less effect on induction from currents than on induction from the voltages since for the former the equivalent ground plane is much below the surface. Circuits on and even somewhat below the earth's surface are subject to the inductive effects of the currents of parallel power circuits though unaffected by the voltages."

DIAMETER OF POWER CONDUCTORS.

Induction from power-circuit voltages increases slowly with the conductor diameter, due to the increased value of the electric charges on the line.

For all configurations increase in the size of the conductors is accompanied by an increase in the characteristic residual voltage of the line. This term is defined in the section dealing with the geometrical arrangement of the conductors.

SPACING OF POWER CONDUCTORS.

"In general, for all types of power circuit an increase in the spacing of the conductors causes an approximate proportionate increase in the magnitudes of the coefficients of induction from the balanced voltages and currents." This conclusion is in agreement with the formulæ given by Lienemann.

"The effect of the spacing of the power conductors on the coefficients of induction from residual currents is very small." "The coefficients of induction from residual voltage increase slowly with the spacing of the conductors due to increased charge per unit of voltage."

In the case of the equilateral triangular configuration the characteristic residual voltage increases approximately with increasing conductor spacing.

EXCEPTIONAL EFFECTS WITH VERTICAL CONFIGURATION.

"The different power-line configurations are, with the exception of the vertical, quite similar as regards manner of variation of the coefficients of induction with the variation of the cross-sectional dimensions of the parallel." "There are some marked peculiarities of the electric and magnetic fields about vertical power circuits, due to balanced voltages and currents. For example, as the horizontal separation increases the coefficients of induction from balanced currents decrease very rapidly at first, pass a sharp minimum, increase rapidly, reach a maximum and thereafter decrease at a rate approximating to that of curves for other configurations. Curves of a somewhat similar nature occur for other variables. For balanced currents the effects are much more pronounced than for balanced voltages." Brauns first pointed out these minima and maxima for balanced voltages in 1907.

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* Except transposition schemes which are dealt with in Section 7.

GEOMETRICAL ARRANGEMENT OF THE POWER CONDUCTORS.

In addition to determining the intensity of the inductive effects produced in parallel communication circuits by the balanced voltages and currents in the power circuit, the arrangement and spacing of the power-circuit conductors gives rise to inequalities among the capacities of several conductors to each other and to earth. In the case of a system insulated from earth, unbalances among the admittances of the several conductors will, in general, cause their voltages to earth to be unbalanced, even though the voltages between conductors are balanced. A residual voltage is thus created by the line unbalance.

Characteristic residual voltage.—The line unbalance of a particular type of power-circuit configuration is indicated by the " characteristic residual voltage " by which is termed " the residual voltage of a short uniform non-transposed power circuit when isolated from earth and energized with balanced three-phase voltages between conductors."

The geometrical arrangement which, for a given size and separation of conductors, gives a minimum characteristic residual voltage, does not of necessity give the minimum interference effects due to balanced currents and voltages, when paralleled by a communication circuit. Within the limits of a parallel the configuration which will give the minimum interference effects should be chosen. Outside the limits of the parallel the conductor arrangement may be made such as to give the minimum residual voltage.

The two cases will be considered separately.

CONFIGURATION TO GIVE MINIMUM CHARACTERISTIC RESIDUAL VOLTAGE.

Formulæ have been developed enabling the residual voltage of lines which are short compared with a wave-length to be determined from the physical dimensions of the line. From the formulæ a study was made during the Californian investigation of the variation of the characteristic residual voltage of circuits with the relative position, spacing, size and height of conductors and position of the earth wire. The calculated results were shown graphically by curves attached to Technical Report No. 51. From these curves the range of values to be expected with various configurations are shown in Table 2.

It will be observed that of the several configurations studied the triangular arrangement gives the lowest characteristic residual voltage. For this configuration the characteristic residual voltage is practically the same whether the base of the triangle is horizontal, vertical or otherwise. With the same ratios of height and size to spacing of outside conductors, the vertical configuration has a larger characteristic residual voltage than the symmetrical horizontal. This difference is small, however, being of the order of 1 per cent of the balanced three-phase voltage between conductors. " When the spacing of adjacent conductors in the horizontal configuration is made unequal the residual voltage is increased over the vertical, and this arrangement gives rise to the maximum characteristic residual voltage found."

For the peaked triangular configuration (i.e. ratio of altitude to base is $> \sqrt{3}/2$) with base horizontal and vertex upward, and for the flattened triangular configuration (i.e. ratio of altitude to base is $< \sqrt{3}/2$) with base horizontal and vertex downward, the characteristic residual voltage is zero with a particular value of the altitudes of the triangle in each case, depending on the height of the conductors. Curves are given in Technical Report No. 51 " showing the relationships of height, base and altitude of isosceles triangles, the bases being horizontal, for which the characteristic voltage is zero."

TABLE 2.

Range of Characteristic Residual Voltage : Single-Circuit Lines.

Configuration	Characteristic residual voltage: per cent of balanced 3-phase voltage between conductors
Equilateral triangle	0·5–4
Vertical	6–11
Horizontal—	
Symmetrical	5–9
Unsymmetrical	7–13
Isosceles triangle—	
Base horizontal	0–8
Base vertical	0·5–9
" L "*	2
Inverted " L "*	5·5

* In these two cases single values only are available.

No mention has been made in the preceding discussion of the effect of unbalances in the insulation resistance of the conductors. Experimental tests made by the Californian Railroad Commission on a 37-mile line under wet weather conditions show that " unbalanced leakage is of relatively small importance as compared to unbalanced capacitances in determining the residual voltage of a well-maintained isolated system " (30).

Table 2 in Appendix 3 gives the characteristic residual voltage for typical single and twin-circuit lines.

CONFIGURATION TO GIVE MINIMUM INTERFERENCE EFFECTS FROM BALANCED VOLTAGES AND CURRENTS.

To obtain a comparison of different configurations of single-circuit power lines with respect to induction in a parallel communication circuit, representative dimensions were chosen during the Californian investigation for 100, 60, 30 and 11 kV lines and the induced voltages in a parallel communication circuit were determined from the curves.

"The figures in Table 3 show the range of horizontal separations within which the specified configuration gives the minimum coefficients of induction." "It is not possible to draw a generally applicable conclusion regarding the most advantageous type of power circuit for minimizing the inductive disturbances, as it varies with the spacing of the power conductors, the type of induction and the horizontal separation."

The table shows that "considering the range of separations from 50 to 75 ft., which will include most cases of parallel lines separated by the width of a highway," the vertical type of power circuit will nearly always cause the smallest inductive effects for lines over 30 kV. For power circuits of less than 30 kV the vertical and equilateral triangular configurations have nearly equal effects, and for these circuits the triangular configuration may be preferred under certain conditions. The induction from the latter type of circuit is practically the same whether the base is horizontal or vertical, and, if vertical, whether the vertex is toward or away from the communication circuit.

TABLE 3.

Limits of Horizontal Separation (Feet) for Configuration giving Minimum Induction.

		Earthed circuit				Metallic circuit			
Configuration		△ ◁ ▷	•—•—•	•——•–•	⋮	△ ◁ ▷	•—•—∘	•——•–•	⋮
Balanced voltages	100 kV	95–170	170–1 000	—	30–95	140–280	280–1 000	—	30–140
	60 kV	70–170	170–600	—	30–70	110–250	250–600	—	30–110
	30 kV	65–125	—	125–350	30–65	95–195	—	195–350	30–95
	11 kV	40–120	—	120–200	30–40	70–180	—	180–200	30–70
Balanced currents	100 kV	580–1 000	—	—	30–580	30–50	—	—	50–1 000
	60 kV	460–600	—	—	30–460	30–45	—	—	45–600
	30 kV	—	—	—	30–350	30–55	—	—	55–350
	11 kV	—	—	—	30–200	30–45	—	—	45–200

Horizontal types of circuit give the greatest inductive effects for lines separated by the width of an ordinary roadway, but for large separations give the smallest coefficients of induction from balanced voltages. For horizontal circuits a displacement of the intermediate conductor from mid-position up to 30 per cent of the spacing of the outside conductors was considered. Induction from balanced currents is approximately a minimum when the intermediate conductor is in the mid-position, but the total change due to extreme displacements amounts to only a few per cent. The coefficients of induction from balanced voltages vary between limits of 60 to 190 per cent of those for the mid-position, the lowest values occurring when the intermediate conductor is displaced towards the communication circuit. Where an unsymmetrical configuration is used it is therefore advantageous to have the intermediate conductor on the side towards the communication circuit.

Triangular configurations other than equilateral.—The Californian Railroad Commission's Report gives curves showing the variation of induction from both balanced voltages and currents as the altitude of the power-circuit triangle is increased. The curves apply to both horizontal and vertical base triangles and show minimum induction for certain limiting cases corresponding to a vertical or horizontal configuration. The magnitude of the variation depends largely on the height of the power conductors and the relative position of the circuits.

TWIN-CIRCUIT POWER LINES.

INTERCONNECTION FOR MINIMUM UNBALANCE.

When two synchronous circuits are carried on the same line of poles, it is possible to interconnect them, or otherwise fix the phase relationships between the various conductors, so that their capacity unbalances tend to neutralize. Appendix 3, already referred to, shows the characteristic residual voltage due to this capacitance unbalance for six different methods of interconnecting twin-circuit lines. It is shown that for twin circuits of any type the maximum unbalances occur when conductors at the same potential are symmetrically located with respect to an intermediate vertical plane.

"For circuits of the vertical type, or with top and lowest conductors in the vertical plane and middle conductors displaced outwards a small distance, the minimum resultant unbalances are obtained when the top conductors of the two circuits are at common potential and the middle and lowest conductors of one circuit are at the potentials of the lowest and middle conductors respectively of the other." For triangular and horizontal circuits the minimum resultant unbalances are obtained when similarly placed conductors of each circuit are at common potential.

Figures given in the Appendix show that "of the cases studied, with one exception, twin circuits have a very material advantage over the corresponding single circuit, provided care is taken to interconnect them so as to secure minimum characteristic residual voltage. On the other hand, the result may be very much worse if such care is not taken."

When earth wires are used, or in cases where unsymmetrical circuits or more than two circuits are involved, a special study is necessary to determine the best arrangement.

Transposition of the conductors materially reduces the capacitance unbalance of both single-circuit and twin-circuit lines.

INTERCONNECTION TO GIVE MINIMUM INDUCTION.

With twin circuits of the vertical type, or having the middle conductors slightly displaced outward from the plane of the top and lowest conductors, the two circuits may be so operated that the induction from them is less than that from a single circuit of the same type. In general, the most favourable condition is to have the diagonally opposite conductors at common potential. For circuits of other types it is not possible to give a general recommendation. In some cases it is possible to interconnect the two circuits so that the induction is less than it would be for either one alone, but no method of interconnection of two horizontal-type power circuits gives induction from the balanced voltages less than that due to a single circuit of the same type.

Induction from Residual Voltages and Currents.

No considerable advantage is gained by the use of any particular configuration for a single-circuit line, or from any particular method of interconnection of twin-circuit lines with respect to the induction from the residual components of current and voltage.

EARTH-CONNECTED SYSTEMS.

Single earth connection.—The effect of earthing the neutral at one end of the power line is to reduce the residual voltage, since a residual current can now flow. The value of this residual current is given "by the product of one-third the residual voltage which would exist were the line isolated from earth, and the admittance to earth of the conductors of the circuit in parallel."

Insertion of resistance in the earth connection to reduce undesirable large fault currents has little effect in reducing the residual capacity currents, as pointed out by Marchant (25).

Multiple earthing.—The third-harmonic currents and voltages which tend to be present whenever transformers are connected to the line are residual currents and voltages. In cases where a simple system, such as a transmission line transmitting power between two points only, is concerned, earthing the system at the second point leads to an undesirable increase in triple-harmonic currents through the earth connections and earth. Practical experience has shown that this increase in residual current may result in serious interference.

With a view to limiting this increase in triple-harmonic currents the regulations of the Board of Trade* allow each distinct high-pressure three-phase circuit to be insulated from earth or earthed at one point only. If the earth connection is made through a resistance, this must be low enough to ensure that the system is disconnected when a fault occurs.

On extensive systems interconnecting several generating stations, earthing the system at one point only causes the operation of protective gear to be uncertain. It is possible that the fault may not be disconnected rapidly. The continuance of the large residual currents resulting therefrom provides the conditions which may result in serious interference. In order to reduce the induction effects, which are liable to cause damage to plant, acoustic shock and danger to life, it appears that restricted multiple earthing is necessary although the effect on induction during normal conditions has not been fully investigated.

Stigant and Lacey † state, however, that as a result of experience gained in the U.S.A. the restriction on multiple earthing is unnecessary; and many large systems are said to operate with several neutral points earthed and with little telephone interference.

As a result of certain tests described in Appendix 4, "multiple earthing on the North-East Coast systems has been agreed to, subject to certain qualifications which include an embargo on generators feeding directly into a circuit" (32).

Petersen earth coils.—Earthing the neutral of power circuits through reactance coils has been adopted in many cases in Europe, and reference is made to this matter in Appendix 4. Although the Petersen earth coil appears promising as limiting the magnetic induction arising from faults to earth, experiences appear to be conflicting; and the possibility of over voltages arising with the earth coil systems is apparently not fully understood.

OTHER CAUSES OF RESIDUALS.

Single-phase tappings.—Single-phase tappings, metallically connected to a three-phase circuit, unbalance the line admittances. "Even short branches of this character may cause an unbalance equal to that of the three-phase circuit without transpositions" (30). Elimination of the metallic connection by the insertion of a transformer with a 1/1 ratio removes the unbalanced admittances from the three-phase line.

Unbalanced loads.—Unbalanced load between phases and earth on star-connected circuits with earthed neutral can cause both types of residual. Removal of the earth path by allowing only one point to be earthed on the line is the most effective and reliable remedy to eliminate the residual currents. A slight voltage unbalance will, apparently, remain, but there is no evidence that this is of importance.

Unequal ratios of transformers.—Unequal ratios, or unequal impedances of the transformer phases, may be the cause of residual components. In the same way as mentioned under paragraph (*b*) above, allowing only one earthed neutral point on the circuit eliminates current residuals.

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* Now the Electricity Commissioners' Regulations.
† "The J. and P. Transformer Book," p. 236.

ABNORMAL AND TRANSIENT CONDITIONS.

Under abnormal conditions, such as those due to earth faults and switching operations, large residual components exist for a very short time usually. Interference is, therefore, very much greater during this time than that existing under normal conditions.

Switching operations.—Large residual voltages and currents exist momentarily during switching operations, when the phases of a three-phase system are not connected or disconnected simultaneously. Oil-break switches, having their poles mechanically interconnected for simultaneous action, were considered by the Californian Railroad Commission to be preferable to air switches and non-interconnected single-pole oil switches. A description of some air-break switch tests (98) shows that an air-break switch may take from 120 to 1 500 cycles to interrupt a circuit, depending mainly on weather conditions.

Charging electrolytic lightning arresters.—" Transient disturbances of severe nature to telephone circuits are sometimes caused by the charging of electrolytic lightning arresters," according to the Preliminary Report of the Californian Investigation. The use of charging contacts with spring clips and auxiliary charging resistances in order to prevent arcing and to reduce the current rush enables such interference to be greatly reduced.

SHIELDING EFFECT OF EARTHED BODIES.

A summary of the experimental results obtained by the Californian Railroad Commission on the shielding effects of earthed conductors is contained in Appendix 5, together with results obtained in England, Germany and New Zealand.

The Committees responsible for drawing up the French and German rules seem to have arrived at the conclusions that the effect of shielding due to neighbouring earthed bodies is insufficient for such to be an effective remedy in itself for electric induction. The reduction is, however, sufficient to warrant its inclusion in the calculations. Values are given in the German and French rules as follows:—

Reduction factor $p = 0{\cdot}75$ for a continuous earth wire (lightning guard wire) on the power line.

Reduction factor $q = 0{\cdot}7$ for a continuous row of trees in the neighbourhood of the power line.

Reduction factor $r = 0{\cdot}7$ for a continuous row of trees in the neighbourhood of the communication line.

Factors q and r are to be made $= 1$ if the tree-tops are more than 3 metres from the line concerned.

The question of shielding is considered in some detail in the Appendix, since there appears to be an impression that by the use of one or two earth wires interference due to electric induction can be obviated. The data shows that, in general, only a small reduction is obtained, and that even with a large number of earthed wires the elimination is by no means complete.

UNDERGROUND CABLES.

No information has been collected as to the interference caused by power circuits contained in lead-covered underground cables.

(4) TRACTION CIRCUITS.

ALTERNATING-CURRENT SYSTEMS.

An empirical formula, determined from tests made at 15 to 50 cycles per second, has been given for the mutual inductance in the case of a single interfering line, such as an a.c. railway, and a communication circuit with earth return:—

$$M = \frac{4}{\sqrt{a}} \times 10^{-3} \text{ henry per kilometre,}$$

where a is the separation in metres. Jäger (88) gives an experimental curve showing a similar result.

It may be stated here that in the U.S.A. the chief trouble from 25-cycle traction is not noise but operation of bells, production of e.m.f., etc. The telephone cable is found to be an ineffective remedy against magnetic induction for 25-cycle railways—the booster seems to be the only successful device. This is unpopular with the railway authorities.

DIRECT-CURRENT SYSTEMS.

Tramways.—Bartholomew (32) mentions that if the tramway system is extensive, with substations feeding the system in common, the disturbance is usually more severe owing to balancing currents constantly flowing between substations. Independent feeding of each section of the trolley wire will usually reduce trouble. In such cases it should be pointed out that this may result in an uneconomical feeder lay-out or poor voltage regulation.

Tests were carried out during a joint investigation by the General Electric Company and the American Telephone and Telegraph Company, both of America (125), to determine causes of disturbance produced by trolley cars, but to what extent trolley arcing is a serious disturbance, we have no definite evidence. The success of the application of resonant shunts in reducing supply harmonics, and with them the disturbing noise, indicates that this cause is not important. Modifications in the design of the trolley-wire lay-out and hangers have not been suggested as a remedy.

Railways.—On d.c. railways the most serious disturbances occur during conditions of short-circuit. In order to limit the duration of the transient conditions, high-speed circuit breakers have been developed (133).

Comparative figures showing the values of the induced voltages with and without high-speed circuit breakers are not available, so that the degree of protection afforded is not known. Wüthrich has given a summary of the views of Behn-Eschenburg and Kristen in which it was stated that " the maximum induced pressures are not reduced by the quick-acting switches; the advantages secured reside in the fact that the duration of action of the phenomena is reduced and the disturbances thus rendered less harmful."

(5) TELEGRAPH CIRCUITS.

Telegraph circuits are usually single-wire circuits with an earth return. The highest pressure employed in this country is 120 volts, higher voltages being used in some other countries. There are various types of circuit giving a range of speed of working of from 20 to 200 words per minute, and sometimes higher. The minimum current required to operate the relays varies from 0·5 to 5 milliamperes, but for certain types of apparatus, and for the higher speed circuits generally, it may be larger.

Interference to telegraph circuits chiefly occurs through induction from the fundamental frequency of the power or traction circuit. Since telegraph circuits are usually operated by nominal direct current and the disturbing current is alternating, many remedies have been evolved by which telegraph apparatus may be protected from the effects of induction. In Appendix 6 numerous devices are described which have been tried, or suggested, mainly to overcome induction due to single-phase railways.

The majority of these devices call either for some special modification of the apparatus, or for the insertion of additional apparatus into the telegraph circuit. With certain of the systems described successful working has been obtained with induced voltages considerably above 100, and, in at least one case, up to 300 volts. Most of these tests have been carried out in France.

The use of metallic circuits for telegraphs should not require any of the above modifications to apparatus, but it does not appear to have been applied in practice as a usual remedy. Apparatus should be connected symmetrically to both wires of a metallic circuit in order to prevent interference due to capacity currents resulting from an unbalance of the line.

(6) TELEPHONE CIRCUITS.

Open-Wire Circuits.*

BALANCE OF TELEPHONE CIRCUITS.

A telephone circuit would be balanced if, in each elementary section of its length, its two sides had equal self and mutual impedances and equal admittances to earth and to other conductors. Under these conditions, with equal longitudinal voltages induced in each side, there would be no transverse voltage. This definition does not require longitudinal uniformity, but only that corresponding constants of the two sides should be equal at the same point, and similarly through the circuit.

There are two general types of unbalance:—

(i) Self unbalances involving only wires and earth,
(ii) Mutual unbalances involving other conductors.

Removal of unbalances.—Since both sides of a circuit are constructed of the same wire and are the same height above earth, self unbalances are not inherent. They are largely accidental due to defective joints, defective loading coils, broken insulators, tree leaks, dissymmetry in apparatus inserting series impedances in circuit or connection of admittances between the sides of the circuit and earth.

By transpositions, mutual unbalances in one section neutralize those in the next section.

"The degree of balance that can be obtained commercially in open-wire circuits can be fairly expressed as one with which the telephone circuit is undisturbed by other telephone or telegraph circuits on the same route" (32). The absence of cross-talk between communication circuits is not, however, an effective criterion of the balance of a circuit with respect to other external disturbances (110).

Effect of unbalances.—Differences in admittance to earth, or in series impedance of the two sides of a circuit, will cause disturbing currents to flow through the terminal apparatus, even though both wires may be similarly situated with respect to the source of interference.

Small defects in the circuits and slight unbalances in apparatus, particularly if such is earth-connected, become of importance, since the induced voltages may be high compared with the operating voltage.

CONDUCTOR ARRANGEMENTS TO GIVE MINIMUM INDUCTION.

Three methods of arranging the four conductors forming a phantom group were considered by the Californian Railroad Commission (30).

(i) Horizontal phantom:

All four conductors on one arm, adjacent wires forming the two side circuits.

(ii) Vertical phantom:

Two conductors on one arm grouped with the two on the arm immediately below. The two side circuits consist of conductors on the same arm.

(iii) Square phantom:

As the vertical phantom, but the two side circuits made up from diagonally opposite conductors.

It was found that the coefficients of induction for the transverse voltages induced in the phantom circuits of the square phantom group were "less than 4 per cent and in one case as low as 0·02 per cent of the corresponding coefficients for the horizontal phantom." In most cases, however, the coefficients of induction for the two side circuits of the square phantom group are greater than those for the side circuits with either of the other two methods of conductor arrangement. The relative magnitudes of the coefficients for horizontal and vertical phantoms depend largely upon the configuration of the power circuit and the type of induction.

The transverse voltages induced in the side circuits of vertical and horizontal phantoms are closely proportional to the spacing of the conductors.

Curves were also prepared showing the induction coefficient as functions of the angular position of the conductors for two values of the separation. The curves for induction from residual voltages and currents are approximately sinusoidal. "The angular position for which the coefficient is zero varies with the relative position of the circuits."

The method of arranging the telephone conductors in forming the phantom group has no appreciable effect on the longitudinal voltages induced by voltages or currents.

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* Except transposition schemes which are dealt with in Section 7.

TELEPHONE CABLE CIRCUITS.

Communication circuits contained in underground cable are not subject to electric induction.

The transverse induced voltage due to magnetic induction will be considerably diminished, since this decreases with reduction in conductor spacing and in a cable metallic circuit conductors are twisted together, while, when two such physical circuits are connected to form a phantom circuit, the physical circuits are twisted together to form a quad which maintains its identity throughout the cable.

The consequence of earthing the lead sheath is to bring into play a compensating effect which reduces to some extent the longitudinal induced voltage. A number of writers have considered this effect in particular connection with induction due to single-phase railways. Jäger (88) gives a figure of 29 per cent for the amount of compensation in an existing normal cable with good sheath connection. In tests carried out by Siemens and Halske (80) a reduction of 80 per cent was obtained using a specially armoured cable. The compensating effects are greater for the higher frequency components.

Telephone circuits placed in cable demand a high degree of balance to avoid cross-talk between adjacent circuits, so that interference would be less than on open-wire circuits even if the coefficients of induction were the same in each case. It is clear that weather and other conditions which cause the circuit unbalance of open-wire lines to vary are absent in the case of cabled circuits.

In Great Britain, and in most other countries in Europe, the majority of important telephone circuits have been placed underground.

No experiences are available regarding interference to cabled circuits due to power lines. Considerable experience is available in cases where single-phase railways are concerned, and this tends to show that on sections with heavy traffic and during short-circuit conditions interference will occur on cabled circuits.

The above discussion applies to cables carried overhead as well as to underground cables, provided the sheath is well earthed.

REDUCTION OF EFFECTS PRODUCED IN TELEPHONE RECEIVER.

BY TRANSVERSE INDUCTION.

Transposition of the telephone conductors eliminates or materially reduces the transverse voltage due to induction from both the balanced and residual components of voltage and current in the power circuit.

BY LONGITUDINAL INDUCTION.

Telephone transformers.—It is evident that any circuit liable to be connected to the circuit exposed to induction requires to be equally free from unbalance. Separation of such circuits may be obtained by making the connections between the circuits through transformers or repeating coils. Well-balanced circuits can therefore be connected to circuits of a lower standard or to exchange apparatus without degrading the whole combination. The induced voltage due to longitudinal induction is separated from exchange apparatus, thus avoiding possible danger to apparatus. A certain loss in speech efficiency is introduced with these transformers and changes in the signalling arrangements are necessary in some cases (32).

The use of transformers between the local subscribers' circuit and trunk, or long junction circuits, is standard practice in this country, and also for toll circuits of the Bell system in the U.S.A.

Overvoltage protectors.—As explained in Section 2, dangerous noise is caused in the receiver when the induced voltage exceeds the protector breakdown voltage, a condition which may occur during transient power-circuit conditions. This danger arises since the safety device on one wire operates before that on the other. In order to meet this difficulty attempts have been made to produce a protective device which would give simultaneous operation, e.g. vacuum-tube protectors with three electrodes; but, although a number of these have been described in various publications a thoroughly satisfactory type, or one providing for the simultaneous earthing of both sides of the circuit, has not yet been constructed.

Acoustic shocks have affected the personnel of the German Telegraph Administration considerably.

Special circuits.—Telephone transformers insulated to withstand a very high voltage between windings are employed on telephone circuits used by power companies for control purposes (22). Separation in these cases is small and induction is intense.

Since these circuits are of a special nature and of great importance economic considerations occupy a minor place.

Drainage coils.—The use of a drainage coil, consisting of a high-impedance coil connected across the conductors of the telephone circuit and earthed at its mid-point, is mentioned by various authorities. The general conclusion is that, although these coils may be used with good effect on strongly induced lines, such as private lines carried on power poles, they cannot be regarded as a general remedy for public service lines (118).

These and other special systems are mentioned in Appendix 7.

Earth-return signalling circuits.—The earth is used as a return for signalling currents on some junction circuits. On such circuits interference is possible, due to differences in earth potential—as well as that due to induction—from traction circuits.

In Appendix 8, reference is made to a portable noise-measuring set developed in the U.S.A., by means of which the noise on any circuit can be directly measured in terms of an arbitrary noise unit.

(7) TRANSPOSITION SCHEMES.

Transpositions in power and telephone circuits constitute a very important factor in mitigating the interference experienced from parallelism of the two classes of circuit. They also serve to improve the balance of the individual circuits.

TELEPHONE CIRCUITS.

In order to reduce cross-talk between metallic telephone circuits and induction from single-wire telegraph circuits it is usual to transpose metallic circuits on open-wire lines. Two systems of transpositions have been used. The symmetrical twist system is the older and in it groups of four adjacent wires are chosen as units, so that the wires of a group occupy positions on the pole-arm corresponding to the corners of a square. The diagonal wires form the two circuits. At successive poles each wire changes its position to the next corner of the square, so that the four wires go through a complete revolution every four poles.

The transposition system of cross-overs has been employed in the past by the American Telegraph and Telephone Company. On this system all the wires are run straight, and each circuit is made up from two adjacent wires on the same arm. The two wires forming a circuit are crossed at intervals on the line, whilst cross-talk between circuits is obviated by a systematic arrangement of crosses in those circuits which are likely to interfere with one another. Crosses are so placed that over an 8-mile section each circuit is balanced against the others. The transposition points vary for each circuit. This system has been adopted as the standard transposition system by the British Post Office.

POWER CIRCUITS.

Barrel.—Transposition of the power conductors is an effective remedy for unbalanced capacitances, according to the final report of the Californian Railroad Commission (30). " Such transpositions must be located with proper regard to changes in configuration, and at short enough distances from each other so that there is no material difference in the electrical conditions at two such points at any given instant."

Owing to the fact that neither along the power circuit nor along the communication circuit is the speed of propagation of the electric waves infinite, the efficiency of a transposition scheme involving long barrels decreases for the higher frequency components of the power wave. The effects of both attenuation and phase-change are discussed more fully in Appendix 9.

Where there is more than one barrel, three simple arrangements may be used having barrels of equal length. Using like transpositions throughout, equally spaced, the barrelling is " *continuous.*" With every third transposition omitted the barrels are of the " *halting* " type. The same with the transpositions of alternate barrels reversed are designated as " *halting-reversing.*"

The following paragraph taken from Technical Report No. 51 of the Californian Railroad Commission sums up the length and type of transposition barrels which appear desirable to reduce the residual voltages due to line unbalance:—

" In determining the length of barrels required to limit the residual voltage of power circuits isolated from earth to a given magnitude, the characteristic residual voltage of the circuit is an important factor, shorter barrels being required with larger characteristic residual voltages. The exact relationship of these two factors for a constant residual voltage has not been determined. Under average conditions of wave-form it should be expected that 9-mile barrels will effectually balance triangular lines (or twin-circuit lines so interconnected that their characteristic residual voltages are of the same order of magnitude as that of a single-circuit triangular line) and that 6-mile barrels will balance lines of other configurations, so as to limit the residual voltages of fundamental and higher frequencies to relatively small magnitudes as compared with those of a non-transposed line." " Halting "-type barrels will probably be more effective, since the effects of phase-change are thereby reduced.

CO-ORDINATION OF TRANSPOSITION SCHEMES.

The effect of transpositions in each circuit on the induction from the balanced and residual components of current and voltage is shown by the following table:—

TABLE 4.

Voltage or current component	Induction	Effect on induction due to	
		Power transposition	Communication transposition
Balanced	Longitudinal	Reduction	None
Balanced	Transverse	None	Reduction
Residual	Longitudinal	None	None
Residual	Transverse	None	Reduction

It will be seen that the transposition of neither circuit alone is a sufficient remedy, and that no transpositions have any effect on the longitudinal induction from residuals. The importance of reducing these in the first place is therefore apparent. Longitudinal induction due to balanced components is reduced to some extent by the power transpositions, whatever their locations. If the power and telephone transpositions are not co-ordinated, transverse induction may be greater with both power and telephone transpositions present than if either kind were absent.

The object of co-ordinated systems of power and telephone transpositions is to provide such relative location of transpositions in the two classes of circuit, that maximum effectiveness in reducing the unbalanced exposure for both balanced and residual voltages and currents is secured. The *unbalanced exposure* is defined as the length of parallel between two non-transposed circuits of the given configuration and separation which will produce inductive effects of the same magnitude as those produced in the actual parallel.

In practice, points of discontinuity occur due to an abrupt change of the separation, or of the physical or electrical characteristics of either circuit. These divide the complete parallel into a number of different uniform parallels, each of which needs to be considered separately. " Ordinarily it is desirable to obtain a balance (zero unbalanced exposure) within each such uniform section " (30).

The method for obtaining the amounts of unbalanced exposure in an actual parallel is given in Appendix 10, where a practical example is referred to.

Even though the transpositions are so co-ordinated that the unbalanced exposures as calculated are zero, neutralization is not perfect. This is due to the following causes:—

(a) Non-uniformity of uniform parallels, since only major points in actual lines can be taken into account and numerous minor ones must be disregarded.
(b) Attenuation and phase-change in the power and communication circuits are neglected. The unbalanced exposures thus introduced may be considerable.
(c) Since it is impracticable to balance perfectly the series impedance and the admittances to earth of the sides of a telephone circuit, longitudinal induction causes current in the telephone circuits.

Power circuit transposition as part of a co-ordinated scheme.—Special transpositions are possible in which pairs of conductors are interchanged only, enabling the effect of cross-overs between power and telephone lines to be approximately neutralized when the separation is large compared with the length of the telephone cross-arms and is the same on both sides of the cross-over. By superimposing a cyclic transposition upon such a special transposition the effect of an ordinary transposition is obtained. It is thus possible to eliminate the point of discontinuity or to use it as an ordinary transposition point, where the above limitations allow.

Telephone circuit transposition as part of a co-ordinated scheme.—Studies were made during the Californian investigation of the unbalances present with various arrangements of telephone transposition sections and power barrels. As a partial result of these studies it was concluded that the standard telephone transposition scheme "is unsuitable for co-ordination with power barrels." Large unbalances on some circuits and long distances between balance points on others are characteristic of this system, when considered in conjunction with a parallel power circuit transposed in other than half-mile barrels.

To meet the need of a system which would give increased flexibility in co-ordination with power transposition barrels of several lengths, the American Telephone and Telegraph Company has developed three methods which, singly or in combination, make it practicable to reduce the unbalanced exposures to small amounts, while at the same time the standard of balance with respect to cross-talk and telegraph induction is maintained:—

(1) "E" and "L" sections, nominally 8 and 4 miles in length, balanced to nominal $\frac{1}{2}$, 3 and multiples of 3-mile barrels.
2) Consecutive "X" sections, that is, successive sections $\frac{1}{2}$ mile or less in length.
(3) "Whole line" transpositions, whereby extra transpositions are inserted in all the circuits of the telephone line.

These are described more fully in Appendix 11.

Results obtained.—33-kV transmission lines, transposed in accordance with the recommendations of the C.R.R.C., have given rise to no complaints of interference at Adelaide in spite of many long parallels with telephone lines at a separation equal to the road width.

Considerable reduction in interference has also been obtained by a co-ordinated scheme of transpositions at Iowa, U.S.A. (96).

(8) HARMONICS.

Under normal operating conditions interference to telephone circuits is almost entirely due to higher harmonics of the power-circuit voltages and currents. These cover a considerable portion of the range of frequencies used for the transmission of human speech, and over which the telephone is most sensitive.

Interference Effects of the Various Harmonics; Telephone-Interference-Factor-Meter.

Experimental tests have been carried out by the American Telephone and Telegraph Company at various times in order to determine the relative effect of harmonics of different frequencies in producing interference in telephone systems. These indicate a maximum interfering effect at about 1 100 cycles per second. Particulars of these tests are given in Appendix 12, where also a network is described, such that the current in one branch resulting from a complex voltage wave at the terminals of the network gives an indication of the disturbance which would be caused in a telephone receiver through the distortion of the voltage wave in question. When the distortion is due to the presence of a number of harmonics a reading is given which is proportional to the square root of the sum of the squares of the individual harmonics. Data obtained on the summation law of a number of noises of various frequencies indicate that this law varies under different extreme conditions.

Analysis of Wave Shape.

When it is necessary to locate the origin of harmonics causing interference, exact measurements of their magnitudes will not be required so much as the determination of their frequencies. Methods for a complete analysis of the wave shape are given in Appendix 12.

Sources of Harmonics.

Features in the design of machines or apparatus which contribute to the production of disturbing harmonics are dealt with at greater length in Appendix 13. Together with the various technical devices which have been proposed for diminishing the harmonics, they are summarized in the following paragraphs.

A.C. generators.—Generator harmonics may be divided into two groups:—

(1) Spacing ripples or harmonics.
(2) Tooth ripples or harmonics.

While the causes of these harmonics are clearly different when the phenomena are discussed in the simple fundamental case, there seems to be a possibility of confusion in actual cases. This may be partly because the orders of the harmonics of each type present are likely to be the same.

Spacing harmonics are not present when there is a sine wave of flux.

In salient-pole alternators, harmonics may be largely avoided by shaping the pole-shoes so that the air-gap is increased from the centre of the pole-pitch to the pole-shoe tips. Then in conjunction with a suitable interpolar gap a near approach to a sinusoidal flux-space wave may be obtained.

The harmonics present in the flux wave of a non-salient pole turbo-generator due to the concentration of the exciting winding into the rotor slots are of the order $(2R \pm 1)$, where R is the number of rotor slots per pole. They reappear greatly reduced in the phase e.m.f., except when both rotor and stator have approximately equal slot pitch. In this case there is no diminution.

Suitable chording of the winding to some fraction of the pole pitch (possible in two-layer windings), with a whole number of slots per pole, enables certain harmonics to be reduced as indicated in the Appendix. With high-speed alternators, having few poles and coils of very wide span, a certain amount of chording has much in its favour.

The toothed armature may be reduced in effect to a smooth-core armature with the distribution factors as for uniform distribution, if either the armature slots or the edges of the pole-shoes are skewed along their axial length through an amount equal to a tooth-pitch.

A simpler and almost equally effective method is to move all the poles of one sign circumferentially in the same direction through half a tooth-pitch.

The use of a fractional number of slots per pole pair, as by the use of a d.c. two-layer wave winding, reduces the reduction factors for the harmonics to practically those for a uniformly distributed winding. In the case of single-layer windings this condition may be reached by—

(a) Fractional number of wound slots, using divided coils.
(b) Whole number of wound slots, plus a fractional number of empty slots per pole-pair.

Increasing values of the slots per pole per phase closely approach the curve for uniform distribution over one-third of the pole-pitch, due to the coil sides of a phase occupying different positions in successive fields.

Shaping of the pole-shoes of salient-pole alternators also tends to reduce the tooth ripple and a careful adjustment of combined air-gap length and tooth reluctance may result in a negligible ripple.

If the unwound part of the rotor is left unslotted or if magnetic wedges are used to close these slots, harmonics—particularly the third—may be increased, as pointed out by Smith and Boulding.

Where damper windings are present in the pole-shoes of salient-pole alternators, the pitch of the damper bars should not be the same as the armature slot-pitch, in order to avoid conditions similar to that when the rotor and stator slot-pitches of turbo-alternators are nearly the same.

Harmonics which are multiples of the third give rise to residual currents and voltages and are therefore specially to be avoided.

D.C. generators and motors.—Tooth ripples are present due to the slots in the same way as in alternators, their frequency being equal to the number of slots passing the brushes per second.

Ripples may also be caused by the commutator segments, their frequency being equal to the number of segments passing the brushes per second.

Remedies mentioned above are, in some cases, applicable. Shaping of pole-shoes and remedies reducing the winding in effect to a uniformly-distributed winding reduce the slot ripples.

Rotary convertors.—Jakeman has pointed out that by a certain arrangement of the six rings the slots per pole may be made fractional, reducing largely the slot ripple. The arrangement of tapping points also reduces the sixth frequency ripple. A 9-ring rotary convertor with a fractional number of slots per pole has also been proposed.

Other remedies which endeavour to overcome tooth ripples by making the winding as far as possible equivalent to a uniformly-distributed winding are—

(a) To displace the pole-shoes circumferentially.
(b) To skew the pole-shoes.
(c) To skew the slots.

Each of these remedies has been mentioned in connection with a.c. generators.

Transformers.—With a sine wave of flux and consequently of induced e.m.f. if conditions allow, the no-load current may contain a prominent third harmonic, which produces a peakiness in the wave of the magnetizing current component. This is mainly through a variation in the permeability of the sheet steel and only in a very small degree through the hysteresis component of the current due to cyclic hysteresis.

With a sine wave of no-load current, the flux and consequently the induced e.m.f. may, if conditions allow, contain prominent third harmonics which produce a flat-topped flux and peaked induced e.m.f. waves.

The fifth and higher harmonics may also be present with reduced amplitude, but as regards harmonics other than triple harmonics there is always an external path enabling corresponding currents to flow. The voltage harmonics remaining depend on the impedance of such paths.

The provision of a low impedance path to enable the third-harmonic currents to flow, leads to a small resultant third-harmonic flux and in consequence to a small third-harmonic voltage. The path supplied must naturally be confined to the close neighbourhood of the transformer, to avoid the possibility of these third-harmonic currents causing interference. Transformers with one or both windings connected in delta fulfil this condition. Where a star/star connection is necessary, a delta-connected tertiary winding is suitable. Where transformers connected star/star are already installed, the provision of an auxiliary transformer with a delta-connected secondary winding provides a path for third-harmonic currents when the neutrals are connected.

These conclusions apply to single-phase transformers of both shell and core types, and to three-phase shell-type transformers. With three-phase core-type transformers any third-harmonic fluxes must find their return path outside the core. Such a path is of very high reluctance and consequently the third harmonics in the flux and induced pressure waves are very small.

The relationship between triple-harmonic residuals and the magnetic-flux density in transformers is the subject of a report in connection with the Californian Railroad Commission, based on theoretical and practical work. The conclusion reached, which is confirmed by other investigators, is that avoidance of excessive flux densities as far as possible is the fundamental remedy.

Single-phase commutator motors.—It has been found that disturbances due to this type of traction motor are chiefly due to the high-frequency currents in the commutating armature coils (19). These currents induce in the field winding a high-frequency voltage, which sends a corresponding current through the motor circuit.

From a mathematical investigation a remedy, whereby oscillations due to commutation can be eliminated, has been developed and tested in conjunction with the A.S.E.A. The remedy consists in placing a condenser as a shunt across the field winding of the motor, by means of which the high-frequency voltage induced in the field winding is effectively short-circuited. By connecting two motors in series, the remaining higher harmonics are still more reduced, so that they only amount to 0·03 per cent of the total current. The same phenomenon occurs in direct-current motors, but in this case, these currents are damped by the short-circuiting effect of the non-laminated yoke.

Mercury rectifiers.—Due to the nature of mercury rectifiers ripples are inherent. The d.c. voltage wave-form may be considered as consisting of a constant component, superimposed upon which is a ripple of complex wave-form, the fundamental requency of which is *N* times the supply frequency, where *N* is the number of anodes.

Figures given from various sources show that for a six-phase rectifier the sixth harmonic may amount to nearly 10 per cent of the constant voltage.

General Remedies.

Resonant circuits.—A shunt placed across the source of the ripple and adjusted to the frequency of the harmonic requiring to be eliminated has been found of great value. In order to reduce the magnitude of the harmonic the impedance of the source must be high compared with that of the resonant shunt for the particular frequency. It may be necessary to add a series inductance and connect the resonant shunt as a long shunt across the source and external inductance.

Where the ripple present is due to one pronounced harmonic, this method is an advantage; but where the ripple consists of a number of harmonics this method is likely to be of little use.

Considerable success has attended the application of resonant shunts to the elimination of the ripples from mercury rectifiers (33) and also to the elimination of the tooth ripple from d.c. machines.

Floating battery.—A battery floating across the terminals of a rotary convertor has been effective in reducing the interference to adjoining telephone circuits (32).

(9) CONCLUSIONS.

From a review of the information published up to the year 1925, the several causes of interference appear to have been extensively studied and effective preventatives and protective devices to be well known. Outstanding problems then remaining to be settled were:—

(i) The method of calculation to be adopted for estimating the voltage induced in a communication circuit due to the residual current in a traction circuit with earth return, or power circuit with earthed neutral under short-circuit conditions. This depends to a certain extent on the geological formation of the locality; but there remains a wide divergence between the results given by the application of the different formulæ. Field tests in a number of different localities are required before the induced voltage in the communication circuit can be estimated with any degree of certainty.

(ii) The amount of induced energy necessary to produce acoustic shock.

(iii) The amount of noise that can be tolerated in a telephone receiver without undue interference to speech.*

(iv) The effect of the provision of more than one neutral earth connection on an extensive system interconnecting several generating stations on the interference caused by the normal working of the system. Also, the effect of using reactances in the earth connection requires study. Sufficient experience has probably been gained on this point to enable a decision to be reached if the evidence were collated.

Both the V.D.E. (129) and the Comité Consultatif International (102) have issued guiding rules giving limits which express the màximum permissible amount of disturbance and danger, together with formulæ enabling calculations to be made for particular parallels in order to determine whether these limits are exceeded. The rules drawn up by the V.D.E. were adopted in Germany in 1925. Table 5, prepared by the investigators, is included here, in order to show in a condensed form the chief features of the proposed instructions drawn up by the C.C.I.

The outstanding feature in both the German and French Rules is that the limits are based for the main part on induction during fault conditions, e.g. due to an earthed phase.

As a result of investigations in the field the Californian Railroad Commission (C.R.R.C.) issued in 1918 its General Order No. 52 (31) for open-wire power lines with line voltage above 5 000 volts. These rules lay down, in general terms, the lines on which power systems should be designed and operated.

As a rule, only a close study of the conditions will enable the best results to be obtained in any given case, but the following generalized conclusions, drawn from the various authorities already quoted, may be of service both to power and communication authorities in connection with future lay-outs and projects.

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* Tests carried out in the Research Section of the Post Office indicate that for international or important circuits the induced voltage on the line terminals should not exceed (as regards the intensity of noise in the telephone receivers) an alternating voltage of 3 millivolts at 800 cycles per second. From the point of view of the effectiveness of the connection, there is no reason to differentiate between open wire and cable lines in setting this limit (cf. C.C.I., Proposed Instructions, Table 5).

Design of Machinery and Apparatus.

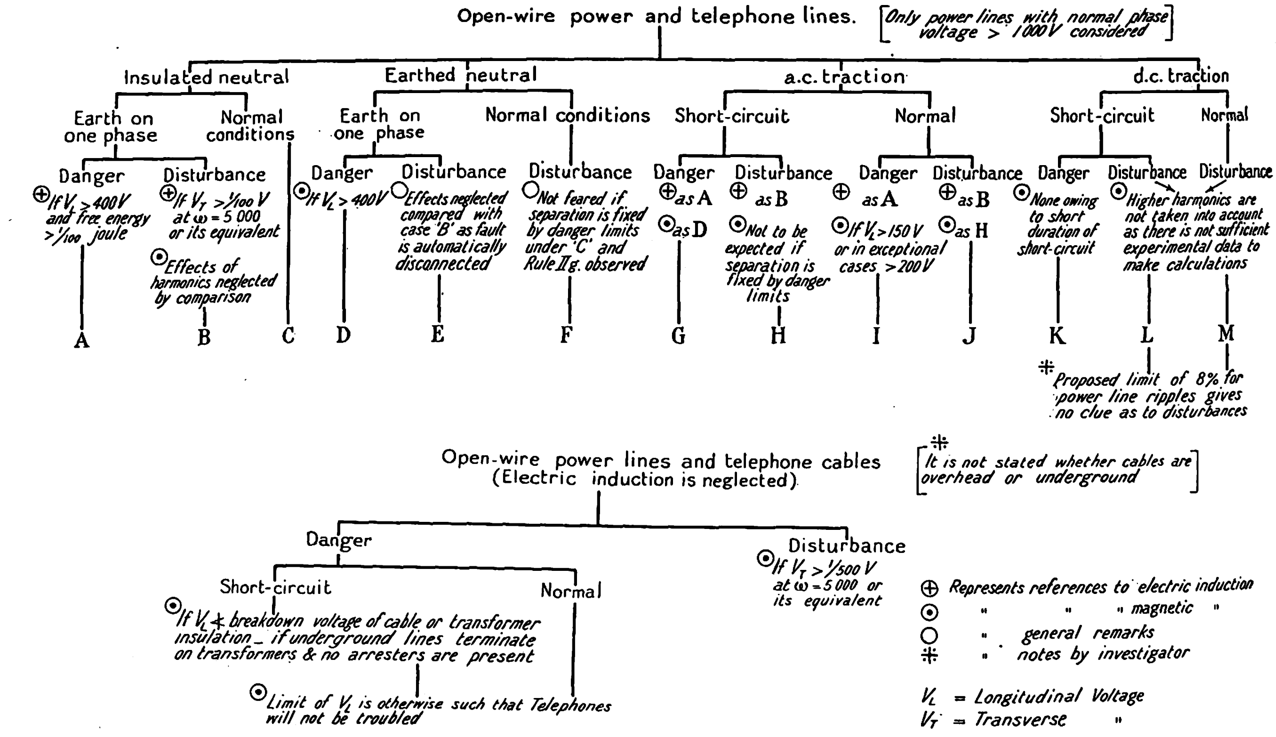
RECOMMENDATIONS.

(1) The wave-form of electromotive force of rotating machines should be approximately sine-shaped under all conditions of load. The C.R.R.C. specify that the maximum deviation of the wave-form from the equivalent sine wave, when superimposed so as to give the least difference, shall not exceed 10 per cent of the maximum ordinate of the equivalent sine wave. The equivalent sine wave is taken as one having the same root-mean-square value and the same wavelength (frequency). The B.E.S.A. rules make provision for a similar requirement.*

Table 5.

Table prepared by Investigator to show Chief Features of the " Proposed Instructions."

Most unfavourable conditions are considered when fixing limits.


Open-wire power and telephone lines.
[Only power lines with normal phase voltage > 1000V considered]
Insulated neutral
Earth on one phase
Normal conditions
Danger
⊕If V_L > 400V and free energy > 1/100 joule
Disturbance
⊕If V_T > 1/100 V at ω = 5 000 or its equivalent
⊙Effects of harmonics neglected by comparison
Earthed neutral
Earth on one phase
Normal conditions
Danger
⊙If V_L > 400V
Disturbance
○Effects neglected compared with case 'B' as fault is automatically disconnected
Disturbance
○Not feared if separation is fixed by danger limits under 'C' and Rule IIg. observed
a.c. traction
Short-circuit
Danger
⊕as A
⊙as D
Disturbance
⊕ as B
⊙Not to be expected if separation is fixed by danger limits
Normal
Danger
⊕ as A
⊙If V_L > 150 V or in exceptional cases > 200 V
Disturbance
⊕as B
⊙as H
d.c. traction
Short-circuit
Danger
⊙None owing to short duration of short-circuit
Disturbance
⊙Higher harmonics are not taken into account as there is not sufficient experimental data to make calculations
Normal
Disturbance
A
B
C
D
E
F
G
H
I
J
K
L
M
⁜Proposed limit of 8% for power line ripples gives no clue as to disturbances
Open-wire power lines and telephone cables (Electric induction is neglected)
⁜[It is not stated whether cables are overhead or underground]
Danger
Short-circuit
⊙If V_L ≮ breakdown voltage of cable or transformer insulation – if underground lines terminate on transformers & no arresters are present
Normal
⊙Limit of V_L is otherwise such that Telephones will not be troubled
Disturbance
⊙If V_T > 1/500 V at ω = 5 000 or its equivalent
⊕ Represents references to electric induction
⊙ " " " magnetic "
○ " general remarks
⁜ " notes by investigator
V_L = Longitudinal Voltage
V_T = Transverse "

(2) In the design of stationary direct-current machines and traction motors, use may be made of various technical devices in order to limit the amplitude of the ripples produced by the slots, etc.†

(3) The disturbance caused by rotary convertors can frequently be greatly reduced by a slight displacement of the poles. A special arrangement of the tapping points gives greatly improved results.

(4) No methods are known whereby the design of mercury-arc rectifiers, themselves, has enabled the sixth frequency ripple to be eliminated. Special precautions may be necessary when mercury-arc rectifiers are connected to the system.

(5) Large triple-frequency voltages and currents may be produced by transformers in which the iron is highly saturated. " With a view to limiting the saturation of the iron, the exciting current at normal voltage should not exceed 10 per cent of the normal full-load current " (C.R.R.C.). When transformers are connected together for three-phase working, the type of connection may be so chosen as to provide a local path for the necessary third harmonic of current. The line voltage and current are then sine-shaped. Three-phase core-type transformers are inherently less liable to produce third-harmonic voltages than three-phase shell-type.

(6) With a polyphase system, switches having their poles mechanically interconnected for simultaneous action must be employed. " Wherever practicable all switching operations should be made on the station side of transformer banks as the transient disturbances on the line are thereby less severe " (C.R.R.C.).

Open-wire power lines.—(7) Excessive conductor spacing should be avoided.

(8) Taking into account the inductive effects, the

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* The rules drawn up by the C.C.I. limit the maximum deviation under the same conditions to 5 per cent of the maximum ordinate of the equivalent sine wave.

In B.E.S.A. Specifications, Nos. 169, 225, 226, published in December 1925, more stringent limitations are imposed in the case of certain classes of machine; the 10 per cent limit referred to above is reduced to 5 per cent, and a still smaller limit is set to high-frequency ripples in the following terms:—

> When a ripple of frequency of 400 per second or above is present in the wave form of electromotive force between any line terminal and neutral, the deviation of this ripple from a mean curve drawn through the ripple shall not exceed 2½ per cent of the maximum ordinate of the mean curve.

† In their final form the C.C.I. rules state that in the case of continuous-current machines, other than convertors and mercury-arc rectifiers, the maximum deviation of the voltage in respect to the average voltage shall not exceed 3 per cent.

reduction of line unbalance and practical considerations of construction, " the equilateral triangular configuration (either horizontal base or vertical base) is in general recommended for single-circuit power lines; and the vertical configuration (including type of construction with middle conductors displaced slightly outwards from the vertical plane of the other two) for twin-circuit power lines " (C.R.R.C.).

(9) Transposition of the whole line should be carried out with " halting "-type barrels of limited length. Single-circuit lines with a triangular arrangement of conductors, or twin-circuit lines so interconnected that their characteristic residual voltage is small, can generally be effectively balanced by 9-mile barrels; 6-mile barrels will balance lines of other configuration (C.R.R.C.).*

(10) Twin-circuit lines are definitely advantageous, as it is possible so to fix the phase relations of the conductors of the two circuits that a partial neutralization of the inductive effects takes place.

(11) In a three-phase system it is essential that the load should be evenly distributed between the phases. Single-phase branches, metallically connected to the conductors, should not be allowed.

(12) Resistance inserted in the earth connection of the star point of the power system will effectively reduce interference trouble in case of breakdown.

Open-wire telephone lines.—(13) Co-ordinated transpositions in power and telephone circuits constitute a most important factor in reducing the interference experienced from parallelism of the two classes of circuit. The " Standard " system of telephone transpositions of the British Post Office is not suitable for use in conjunction with power transposition schemes; but transposition methods for telephone circuits have been developed in America, which make it practicable to reduce the unbalanced exposure to small amounts.

Underground circuits.—(14) Telephone or telegraph circuits carried in underground cables are not subject to interference due to electrostatic induction. Disturbance due to magnetic induction may be very nearly eliminated by accurate balancing of the circuits. Although protection against disturbance does not require a fixed minimum distance of separation, experience has shown that interference will occur due to traction lines, and therefore due to power lines with an earth fault, and communication cables should not be laid in close proximity to such lines.

APPENDIX 1.

LIST OF ARTICLES, ETC., ON WHICH THE SUMMARY IS BASED.

1. " Interference with Communication Circuits," giving the results of investigations on the Mitterwald Railway, Austria. L. Truxa. *Zeitschrift des Oesterr. Ing. u. Arckitekter Verein. Bull.*, vol. 73, p. 149. *Electrician*, October 21, 1921, p. 515.
2. Application of Negative Transformers on the Single-Phase Line from Perpignan to Villefranche of the Midi Railway (France). Ch. Dachary. *Revue Générale de l'Élec.*, vol. 1, p. 331, March 3, 1917, p. 535, April 7, 1917.
3. Question of Power and System in Connection with the Electrification of the Swedish Railways. J. Korne. *Teknisk Tidskrift*, vol. 53 (*Elektrotechnik*), pp. 37–45. *Engineering Abstracts*, vol. 16, No. 251, 1923.
4. Successful Operation of a Telephone System Paralleling H.T. Power Lines. C. E. Bennett. *Gen. El. Review*, December 1914, vol. 17, pp. 1175–1181.
5. Telephones for Power Transmission Lines. J. B. Taylor. *Gen. El. Review*, July 1914, vol. 17, pp. 753, 754.
6. Apparatus for the Protection of Weak Current Cables against the Induction Effect of Traction Currents of Electric Railways. J. Kühle. *Der electrische Betrieb.*, November 26, 1923, vol. 21.
7. " The Influence of Electric Railway Working on the Communication Lines Running along the Railway," giving an account and the results of experiments carried out on the Berne-Scherzligen section of the Swiss Federal Railways. *Swiss Federal Railways Report.*
8. Experiment with the Three-Wire System and Negative Transformers on the Thun-Ostermundigen Section (Swiss Federal Railways). *Swiss Federal Railways Report.*
9. Review of Work of Sub-Committee on Wave-Shape Standard of the Standards Committee (A.I.E.E.). H. S. Osborne. *Trans. A.I.E.E.*, vol. 38, p. 261, 1919.
10. Potential Wave of A.C. Generators. W. J. Foster. *Trans. A.I.E.E.*, 1913.
11. A Proposed Wave-Shape Standard. C. M. Davies. *Trans. A.I.E.E.*, 1913.
12. Wave-Form Distortions and their Effects on Electrical Apparatus. P. M. Lincoln. *Trans. A.I.E.E.*, 1913.
13. Form Factor and its Significance. F. Bedell. *Trans. A.I.E.E.*, 1915.
14. Distortion Factors. F. Bedell. *Trans. A.I.E.E.*, 1915.
15. An Analytical and Graphical Solution for Non-Sinusoidal A.C. F. M. Mizushi. *Trans. A.I.E.E.*, 1915.
16. A.I.E.E. Discussion on Papers, Nos. 13, 14 and 15. *Trans. A.I.E.E.*, 1915.
17. Telephone Disturbance due to Electrified Railways, describing Experiments carried out on the Riksgräns Railway (Scandinavia). A. Holmgren. *Teknisk Tidskrift*, vol. 53 (*Elektrotechnik*), pp. 45–51. *Engineering Abstracts*, vol. 16, No. 206, 1923.
18. Correspondence, supplied by A. R. Everest, criticizing the paper by H. S. Osborne.
19. " Harmonics in Single-Phase Series Motors," describing Experiments carried out by the A.S.E.A. R. Liljeblad. *Teknisk Tidskrift, Elektrotechnik*, October 6, 1923.

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* The C.C.I. allow barrels not exceeding 36 kilometres for triangular circuits and not exceeding 18 kilometres for other configurations.

20. " Report of Committee on Overhead Lines and Inductive Interference," T1–19, including appendix " Telephone Disturbance by Induction." J. B. Taylor. National Electric Light Association, U.S.A., 42nd Convention, May 1919.
21. Power Circuit Interference with Telegraphs and Telephones. S. C. Bartholomew. *Inst. P.O. Elec. Eng.*, December 1914. Abstract, *Electrician*, January 29, 1915, pp. 561–565.
22. Protection to Telephone Circuits used in Electric Power Distribution. E. K. Shelton. *Gen. Elec. Rev.*, December 1916, p. 1126.
23. Report of Inductive Interference Committee, Technical National Section, T7–22. National Electric Light Association, U.S.A., 45th Convention, May 1922.
24. " Inductive Interference of Power Circuits with Communication Circuits," describing tests carried out on the Lake Coleridge transmission system, New Zealand. Caldwell and Marsden. *New Zealand Journal of Science and Technology*, vol. 3, Nos. 5 and 6, 1921, pp. 286–295.
25. Triple Frequency Currents in Earth Return Circuits. E. W. Marchant. British Association, Section G. Abstract, *Electrician*, September 21, 1923, p. 300.
26. " Improving the Shape of Alternator Voltage Waves " and subsequent correspondence. E. W. Marchant. British Association, Section G. Abstract, *Electrician*, October 1923, p. 362.
27. " Communication Circuits," an abstract of an article by A. Holmgren giving further particulars of experiments carried out on the Riksgräns Railway. *Teknisk Tidskrift*, April 1923. Abstract, *Electrician*, April 4, 1924, p. 420.
28. Oscillograph Investigation into Tramway Disturbances at Newcastle-on-Tyne. *Post Office Report*, No. 3227, December 8, 1921.
29. Interference between Telephone and Power Lines. *Post Office Report*, No. 4.
30. Final Report of Californian Railroad Commission on Inductive Interference.
31. General Order No. 52 of Californian Railroad Commission.
32. Power Circuit Interference with Telegraphs and Telephones (1924). S. C. Bartholomew. *Journal I.E.E.*, October 1924.
33. Method of Getting Rid of Telephone Interference from a Mercury-Arc Rectifier. Prof. E. W. Marchant. *Journal I.E.E.*, vol. 62, 1924.
34. Electrification of the French Midi Railway. A. Bachellery. *Journal I.E.E.*, vol. 62, 1924, p. 213.
35. On the Influence of High-Tension Lines on the Working of Telephone Lines. F. Schrottke. *E.T.Z.*, vol. 28, 1907, pp. 685–9, 707–12.
36. The Telegraph and Single-Phase Traction. Devaux-Charbonnel. 1916.
37. Rotary Convertors, with special reference to Railway Electrification. F. P. Whitaker. *Journal I.E.E.*, 1921.
38.* Effect of Trolley Induction on Parallel Telephone Lines in use on Electric Railroads in the Vicinity of Schenectady, N.Y. *G.E. Co.'s Standardizing Lab. Report*, No. S.710, November 1916.
39.* Air Gap changed on Rotary to obtain the Armature Tooth Frequency Characteristics. *G.E. Co.'s Standardizing Lab. Report*, No. S.663, October 1916.
40.* Magnetic Wedges to Reduce Armature-Tooth Ripples on Rotary Converters. *G.E. Co.'s Standardizing Lab. Report*, No. S.769, March 1917.
41.* Armature Tooth Frequency of Two C.M. & St. P.R.R. Generators in Series reduced by Phase Displacement of the Armature Teeth and by a Resonant Shunt. *G.E. Co.'s Standardizing Lab. Report*, No. S.735, December 1916.
42.* Telephone Interference Investigation. G. H. Hill.
43.* Inductive Interference from D.C. Generator Circuits. M. A. Rusher. 1919.
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* Nos. 38 to 48, 122 to 128 and 131 to 133, all inclusive, were confidential reports supplied by Mr. A. R. Everest.

APPENDIX 2.

CALCULATION OF INDUCTIVE EFFECTS.

ELECTRIC INDUCTION.

The formulæ worked out by various writers were obtained according to one or other of two general methods of calculation.

METHOD 1.

Kirchhoff's first law is applied to an equivalent circuit representing the circuits involved in the parallel, so that expressions are obtained which give the values of the voltage and current in the disturbed line in terms of the mutual capacities between the conductors and the self-admittances between conductors and earth. The mutual and self-capacities are then expressed in terms of the physical dimensions of the configuration.

This method was applied first by Schrottke (35), who worked out a number of simple cases. An indication of the results obtained is shown in the following case, where a single power conductor and a single communication conductor are concerned.

The equivalent circuit on which the calculation is based is shown in Fig. 1, reproduced with altered notation, from that given by Devaux-Charbonnel (36).

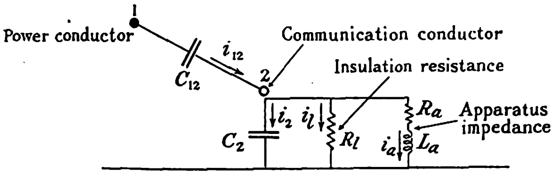

FIG. 1.

Then, applying Kirchhoff's second law—

$$i_{12} = i_2 + i_l + i_a \quad . \quad . \quad . \quad . \quad (1)$$

If v_1 = power-conductor voltage
and v_2 = induced voltage on communication conductor,

then

$$i_{12} = (v_1 - v_2)j\omega C_{12}$$
$$i_2 = v_2 j\omega C_2$$
$$i_l = \frac{v_2}{R_l}$$
$$i_a = \frac{v_2}{R_a + j\omega L_a}$$

Substituting these values in (1), we obtain

$$v_2 = v_1 \frac{\omega C_{12}}{\omega(C_{12} + C_2) - \frac{\omega L_a}{R_a^2 + \omega^2 L_a^2} - j\left(\frac{1}{R_l} + \frac{R_a}{R_a^2 + \omega^2 L_a^2}\right)}$$

If the apparatus is disconnected from the line (i.e. R_a and L_a infinite) the expression for v_2 reduces to

$$v_2 = v_1 \frac{\omega C_{12}}{\omega(C_{12} + C_2) - j\frac{1}{R_l}}$$

or replacing the instantaneous values by R.M.S. values and rewriting

$$V_2 = V_1 \frac{\omega C_{12}}{\sqrt{\omega^2(C_{12} + C_2)^2 + \frac{1}{R_l^2}}} \quad . \quad . \quad . \quad (2)$$

which is the expression obtained by Schrottke (35).

Proceeding as shown by Schrottke, the two limiting conditions can be considered.

(i) *Communication wire insulated from earth* (*i.e.* $R_l = \infty$ *in the limit*).

Then the open-circuit voltage induced is

$$V_{02} = V_1 \frac{C_{12}}{C_{12} + C_2} \quad . \quad . \quad . \quad . \quad (3)$$

(ii) *Communication line earthed* (*i.e.* $R_l = 0$ *in the limit.*

The current flowing though R_l is

$$I_l = \frac{V_2}{R_l}$$

which on substitution for V_2 from (2) becomes

$$= V_1 \frac{\omega C_{12}}{[1 + \omega^2(C_{12} + C_2)^2 R_l^2]^{\frac{1}{2}}} \quad . \quad . \quad . \quad . \quad (4)$$

If $R_l = 0$, the short-circuit current to earth through the communication line is·

$$I_{02} = V_1 \omega C_{12} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

From equations (2), (3), (4) and (5) a relationship is obtained between the open-circuit voltage and short-circuit current and the voltage and current induced when R_l has some finite value. The equation obtained is

$$\left(\frac{V_2}{V_{02}}\right)^2 + \left(\frac{I_2}{I_{02}}\right)^2 = 1 \quad . \quad . \quad . \quad . \quad (6)$$

This is the equation to the circle shown in Fig. 2, which is termed the communication line characteristic by Schrottke.

The angle a shown therein is given by the relation

$$\tan a = \omega(C_{12} + C_2)R_l$$

Hence if the open-circuit voltage and the short-circuit current of the disturbed line are calculated or known, the voltage and current can be obtained when the line is earthed through a resistance R_l.

Expression of results in terms of the physical dimensions.

Although Schrottke (35) left his results in the form shown above—equations (3) and (5)—it is possible to express the capacities between conductors and between conductors and earth in terms of Maxwell's potential coefficients, which are constants depending on the physical dimensions of the configuration. This substitution is discussed more fully under Method 2. Devaux-Charbonnel (36) made this substitution for the simple case we have considered above.

In this case, on substitution in equation (3), we have

$$V_{02} = V_1 \frac{C_{12}}{C_{12} + C_2} = V_1 \frac{p_{12}}{p_{11}} \quad . \quad . \quad . \quad (7)$$

The symbol p throughout this report represents with its appropriate subscript a Maxwell potential coefficient. These are defined under Method 2.

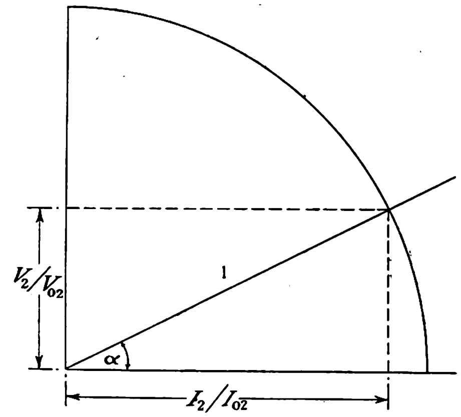

FIG. 2.

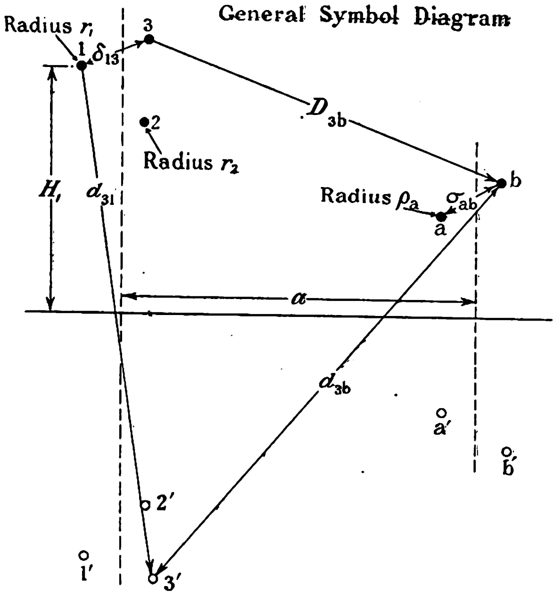

FIG. 3.

Substituting for the potential coefficients

$$V_{02} = V_1 \frac{\log_e \dfrac{d_{12}}{D_{12}}}{\log_e \dfrac{2H_1}{r_1}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

The meanings of the symbols in this equation are given on the symbol diagram in Fig. 3.

Similar calculations were made by Schrottke for the case when a metallic communication circuit forms a parallel with a single-power conductor, but the results are in a cumbrous form. By applying the formulæ obtained to an actual example, Schrottke showed that the results obtained, when two disturbed wires are present but are not connected, are in close agreement with those obtained when only one disturbed wire is present.

When the two disturbed wires are connected together through a low resistance, the calculation can be simplified in the following manner, as pointed out by Schrottke (35). The two disturbed wires are replaced by an equivalent conductor placed mid-way between them and having a radius equal to (radius of wire × spacing of wires)$^{\frac{1}{2}}$. It is possible to show by examples the great accuracy of this approximation.

The equations become exceedingly cumbersome if more conductors are present, as, for example, in a parallel between a three-phase power line and a metallic communication line. In such cases the formulæ given by Schrottke are not in a form suitable for use. It is possible that by substituting potential coefficients for the capacities in these formulæ, the formulæ obtained would be the same as those given by the second method.

METHOD 2.

This method was first applied by Breisig (*Theoretische Telegraphie*, 1st edition, 1910, p. 270 *et seq.*), who pointed out that the method developed by Schrottke becomes troublesome when applied to systems with numerous lines owing to the lengthy calculations of the capacities.

The first step is to determine the electric charges on the conductors. These are obtained in terms of the potentials to earth of the conductors and coefficients which are constants depending on the physical dimensions of the configuration and separation.

Utilizing the method involving image conductors, the following equations give the relations between the potentials and electric charges of a system when n parallel lines are present.

$$\left.\begin{aligned} \dot{V}_1 &= p_{11}\dot{q}_1\dot{q}_2 + p_{21} + \ . \ . \ . \ p_{n1}\dot{q}_n \\ \dot{V}_2 &= p_{12}\dot{q}_1 + p_{22}\dot{q}_2 + \ . \ . \ . \ p_{n2}\dot{q}_n \\ \dot{V}_n &= p_{1n}\dot{q}_1 + p_{2n}\dot{q}_2 + \ . \ . \ . \ p_{nn}\dot{q}_n \end{aligned}\right\} \quad . \quad . \quad . \quad (9)$$

V_1, V_2, . . . V_n are the potentials relative to earth of the conductors denoted by the subscripts; Q_1, Q_2, . . . Q_n are the corresponding charges; p_{11}, p_{12}, p_{13}, etc., are termed "potential coefficients" and are constants depending on the physical dimensions of the system. The value of a potential coefficient is the potential of the conductor denoted by one of the subscripts when the charge on the conductor denoted by the other subscript is unity, the charges of all the other conductors being zero.

This series of equations can be rewritten in order to obtain expressions for the electric charges.

Then

$$\left.\begin{aligned} \dot{q}_1 &= k_{11}\dot{V}_1 + k_{12}\dot{V}_2 + \ . \ . \ . \ k_{1n}\dot{V}_n \\ \dot{q}_2 &= k_{21}\dot{V}_1 + k_{22}\dot{V}_2 + \ . \ . \ . \ k_{2n}\dot{V}_n \\ \dot{q}_n &= k_{n1}\dot{V}_1 + k_{n2}\dot{V}_2 + \ . \ . \ . \ k_{nn}\dot{V}_n \end{aligned}\right\} \quad . \quad . \quad (10)$$

k_{11}, k_{12}, etc., are termed " capacitance coefficients " in Technical Report No. 64 of the Californian Investigation, and correspond to Maxwell's coefficients of capacity and induction termed by Russell the coefficients of self and mutual induction for electrostatic charges.

These coefficients will be referred to throughout this Appendix as " capacitance coefficients " on account of simplicity.

From the series of equations (9) and (10) it is seen that the capacitance and potential coefficients are so related that any capacitance coefficient

$$k_{xy} = \frac{\Delta xy}{\Delta} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

where Δxy signifies the minor or sub-determinant of p_{xy} in the determinant of the potential coefficients in equations (9), namely

$$\Delta = \begin{Bmatrix} p_{11}, p_{21}, \dots p_{n1} \\ p_{12}, p_{22}, \dots p_{n2} \\ p_{1n}, p_{2n}, \dots p_{nn} \end{Bmatrix}$$

A general expression is obtained, therefore, for the charge on a line of length l, namely

$$Q_n = l(\dot{V}_1 k_{1n} + \dot{V}_2 k_{2n} + \dots \dot{V}_n k_{nn}) \quad . \quad (12)$$

From this point two alternative methods of procedure are open. Following the first of these, the expression for the potential of any point " a " in the electric field surrounding the power conductors, when only these conductors and earth are present, is given by

$$l\dot{V}_a = P_{1a}\dot{Q}_1 + p_{2a}\dot{Q}_2 + \dots + p_{na}\dot{Q}_n \quad . \quad (13)$$

A parallel communication conductor passing through " a " will assume the potential V_a if isolated from earth and from other conductors. This will hold true for a number of such isolated conductors in the electric field distant apart ten diameters or more, since the modification to the electric field distribution is relatively inappreciable.

In order to calculate the induced potentials of the conductors of a parallel circuit when thus isolated from earth, from each other, from other conductors and from unexposed sections of the circuit, the charges on the power conductors are first calculated from the general equation (12), the capacitance coefficients being obtained from the values of the potential coefficients through equation (11). In order to evaluate the potential coefficient p_{xy} it is necessary to calculate the work done by an external agent against the repulsive force of a unit positive charge on the conductor denoted by one of the subscripts, in bringing a unit positive charge from infinity to the conductor denoted by the other subscript and whose potential is desired. The values of these potential coefficients are given with accuracy by the general formula

$$p_{xy} = 2 \log \frac{d_{xy}}{D_{xy}} \quad . \quad . \quad . \quad . \quad (14)$$

where d_{xy} is the distance of the axis of the conductor denoted by one subscript to the axis of the image conductor denoted by the other subscript, and D_{xy} is the distance between the axes of the conductors denoted by the subscripts. When the subscripts are alike, say D_{xx}, this distance becomes the radius of the conductor denoted by the subscripts. In order to avoid unnecessary complication, the expression for p_{xy} is given as a simple logarithmic ratio; because if, in equations (11) to (14) inclusive, logarithms are taken to the same base, either e or 10, and the dimensions are expressed in the same units throughout, the voltages induced in the parallel circuit are obtained in volts per volt impressed on the power circuit, without a further consideration of signs and units being necessary.

This method was used by the Californian Railroad Commission in their study of inductive interference.

An alternative way of proceeding from the general expression for the charge on a line, as given in equation (12), is that given by Breisig (*Theoretische Telegraphie*, 1st edition, 1910, p. 272 *et seq.*; 2nd edition, p. 296 *et seq.*) and applied by Brauns (111) to practical cases.

Considering the case in which line n lies in the fields of $n-1$ lines; then from equation (12),

$$\dot{Q}_n = l(\dot{V}_1 k_{1n} + \dot{V}_2 k_{2n} + \dots \dot{V}_n k_{nn})$$

It is clear from Kirchhoff's first law that the value of the current flowing along wire n from an external source must be equal to the time rate of increase of the charge Q_n on line n plus the currents flowing from line n to earth and to the other lines. When n is a communication conductor, the value of the above current is zero. The general equation expressing this is

$$\begin{aligned} 0 = j\omega l(&\dot{V}_1 k_{1n} + \dot{V}_2 k_{2n} + \dots \dot{V}_n k_{nn}) \\ &+ G_{1n}(\dot{V}_n - \dot{V}_1) + G_{2n}(\dot{V}_n - \dot{V}_2) \\ &\quad + \dots G_{n-1}(\dot{V}_n - \dot{V}_{n-1}) + G_{nn}\dot{V}_n \dots \quad (15) \end{aligned}$$

where G_{xy} denotes the conductance between the conductors represented by the subscripts, and G_{xx} the conductance between the conductor denoted by the subscripts and earth.

If a special case be considered in which only one line, the nth, of the n lines present is a communication conductor, the remaining $n-1$ lines being power conductors, then equation (15) is reduced to the form

$$\begin{aligned} 0 = j\omega l(\dot{V}_1 k_{1n} + \dot{V}_2 k_{2n} + \dots \dot{V}_{n-1} k_{n-1, n}) \\ + \dot{V}_n(G_n + j\omega l k_{nn}) \end{aligned}$$

since there are no connections between the communication line and the power lines.

Hence the induced voltage

$$\dot{V}_n = -j\omega l \frac{(\dot{V}_1 k_{1n} + \dot{V}_2 k_{2n} + \dots \dot{V}_{n-1} k_{n-1,n})}{G_n + j\omega l k_{nn}} \quad . \quad (16)$$

and the open-circuit voltage when $G_n = 0$, is

$$\dot{V}_{0n} = -\frac{1}{k_{nn}}(\dot{V}_1 k_{1n} + \dot{V}_2 k_{2n} + \dots \dot{V}_{n-1} k_{n-1, n}) \quad (17)$$

The current flowing from line n to earth is given by

$$\dot{I}_n = \dot{V}_n G_n = -j\omega l \frac{(\dot{V}_1 k_{1n} + \dot{V}_2 k_{2n} + \dots \dot{V}_{n-1} k_{n-1, n})}{\dfrac{1 + j\omega l k_{nn}}{G_n}} \quad (18)$$

and the short-circuit current when $G_n = \infty$ is

$$\dot{I}_{0n} = -j\omega l(\dot{V}k_{1n} + \dot{V}_2k_{2n} + \dots \dot{V}_{n-1}k_{n-1,\,n})$$
$$= j\omega l\dot{V}_{0n}k_{nn} \quad . \quad (19)$$

From equations (16) to (19) inclusive the following is obtained

$$\frac{\dot{V}_n}{\dot{V}_{0n}} + \frac{\dot{I}_n}{\dot{I}_{0n}} = 1$$

This represents two vectors which are in quadrature when $1/G_n$ is a non-inductive resistance, giving, therefore,

$$\left(\frac{V_n}{V_{0n}}\right)^2 + \left(\frac{I_n}{I_{0n}}\right)^2 = 1$$

which is in agreement with equation (6) obtained by Schrottke.

From the general equations (17) and (19) for the case when only one communication conductor is present, the form of these equations, when particular conditions of the power conditions are considered, have been obtained by Breisig (*Theoretische Telegraphie*, 2nd edition, p. 296) and Brauns (loc. cit.).

As an example, the case is considered when a parallel consists of one power and one communication conductor, denoted by symbols 1 and 2 respectively. Then

$$\dot{V}_{02} = -\frac{1}{k_{22}}\dot{V}_1k_{12}$$

from equation (17).

Then substituting for k_{12} by means of equation (11), we have, therefore,

$$V_{02} = V_1\frac{p_{12}}{p_{11}} \quad . \quad . \quad . \quad . \quad . \quad (19a)$$

which in terms of the physical dimensions of the parallel becomes by using equation (14)

$$V_{02} = V_1\frac{\log\dfrac{d_{12}}{D_{12}}}{\log\dfrac{2H_1}{r_1}} \quad . \quad . \quad . \quad . \quad . \quad (19b)$$

which is identical with the result obtained from Schrottke's method and given by equation (8). Similarly, I_{02} can be obtained. Brauns (111) worked out a number of practical cases involving one, two and three power lines with and without an earth fault on one phase.

When two communication conductors are present, similar general equations can be obtained as worked out by Breisig (*Theoretische Telegraphie*, 2nd edition, p. 302) for the case when only one power line is present. Brauns in a published article, in which practical cases with a metallic communication circuit present are considered, avoids this additional series of equations by assuming in the first place that the open-circuit voltage induced on one communication conductor is the same whether a second communication conductor is present or not. The results finally arrived at in this article for the disturbing current flowing through the terminal apparatus differ considerably from those calculated according to the formulæ from which were derived the limits of separation laid down in the "French Rules." After a considerable amount of work by the present investigators this difference was traced to the use by Brauns of an equivalent conductor in a similar manner to Schrottke for the purpose of obtaining the total short-circuit current when both wires were earthed.

The combination of methods used to obtain the formulæ contained in the "French Rules" will now be described.

Kirchhoff's first law is applied to the more complicated case when three power conductors and a two-conductor (metallic) communication circuit are present and form a parallel. The equations thus obtained express the relationships between the apparatus resistance, conductor potentials and the capacities between conductors and earth and between conductors. In order to simplify the subsequent calculation the capacities in these equations are expressed at once in terms of the capacitance coefficients mentioned previously, which are connected by the following relations:—

$$k_{xy} = -C_{xy}$$

where x and y represent different conductors, and

$$k_{xx} = C_{x1} + C_{x2} + \dots C_{x,\,x-1} + C_{xx} + C_{x,\,x+1} + \dots C_{xn}$$

The equations then resulting are similar in type to those obtained by Breisig for the simpler case when only one power conductor is present instead of three. Proceeding then according to Method 2, potential coefficients are substituted for the capacitance coefficients, the equations being simplified by neglecting terms, the numerical values of which would be relatively so small in actual examples that they would not affect results. At the same time, one power conductor is assumed to be earthed due to a fault, a system with neutral insulated being considered. It is further assumed that the power line is sufficiently well transposed to enable certain simplifications to be made.

Formulæ giving the electric induction in the case of a number of practical cases involving one, two and three power lines, with and without an earth fault on one phase, are given in Table 1 to this Appendix. Attention has been drawn in a footnote to those cases in which the result obtained by Brauns differs from the formula given.

It will be realized that the formulæ in Table 1 are complicated and that some time would be required to work out actual cases. Further, the effect of separation and other dimensions is not directly apparent. Lienemann (100) simplified the formulæ obtained by Brauns by changing the equations from the awkward logarithmic form and was thus able to express the interference effects directly in terms of the separation and other dimensions. By writing the natural logarithms in Brauns' formulæ in a certain form, they can be replaced by rapidly converging series from the relations given by

$$\log_e(1 \pm x) = \pm x\left(1 \mp \frac{x}{2} + \frac{x^2}{3} \mp \frac{x^3}{4} + \dots\right) \quad (20)$$

and

$$\log_e\left(\frac{1+x}{1-x}\right) = 2x\left(1 + \frac{x^2}{3} + \frac{x^4}{5} + \dots\right) \quad . \quad (21)$$

TABLE 1.

Revised Formulæ for Electric Induction.

	Interfering lines	Open-circuit voltage		Single communication line (4) present	Metallic circuit (conductors 4 and 5). Current through apparatus	
No.	Type	V_{04}	V_{05}	Short-circuit current I_{04} amps.	Circuit insulated I_{45} amps.	Conductor 5 earthed I^0_{45} amps.
	Common factor	V	V	$\frac{\omega l V}{18 \times 10^6}$	$\frac{\omega l V}{18 \times 10^6}$	$\frac{\omega l V}{18 \times 10^6}$
1	A.C. railway (line 1)	$\frac{p_{14}}{p_{11}}$	$\frac{p_{15}}{p_{11}}$	$\frac{p_{14}}{p_{11}p_{44}}$	$\frac{p_{14} - p_{15}}{2p_{11}(p_{44} - p_{45})}$ *	$\frac{p_{15}p_{45} - p_{14}p_{44}}{p_{11}(p^2_{44} - p^2_{45})}$ †
2	Single-phase line (conductors 1 and 2):—					
	(*a*) Normal conditions	$\frac{p_{14} - p_{24}}{p_{11} - p_{12}}$	$\frac{p_{15} - p_{25}}{p_{11} - p_{12}}$	$\frac{p_{14} - p_{24}}{(p_{11} - p_{12})p_{44}}$	$\frac{(p_{14} - p_{24}) - (p_{15} - p_{25})}{2(p_{11} + p_{12})(p_{44} - p_{45})}$ *	$\frac{p_{44}(p_{14} - p_{24}) - p_{45}(p_{15} - p_{25})}{(p_{11} + p_{12})(p^2_{44} - p^2_{45})}$ †
	(*b*) Earth on phase 2	$2\frac{p_{14}}{p_{11} + p_{12}}$	$2\frac{p_{15}}{p_{11} + p_{12}}$	$2\frac{p_{14}}{(p_{11} + p_{12})p_{44}}$	$\frac{p_{14} - p_{15}}{(p_{11} + p_{12})(p_{44} - p_{45})}$ *‡	$\frac{2(p_{15}p_{45} - p_{14}p_{44})}{(p_{11} + p_{12})(p^2_{44} - p^2_{45})}$ †
3	Three-phase line (conductors 1, 2 and 3):—					
	(*a*) Normal conditions	$\frac{K_4}{p_{11} - p_{12}}$	$\frac{K_5}{p_{11} - p_{12}}$	$\frac{K_4}{(p_{11} - p_{12})p_{44}}$	$\frac{K_{4-5}}{(p_{11} + 2p_{12})(p_{44} - p_{45})}$ *‡	Unwieldy
	(*b*) Earth on phase 3	$\frac{\sqrt{3}K'_4}{p_{11} + 2p_{12}}$	$\frac{\sqrt{3}K'_5}{p_{11} + 2p_{12}}$	$\frac{\sqrt{3}K'_4}{(p_{11} + 2p_{12})p_{44}}$	$\frac{p_{14} - p_{15}}{(p_{11} + 2p_{12})(p_{44} - p_{45})}$ *	$\frac{p_{15}p_{45} - p_{14}p_{44}}{(p_{11} + 2p_{12})(p^2_{44} - p^2_{45})}$ †

where $K_4 = (p^2_{14} + p^2_{24} + p^2_{34} - p_{14}p_{24} - p_{14}p_{34} - p_{24}p_{34})^{\frac{1}{2}}$

$K_5 = (p^2_{15} + p^2_{25} + p^2_{35} - p_{15}p_{25} - p_{15}p_{35} - p_{25}p_{35})^{\frac{1}{2}}$

$K'_4 = (p^2_{14} + p^2_{24} + p_{14}p_{24})^{\frac{1}{2}}$

$K'_5 = (p^2_{15} + p^2_{25} + p_{15}p_{25})^{\frac{1}{2}}$

$$K_{4-5} = [(p_{14} - p_{15})^2 + (p_{24} - p_{25})^2 + (p_{34} - p_{35})^2 - (p_{14} - p_{15})(p_{24} - p_{25}) - (p_{24} - p_{25})(p_{34} - p_{35}) - (p_{34} - p_{35})(p_{14} - p_{15})]^{\frac{1}{2}}$$

V = normal power-conductor voltage to earth

l = length of parallel in km.

* Denotes a formula giving a result differing from that of Brauns

† Denotes a more accurate formula which can be approximated to the formula given by Brauns.

‡ Denotes a formula which is in agreement with the formula given in the "French Rules."

which are both converging series for values of x between -1 and $+1$. Since the physical dimensions are seldom known accurately, it is assumed that it is only possible to aim at an accuracy of 10 per cent in the calculation. Although when making these substitutions the interference effect is due to the whole series, 10 per cent inaccuracy is permissible in determining the value of this series by taking the first term only. With the above limit of 10 per cent, the limiting values for x are $x \overset{=}{<} 0\cdot 2$ for equation (20) and $x \overset{=}{<} 0\cdot 53$ for equation (21).

As an example, the same case is considered as previously, i.e. when a parallel consists of one power and one communication conductor, denoted by symbols 1 and 2 respectively. The corresponding equation (19*b*), giving the open-circuit voltage as

$$V_{02} = V_1 \frac{\log \dfrac{d_{12}}{D_{12}}}{\log \dfrac{2H_1}{r_1}}.$$

can be worked out to show the type of formula which is produced by applying such approximations. Considering, therefore, the term

$$\log_e \frac{d_{12}}{D_{12}}$$

this can be written, by reference to the symbol diagram, equal to

$$\log_e \sqrt{\frac{a^2 + (b + c)^2}{a^2 + (b - c)^2}}$$

or

$$\tfrac{1}{2} \log_e \frac{1 + \dfrac{2bc}{a^2 + b^2 + c^2}}{1 - \dfrac{2bc}{a^2 + b^2 + c^2}}$$

This is then of the form

$$\log_e \frac{1 + x}{1 - x}$$

where

$$x = \frac{2bc}{a^2 + b^2 + c^2}$$

and is not greater than $0\cdot 5$, except for very close parallels where the separation equals the mean height of the conductors. Writing

$$\log_e \frac{d_{12}}{D_{12}} = \frac{2bc}{a^2 + b^2 + c^2}$$

will, therefore, give too small a value. The other term

$$\log_e \frac{2H_1}{r_1}$$

can be shown to be approximately a constant, for with $r_1 = 4$ mm and $b = 6$ to 10 m,

$$\log_e \frac{2H_1}{r_1} = 3\cdot 6 \times 2\cdot 3 \text{ to within } \pm 3 \text{ per cent}$$

Lienemann assumed a value for

$$\log_e \frac{2H_1}{r_1} = 3\cdot 48 \times 2\cdot 3 = 8$$

which he took on the low side in order to compensate partly for the error in the value of

$$\log_e \frac{d_{12}}{D_{12}}$$

Inserting these simplified values in the equation for V_{02}, we have

$$V_{02} = V_1 \frac{2bc}{a^2 + b^2 + c^2} \times \frac{1}{8} = \frac{V_1}{4} \times \frac{bc}{a^2 + b^2 + c^2} \quad (22)$$

From this equation the effect of separation and the heights of the conductors can be more readily obtained.

Lienemann applied this approximate method of calculation to a number of the formulæ given by Brauns. The simplified expressions corresponding to those cases in which the accuracy of the original formula has been established are given in Table 2. The formulæ for the current through the apparatus where a metallic communication circuit is concerned have been obtained by the investigators by applying the approximations developed by Lienemann to the formulæ given in the "French Rules."

In the preparation of this part of the report the work done by other writers, (24), (62), (90), (94), who have calculated the electric induction for certain cases, was also considered.

MAGNETIC INDUCTION.

The calculation of magnetic induction in cases involving circuits with an earth return is of special importance and is dealt with separately.

GENERAL CASE.

Devaux-Charbonnel showed that the well-known relation $E = j\omega MI$ between the e.m.f. E induced in the secondary of two circuits and the inducing current I of circular frequency ω in the primary, holds so long as the effect of the current in the secondary produced by the induced e.m.f. can be ignored. This is permissible when the impedance of the secondary circuit is high, which is the case in practice.

Brauns (100) has developed formulæ for the magnetic induction between power and communication circuits; but the effect of the earth on modifying the magnetic field of the power line is neglected in these formulæ, which treat of the case when the earth is at an infinite distance away. The method adopted by the Californian Railroad Commission and given in full in the Technical Report No. 64 takes account of the effect of the earth. This method will now be described.

The earth is considered as a common conductor of the three-phase power circuit and the metallic communication circuit, and as a path for eddy currents. The latter tend to reduce the magnetic flux passing through the earth. By replacing the earth by the images of the conductors at a suitable distance below the earth's surface, the effect of the earth can be simulated. But, as the earth is not a perfect conductor, the locus of earth currents is at a considerable depth, and the magnetic neutral zone does not exist at the earth's surface. Its depth varies with the frequency of the

TABLE 2.

Simplified Formulæ for Electric Induction Obtained by Means of Lienemann's Approximations.

Interfering lines		Open-circuit voltage	Single communication conductor present	Metallic circuit
No.	Type	V_{04}	Short-circuit current I_{04} in amps.	Current through apparatus with circuit insulated I_{45} in amps.
	Common factor	V	$\omega l V \times 10^{-9}$	$\omega l V \times 10^{-9}$
1	A.C. railway	$\frac{1}{4} \times \frac{bc}{a^2+b^2+c^2}$	$1 \cdot 5 \times \frac{bc}{a^2+b^2+c^2}$	—
2	Single-phase line:— Earth on phase 2 ..	$\frac{2}{5} \times \frac{bc}{a^2+b^2+c^2}$	—	$\frac{2b\delta\left[(a^2+b^2-c^2)^2+4a^2c^2\right]^{\frac{1}{2}}}{(a^2+b^2+c^2)^2}$
3	Three-phase line:— (*a*) Normal conditions Triangular configuration ..	$0 \cdot 15 \times \frac{\delta \sin a}{a}$	$0 \cdot 9 \times \frac{\delta \sin a}{a}$	—
	(*b*) Earth on phase 3	$0 \cdot 45 \times \frac{bc}{a^2+b^2+c^2}$	—	$2 \cdot 6 \times \frac{b\delta\left[(a^2+b^2-c^2)^2+4a^2c^2\right]^{\frac{1}{2}}}{(a^2+b^2+c^2)^2}$

The meaning of the symbols will be obtained from Fig. 4.

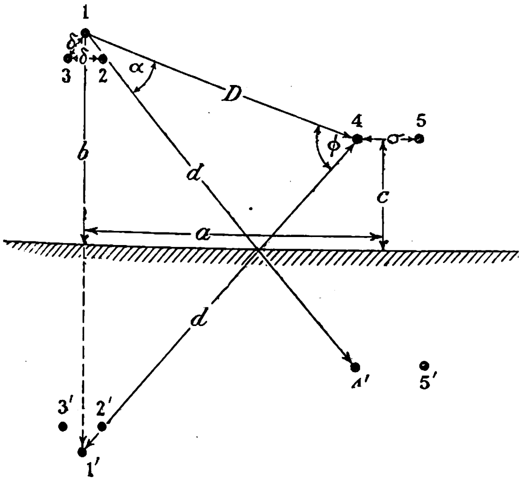

FIG. 4.

current and the character of the country. Tests made at three different localities by the Californian Railroad Commission show "that the image conductors for computations of magnetic induction should be taken with respect to an 'equivalent earth plane,' from 300 to 500 ft. below the surface. The figures given are for 60 cycles. For higher frequencies the equivalent earth plane is nearer the surface."

With the same notation as for electric induction, for the case when a three-phase power line and a metallic communication line form a parallel (where numbers 1, 2 and 3 denote the power conductors and numbers 4 and 5 the communication conductors), the induced voltage is

$$E_4 = -j\omega(\overline{M_{14}I_1} + \overline{M_{24}I_2} + \overline{M_{34}I_3})$$

where

$$M_{14} = 2 \log \frac{d_{14}}{D_{14}}$$

$$M_{24} = 2 \log \frac{d_{24}}{D_{24}}$$

$$M_{34} = 2 \log \frac{d_{34}}{D_{34}}$$

The values in the bracket require to be added vectorially, since I_1, I_2 and I_3 are vectors.

Three sets of components of the currents are considered in this report:—

(i) Balanced three-phase currents.
(ii) Single-phase current in a loop composed of two of the conductors.
(iii) Residual current flowing along the conductors and returning through the earth.

If the phase relationships are known, the resultant induced voltage can be obtained. For the above components we have the following formulæ, giving the magnitude of E_4:—

(i) *For balanced currents.*

$$E_4 = K\omega I \sqrt{\left[M_{14} - \tfrac{1}{2}(M_{24}+M_{34})\right]^2 + \left[\frac{\sqrt{3}}{2}(M_{24}-M_{34})\right]^2}$$

where I is the magnitude of balanced currents.

(ii) *For single-phase current.*

$$E_4 = K\omega I_S(M_{14} - M_{34})$$

assuming single-phase component I_S in conductors 1 and 3.

(iii) *For residual current.*

$$E_4 = \frac{K\omega I_R}{3}(M_{14} + M_{24} + M_{34})$$

where I_R is the magnitude of the residual current.

K is a constant converting E_4 to volts per 1 000 ft. of parallelism and equals $70 \cdot 183 \times 10^{-6}$, when the current is in amperes and the logarithmic ratios involved in the values of M_{14}, etc., are taken to the base 10.

Each of the above formulæ can be easily converted to forms involving physical dimensions—see Table 3 to this Appendix.

"If the separation of the two conductors a and b is small compared to their average separation from the power circuit, then the average of their induced voltages is approximately equal to that along a single conductor midway between them." This approximation was applied by the C.R.R.C. in obtaining the voltages induced in phantom telephone circuits.

"In the case of two or more disturbing circuits, as for example a twin-circuit power line, the resultant induced voltage is the vector sum of the induced voltages due to the individual circuits separately considered. The mutual effects between the several power circuits do not enter to complicate the computations as in the case of electric induction."

CIRCUITS WITH AN EARTH RETURN.

The solution in these cases is more difficult and is not rigid, since the path of the earth currents is not exactly known.

Various approximations are possible, based on a number of limiting cases.

Communication line with earth return.—If the communication line has an earth return, so that line 3 (see Fig. 5) is so far removed that $r_2 \simeq r_4$, then the formula

$$M = 2l \log_e \frac{r_2 r_3}{r_1 r_4} \times 10^{-4} \text{ henry per km}$$

for the mutual inductance M between metallic circuits reduces to

$$M = 2l \log_e \frac{r_3}{r_1} \times 10^{-4} \text{ henry per km}$$

This case does not appear to enter into practice from the evidence collected, although telegraph circuits paralleling metallic single-phase power lines would fulfil the conditions.

It seems doubtful whether, in the usual case, the earth return would be so distant that it would be permissible to write $r_2 = r_4$.

Power line with earth return.—If the power current returns through the earth entirely, this may be taken as a limiting case when considering the distribution of the return current of a single-phase railway. If the return current is assumed to be so far distant from the contact line and metallic communication line that it does not contribute to the mutual inductance, it is possible to write

$$M = 2l \log_e \frac{r_2}{r_1} \times 10^{-4} \text{ henry per km}$$

Although this case corresponds to parallels formed by metallic telephone circuits and a single-phase railway, little consideration has been given to it in general by writers.

Both power and communication circuits with earth return.—For two parallel lines of equal length with a common return over a medium unlimited in extent, Breisig obtained an approximate formula for the mutual inductance M between the circuits from a consideration of the magnetic-field energy. (See *Theoretische Telegraphie*, 2nd edition, p. 163 *et seq.*) This formula, which assumes that the separation a is small compared with the line length l, gives

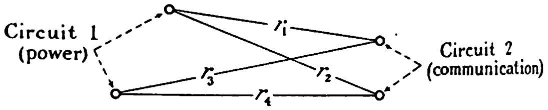

FIG. 5.

$$M = 2l\left(\log_e \frac{2l}{a} - 1\right)10^{-4} \text{ henry per km}$$

According to Breisig this formula represents the mutual inductance of two current systems consisting of two parallel lines of length l and separation a buried in a medium of unlimited dimensions and with their return currents flowing back through the medium.

In actual cases the return currents flow through the earth, which, therefore, forms a medium with a boundary surface and is not homogeneous. Also the conductivity of the earth needs to be looked upon as due only to a reasonably thick water-bearing stratum near the surface. Physically these conditions resemble those in the ideal case calculated in that the return currents spread out to a large extent compared with the currents flowing in the lines. It becomes necessary to modify the above equation in an empirical manner to take account of the effect of the earth currents.

The formula thus becomes

$$M = 2l\left(\log_e \frac{2l}{a} - q\right)10^{-4} \text{ henry per km}$$

where q is a number which varies from about 0·5 to 5, depending on the length of the line according to experiments carried out by Brauns (111).

L. Truxa states that the formula, as given above by Breisig for the mutual inductance between two lines with an earth return, becomes

$$M = 2a \log_e \frac{2\sqrt{bc}}{d} 10^{-4} \text{ henry per km}$$

when the second line, i.e. the communication line, is the longer of the two. The derivation of this formula has not been considered by the present investigators.

In a more recently published article Breisig stated from theoretical considerations the following approximate formula for M *:—

$$M = 2e^{-\omega_0}\left(\log_e \frac{\pi}{\omega_0} - 1\right) - j\frac{\pi}{2}$$

where $\omega_0 = a\sqrt{2\pi\sigma\omega}$
a = separation
σ = conductivity of the earth.

Single-phase railway.—In the case of the single-phase railway, Pleijel (108) has shown that currents are induced in the earth by magnetic induction and these form a circuit along the rails, returning through the earth. The rail current is then the sum of this current I_1 induced in the rail-earth circuit plus that portion I_R of the contact-line current which returns through the rails; while the earth current is the difference between that part I_E of the contact-line current returning through the earth and the current I_1 induced in the earth-rail circuit.

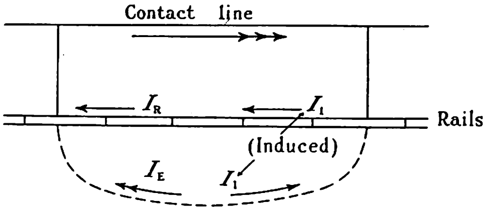
Contact line
I_R
I_1
Rails
(Induced)
I_E
I_1

FIG. 6.

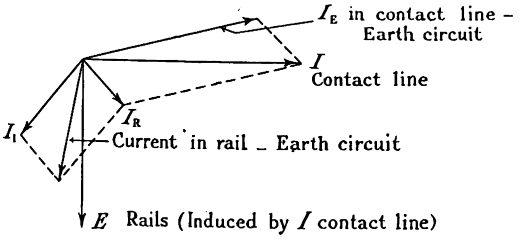
I_E in contact line - Earth circuit
I Contact line
I_R
I_1
Current in rail – Earth circuit
E Rails (Induced by I contact line)

FIG. 7.

Hence it can be considered that there are two circuits carrying current acting on the communication circuits—

(i) Contact-line-rail circuit acting as a metallic circuit along which current I_R and I_1 flows.
(ii) Contact-line-earth circuit, along which current $= I_E - I_1$ flows.

Fig. 6 shows the direction of currents flowing and Fig. 7 the phase relationships for this simple case.

It is also possible to consider the contact line and rails as two lines having an earth return, which gives the corresponding vector diagram, Fig. 8.

Considering the latter diagram, since it is easier to compare the effects of two earth-return circuits, it is clear that the inductive effects would be neutralized if the magnitude and phase of the current I_1 induced in the rail-earth circuit were suitable.

EFFECT OF RAIL CURRENTS.

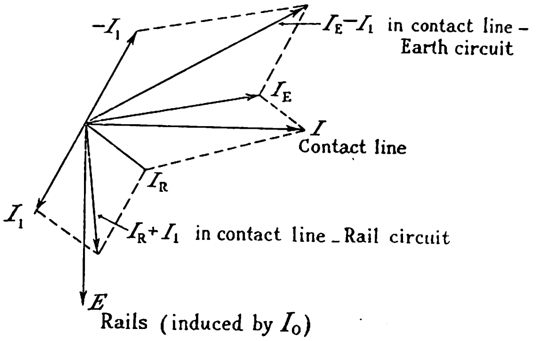
$-I_1$
$I_E - I_1$ in contact line - Earth circuit
I_E
I Contact line
I_R
I_1
$I_R + I_1$ in contact line – Rail circuit
E Rails (induced by I_0)

FIG. 8.

Pleijel has made a theoretical investigation into the distribution of voltage and current in *rail-lines.* He considered a lay-out as shown in Fig. 9; and taking into account the constants of the circuit, there follow the relations (assuming mutual inductance between the contact line and rails equal to M):—

$$-\frac{\delta V}{\delta x} = (r + j\omega l)I - j\omega M I_0$$

$$-\frac{\delta I}{\delta x} = aV$$

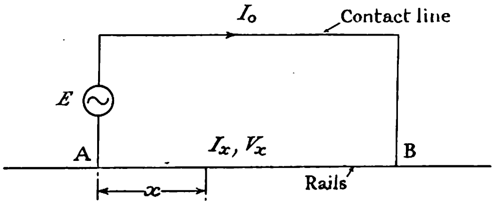
I_0
Contact line
E
A
I_x, V_x
B
x
Rails

FIG. 9.

where I_0 = contact line current
I = current at any point on rails
r and l = resistance and inductance of rails per km.

Writing $I - kI_0 = I_1$

where $k = \dfrac{j\omega M}{r + j\omega l}$

and M = mutual inductance of contact-line and rails per km

we have $-\dfrac{\delta V}{\delta x} = (r + j\omega l)I_1$

From this it is shown that the effective voltage at any point on the rails is entirely determined by I_1, while the other part of the current in the rails, i.e. kI_0, has no effect on the value of the voltage, as the pressure-drop which this current causes is compensated by the induced e.m.f.

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* The derivation of this formula will be considered in the Supplement to this Report. Reference has been made to this formula, in conjunction with those of Pollaczek and Rüdenberg, by the C.C.I. for the purpose of calculating the induction from earth currents due to a short-circuit on a power system with an earthed neutral point.

INDUCTION ON A WIRE PARALLEL TO THE CONTACT LINE.

Considering the case when the induced wire extends far beyond the contact line, it is assumed that the rail constants are uniform, so that the contact-line current divides where it enters the rails and the rail currents gradually decrease in value as the current I_0 leaks into the earth and returns by that path. The distribution of these "true" rail currents is shown in Fig. 10. It is clear that the sum of the "true" rail currents is zero.

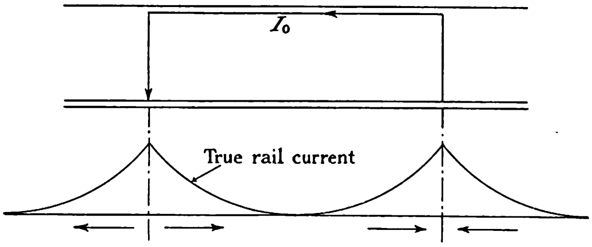

FIG. 10.

In other words, the sum of the currents which produce a pressure-drop in the rails equals zero. Therefore, only the induced part of the rail current, kI_0, causes induction in the inducing line, considering its whole length.

There are thus two currents, I_0 in the contact line and kI_0 in the rail line, each with an earth return, and these act inductively on the communication circuit. Pleijel draws the conclusions from this discussion that the induction is independent of the leakage coefficient of the rail line and also of the conductivity of the earth.

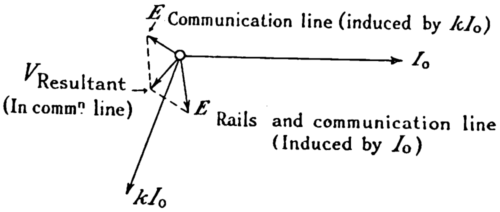
E Communication line (induced by kI_0)
I_0
V Resultant
(In commⁿ line)
E Rails and communication line
(Induced by I_0)
kI_0

FIG. 11.

From the above discussion the induced e.m.f. in the communication line can be written $E = j\omega I_0(M_0 - kM_1)$, taking account of phase relations. M_0 and M_1 are the mutual inductances of the communication circuit and contact-line-earth and rail-earth circuits respectively.

For communication lines with earth return, the formula

$$M = 2l\left(\log_e \frac{2l}{a} - q\right)$$

developed by Breisig for two lines of equal length is then inserted for M_0 and M_1, though in the case considered throughout, the communication line is much longer. Presumably, Pleijel intended that the value given to q should allow for this.

Hence

$$M_0 = 2l\left(\log_e \frac{2l}{h_0} - q\right)10^{-4} \text{ henry per km}$$

$$M_1 = 2l\left(\log_e \frac{2l}{h_1} - q\right)10^{-4} \text{ henry per km}$$

where h_0 = distance from contact line to induced line
h_1 = distance from rail to induced line.

At somewhat large separations, $M_0 \cong M_1$; so that the induction becomes proportional to $1 - k$. Fig. 11 shows how the resultant e.m.f. in the communication line depends on the phase relations.

CONSIDERATION OF THE RESULTS.

ELECTRIC INDUCTION.

It is clear from equation (2), and particularly from equation (3), that by increasing the value of C_2, the capacity of the disturbed line to earth, the induced voltage V_2 or, in particular, V_{02} will be reduced. Such an increase occurs in practice if the disturbed conductor extends beyond the parallel.

It has been suggested by Brauns (119) and by Caldwell and Marsden (24) that capacity could be added by connecting special condensers between the communication conductor and earth. Equation (3) shows that the open-circuit voltage induced in the disturbed line is independent of frequency and of the length of parallel, when the disturbed wire does not extend beyond the limits of the parallel.

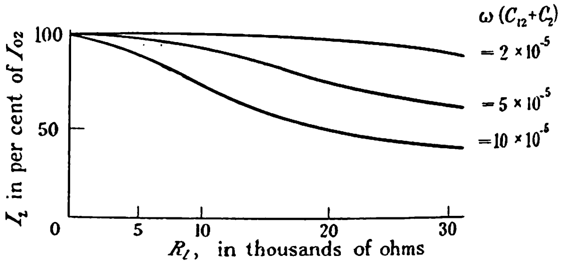

FIG. 12.

Consideration of equation (2) shows that the short-circuit current is proportional to frequency and the length of the parallel. From Fig. 2 it will be seen that the current I_l flowing through the earth resistance R_l only decreases slowly from the value of the short-circuit current I_{02} as the value of R_l increases from zero. The importance of this relation is brought out by Schrottke (35), who showed in an example that, in the case of a long parallel, if a person touches an insulated disturbed line the current passing is not appreciably less than the short-circuit current, although the voltage to earth is reduced to a small fraction of the open-circuit voltage. Fig. 12 has been drawn to show the variation in the induced current with the other variables.

The formulæ obtained by Lienemann (see Table 2) enable certain approximate conclusions to be drawn with regard to the effect of separation of the two circuits, height of conductors, etc., on the induced voltage and current due to one or two interfering lines.

For the more complicated case of induction from a three-phase power circuit, Technical Report No. 65 of the Californian Railroad Commission contains a large number of curves plotted from calculations which were based on formulæ obtained as previously indicated. Curves are given for both magnetic and electric induction. On the conclusions drawn from these curves much of the information given in Section 3 of this *résumé* is based.

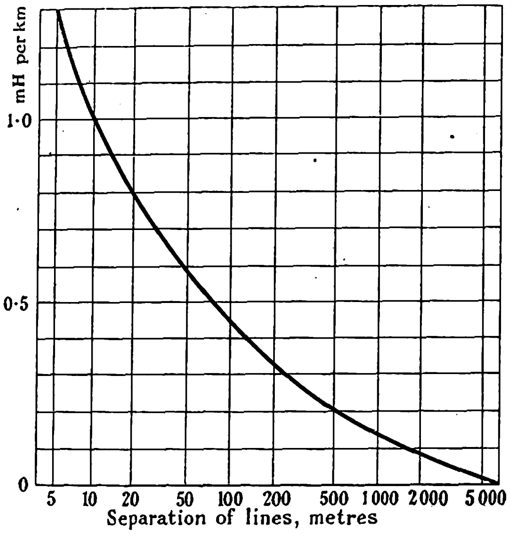

FIG. 13.—Mutual inductance of earth-return circuits, millihenrys per km.

MAGNETIC INDUCTION.

It is not directly clear from the formulæ given how the physical dimensions of the configuration affect the induction coefficients. Due to the relatively great depth of the return current in the earth the induction coefficients due to voltages decrease much more rapidly with increase in horizontal separation than those due to currents. Jäger (88) has given a curve (Fig. 13) which shows the mutual inductance M due to a single interfering line as a function of the separation.* It is based on numerous unspecified experiments at many places and for various lengths and separations of parallels involving earth-return communication lines. In the "French Rules" a formula is given for M as determined from results made at frequencies from 15 to 50 cycles per second as follows:—

$$M = \frac{4}{\sqrt{a}} \times 10^{-3} \text{ henry per km}$$

The relation $M \propto \frac{1}{\sqrt{a}}$

holds quite well over the curve given by Jäger between $a = 20$ and $a = 2\,000$ metres. It is possible that the same series of tests is the source in each case.

TABLE 3.

Formulæ for Induced Voltages due to Magnetic Induction.

Balanced currents.

$$E_4 = K\omega I \sqrt{\log^2 \frac{d^2{}_{14} D_{24} D_{34}}{D^2{}_{14} d_{24} d_{34}} + 3 \log \frac{d_{24} D_{34}}{D_{24} d_{34}}}$$

Single-phase current:

$$E_4 = -j\omega K 2 I_S \log \frac{d_{24} D_{34}}{D_{24} d_{34}}$$

Residual current:

$$E_4 = -j\omega \frac{2K}{3} I_R \log \frac{d_{14} d_{24} d_{34}}{D_{14} D_{24} D_{34}}$$

or approximately

$$E_4 = -j\omega 2 K I_R \log \frac{d_{04}}{D_{04}}$$

Approximations can be made under certain conditions. If the induced voltage due to the residual current is required, it is permissible to replace the three power conductors by one single conductor, the error incurred being usually small. (The accuracy of this approximation increases as the power conductor spacing decreases.)

The formula then becomes $E_4 = K\omega I_R M_{04}$, where M_{04} is based on the mean dimensions of the power wires.

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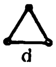
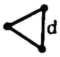
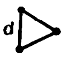
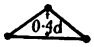
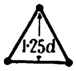
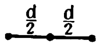
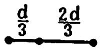
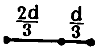
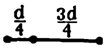
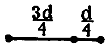
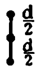
* This curve is in fairly close agreement with results calculated according to Rüdenberg's formula using an earth resistivity of 20 000 ohms per cm cube. The latter formula will be considered in the Supplement.

APPENDIX 3.

Table 1.

Exponents (n) for Formula Expressing Variation of Coefficients with Horizontal Separation.

$$E = K\left(\frac{x}{d}\right)^{-n} \quad \text{or} \quad V = K\left(\frac{a}{\delta}\right)^{-n}$$

Case No.	Configurations	Induction from power-circuit voltages				Induction from power-circuit currents			
		Balanced voltages		Residual voltage		Balanced currents		Residual current	
		Voltage to earth of a single isolated conductor	Voltage between two isolated conductors	Voltage to earth of a single isolated conductor	Voltage between two isolated cor ductors	Mean voltage along a pair of conductors	Difference of voltage along a pair of conductors	Mean voltage along a pair of conductors	Difference of voltage along a pair of conductors
1		1·8	2·6	2·0	2·9	1·1	2·0	—	—
2		1·8	2·6	—	—	1·1	2·0	—	—
3		1·9	2·6	—	—	—	—	—	—
4		1·9	2·8	—	—	1·1	1·9	—	—
5		1·5	2·3	—	—	—	—	—	—
6		2·4	3·5	2·0	2·9	1·4	2·4	1·1	1·5
7		2·4	3·3	—	—	1·4	2·2	—	—
8		2·0	3·0	—	—	—	—	—	—
9		2·3	3·1	—	—	—	—	—	—
10		1·9	3·0	—	—	—	—	—	—
11		1·9	2·9	2·0	2·9	2·0*	3·0*	—	—

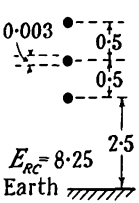
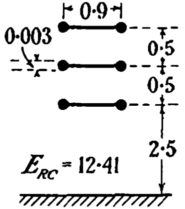
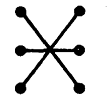
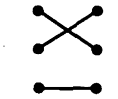
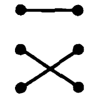
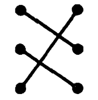
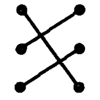
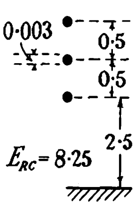
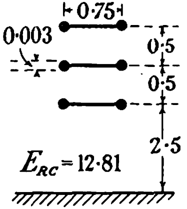
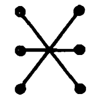
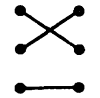
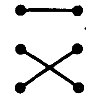
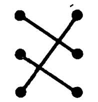
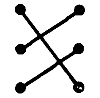
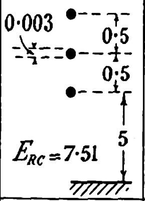
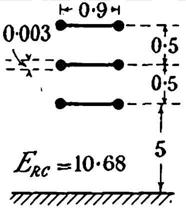
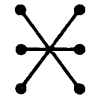
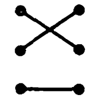
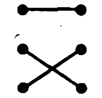
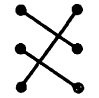
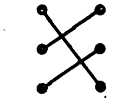
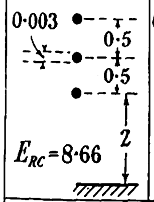
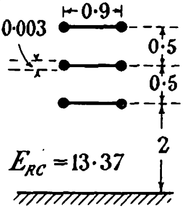
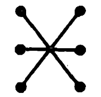
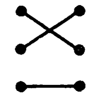
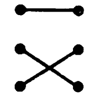
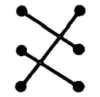
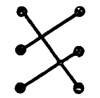
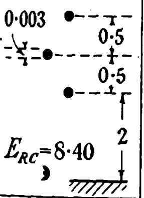
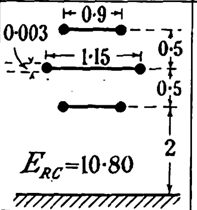
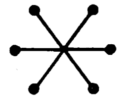
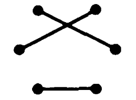
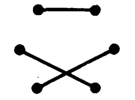
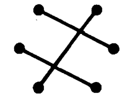
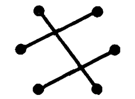
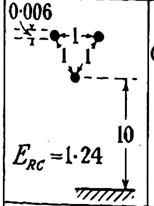
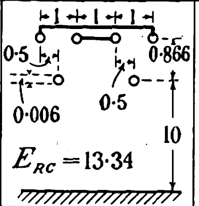
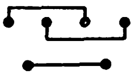
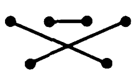
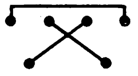
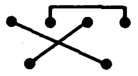
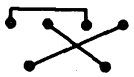
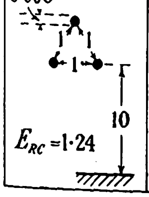
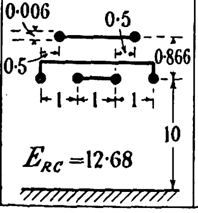
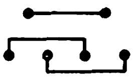
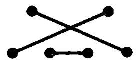
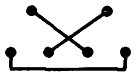
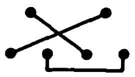
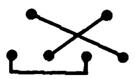
Disturbed conductors at right of power circuit.

* When $H/d > 100$

TABLE 2.

Characteristic Residual Voltages of Conductors in Parallel Single- and Twin-Circuit Lines.

E_{RC} = Characteristic residual voltage in per cent of balanced 3-phase voltage between conductors.

Single circuit	Twin circuits — Method of parallel operation					
	Nº 1	Nº 2	Nº 3	Nº 4	Nº 5	Nº 6
 0·003 0·5 0·5 2·5 Earth E_{RC} = 8·25	 0·9 0·003 0·5 0·5 2·5 E_{RC} = 12·41	 E_{RC} = 10·08	 E_{RC} = 11·31	 E_{RC} = 1·23	 E_{RC} = 6·20	 E_{RC} = 6·20
 0·003 0·5 0·5 2·5 E_{RC} = 8·25	 0·75 0·003 0·5 0·5 2·5 E_{RC} = 12·81	 E_{RC} = 10·63	 E_{RC} = 11·51	 E_{RC} = 0·88	 E_{RC} = 6·41	 E_{RC} = 6·41
 E_{RC} = 7·51	 0·9 0·003 0·5 0·5 5 E_{RC} = 10·68	 E_{RC} = 9·93	 E_{RC} = 8·38	 E_{RC} = 1·54	 E_{RC} = 5·34	 E_{RC} = 5·34
 E_{RC} = 8·66	 0·9 0·003 0·5 0·5 2 E_{RC} = 13·37	 E_{RC} = 10·17	 E_{RC} = 12·61	 E_{RC} = 2·44	 E_{RC} = 6·69	 E_{RC} = 6·69
 E_{RC} = 8·40	 0·9 0·003 1·15 0·5 0·5 2 E_{RC} = 10·80	 E_{RC} = 6·43	 E_{RC} = 10·72	 E_{RC} = 4·30	 E_{RC} = 5·40	 E_{RC} = 5·40
 E_{RC} = 1·24	 1 1 1 1 0·5 0·866 0·006 0·5 10 E_{RC} = 13·34	 E_{RC} = 4·31	 E_{RC} = 13·09	 E_{RC} = 8·78	 E_{RC} = 6·67	 E_{RC} = 6·67
 E_{RC} = 1·24	 0·006 0·5 0·5 0·866 1 1 1 1 10 E_{RC} = 12·68	 E_{RC} = 0·50	 E_{RC} = 10·72	 E_{RC} = 11·23	 E_{RC} = 6·34	 E_{RC} = 6·34

APPENDIX 4.

EARTHING OF NEUTRAL POINTS.

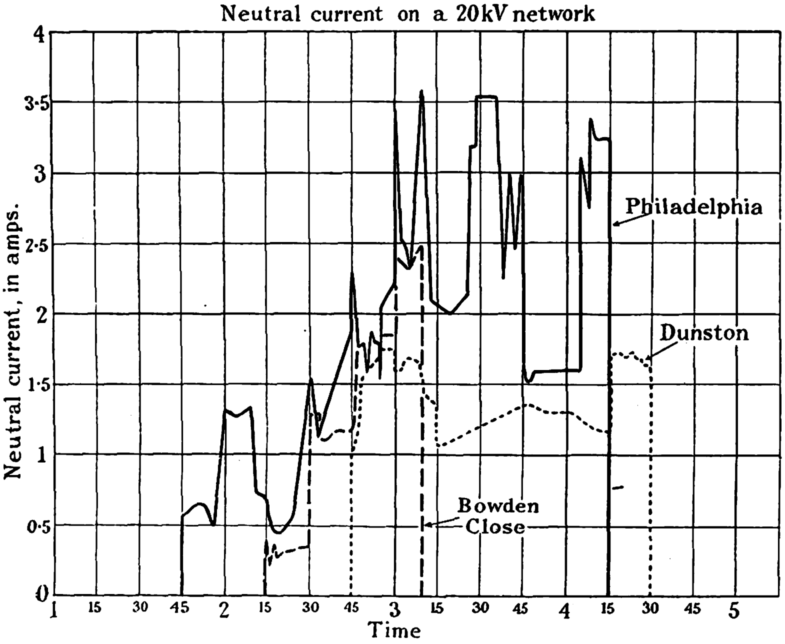
The information given in this Appendix supplements that given in Section 3 of the résumé.

Bartholomew (32) has given details concerning tests carried out on the power systems of the north-east coast in order to determine the increase in interference to the telephone system due to the provision of more than one earth connection to the power system.

It was pointed out by the power company concerned “ that whilst the provision of more than one earth connection might increase the interference from normal working of the power system, it would certainly decrease the possibility of serious trouble arising out of momentary disturbance of larger magnitude and would reduce the risk of these latter continuing for any appreciable time. It was agreed that it would not be wise to have more than one earth on a circuit directly connected with a generator the neutral point of which was earthed, but it was contended that with delta-star transformers feeding a system the triple-frequency currents would be small and would not be likely to increase to any extent the normal interference.”

During the tests which were carried out currents in the earth connections at the various points were measured. The results are shown diagrammatically in Fig. 14 attached to this Appendix, which has been redrawn to show more clearly the main results given in Fig. 43 of the paper referred to above.

With the system earthed at Philadelphia only, the current in that earth connection is 0·6 ampere, which increases to peak values of approximately 3·5 amperes when three or four other points (North Tees, Dunston and Carville), and these three points together with Bowden Close, are earthed in addition. The communication circuits were under observation during these tests, but no effect was observed on the telegraph circuits, “ and although there was an increase in telephone interference this was inappreciable ”: . . . “ the routes of the communication circuits under observation were not favourable for interference.”



SCHEDULE OF TESTS.

Time.	*Neutral earthed at:—*	*Time.*	*Neutral earthed at:—*
1.45 p.m.	Philadelphia.	3.15 p.m.	Philadelphia, North Tees, Dunston.
2.0 p.m.	Philadelphia, North Tees.	3.25 p.m.	Philadelphia, North Tees, Dunston, Carville.
2.15 p.m.	Philadelphia, Bowden Close.	3.35 p.m.	Philadelphia, Dunston.
2.30 p.m.	Philadelphia, North Tees, Bowden Close.	3.45 p.m.	Philadelphia, Dunston.
2.45 p.m.	Philadelphia, North Tees, Bowden Close, Dunston.	4.5 p.m.	Philadelphia, Dunston, Carville.
3.0 p.m.	Philadelphia, North Tees, Bowden Close, Dunston, Carville.	4.15 p.m.	Dunston, Carville.

Note.—Philadelphia is earthed through a resistance.

FIG. 14.

In this test measurements were apparently taken at only one-quarter of the combinations possible with a maximum of five earthing points. Without further data regarding the lay-out of the systems and the distribution, analysis and phase of the triple-harmonic currents, this test seems to be insufficient to enable indiscriminate multiple earthing to be advanced as desirable.

Dewey has found (*Journal A.I.E.E.*, 1923, vol. 42, pp. 589–600) that the normal current interchange on many large extensive systems with several neutral points earthed is usually so small that interference only occurs in a few cases.

GENERATORS CONNECTED DIRECT TO LINE.

Where generators are connected directly to the line, it is possible to reduce the triple-harmonic residual capacity currents by earthing the neutral of the machine having the wave-form which has the smallest triple harmonics, considered from the viewpoint of interference.

The use of a transformer to provide the neutral to be earthed eliminates the triple-harmonic currents due to the corresponding voltage harmonics in the generator wave-form. In order to prevent third-harmonic components appearing in the line due to these transformers, the secondary winding should be connected in closed delta, or an interconnected star primary winding used.

PETERSEN EARTH COIL OR NEUTRAL EARTHING REACTOR.

Earthing the neutral of power circuits through reactance coils has been adopted in many cases in Europe and a test installation has been tried out in the U.S.A. (see W. W. Lewis, *Journal A.I.E.E.*, vol. 42, 1923, pp. 467–484, and Oliver and Eberhardt, *ibid.*, pp. 904–914). In this method, originally described by Petersen (*E.T.Z.*, 1919, January 2nd and 9th), the neutral of the system is earthed through an inductance which is in resonance at the fundamental frequency with the total direct capacity of the system to earth. The effect of this method of earthing is to tend to extinguish arcing faults to earth. The earth current is small when a fault exists to earth, but according to Conwell and Evans (*Trans. A.I.E.E.*, vol. 41, 1922, pp. 75–93) difficulties are introduced in obtaining selective relay protection.

In the U.S.A. test installation it was arranged so that the reactor was short-circuited if the earth fault remained on the circuit more than a few seconds. The service interruptions due to flash-over were mostly eliminated.

Bekker has shown (*Journal I.E.E. Japan*, 1922, No. 409, p. 595, Synopsis in English) that the effect of magnetic induction is rendered independent of the position of the earth fault. For a particular case when a parallel exists over a quarter of the length of the power line at the receiving end and an earth fault occurs at the receiving end, figures are given showing that the magnetic induction with an earth coil is 10 per cent of that occurring with the neutral earthed through a non-inductive resistance equal in value to the reactance of the coil.

The voltage out-of-balance with the Petersen earth coil is three times that of the voltage unbalance of solidly earthed systems. According, however, to L. P. Ferris in the discussion of the paper by Conwell and Evans, theory and experience indicate that induced voltages with one phase earthed are more severe with solidly earthed than with insulated systems, except perhaps on long parallels with very high-voltage systems.

For normal conditions, the effect of the earth coil system has been investigated by H. M. Trueblood (70). Considerable reduction in the triple-harmonic residual voltages and currents occurring with solid or low resistance earthing is indicated, this reduction increasing with the order of the harmonic. Residual currents of non-triple harmonics are reduced to practically the same values which would be present with the system insulated. Fundamental residual components may be increased if the line unbalance be too great. Lewis (see reference above) gives results of tests on the U.S.A. installation, which agree with part of these conclusions. On the system tested, with the neutral dead earthed, a small residual current flowed containing 5th and 7th harmonics; with the neutral earthing reactor, the total residual current was increased 20 per cent, but these particular harmonics were eliminated.

It appears that the earth-coil system is at present limited to high-tension lines up to 60 kV of medium length and up to 100 kV for short lengths.

While a thorough investigation into this question has not been made, it was thought desirable to include the above information in view of several references which have been made of late to this system of earthing, hinting at the possibility of the desirability of its adoption in the future in this country. In this connection Bekker (see above) states that as a remedy for interference, which is a serious complaint in Japan, the Petersen earth-coil seems promising.

APPENDIX 5.

SHIELDING EFFECT OF EARTHED BODIES.

Earthed conductors in the neighbourhood of either the inducing or induced wires tend to shield the induced conductors from both electric and magnetic induction. Shielding is usually assumed to be of importance only in connection with electric induction. "For effective electromagnetic shielding, the shielding circuit should be of low resistance and closely coupled with either the disturbed or disturbing circuit."

Earth wires, as commonly employed for lightning protection on power lines, exert a shielding effect with respect to inductive effects from residual voltages and currents. They may increase, however, the intensity of the induction from balanced voltages and currents, by distortion of the electric and magnetic fields about the power circuit.

It is possible to calculate the amount of shielding without further assumptions, but the increase in labour involved is considerable and only isolated simple cases have been considered. A case where a single power line parallels two communication wires, one of which is earthed, has been worked out by the present investigators. These calculations, which are filed with the original digests (cf. the *résumé*), show that the reduction depends for a given communication wire only upon the proximity of the earthed wire to the communication wire. In the example considered the reduction factor, i.e. the amount by which the induced voltage is reduced, is 44 per cent.

The shielding effect of earth wires of three-phase power lines was considered in Technical Report No. 68 of the Californian Commission.

CALCULATED RESULTS.

Calculations were made for two relatively simple cases, using the methods explained in Appendix 2 when shielding effects were not considered.

The cases were chosen in order to simplify calculations as far as possible.

Table 1 to this Appendix gives the values with the earth wires present as a percentage of the values which would exist were the earth wires not present. This table is of use in indicating that the shielding effect of earth wires cannot be stated simply as a definite percentage. The shielding effect varies with types of induction, separation and other factors.

TABLE 1.

Effect of Earth Wires on Induction from 3-Phase Power Circuits.

Induction with earth wires as percentage of induction without earth wires.

Configuration	Characteristic residual voltage	Horizontal separation, ft.	Induction				
			Balanced voltages	Residual voltage	Balanced voltages and characteristic residual voltage	Balanced currents	Residual currents
o	120	30	102	86·0	104	84·0 124*	95·9
o o o		600	50·1	78·2	33·9	18·4 161*	95·9
o o	35·6	65	82·4	75·6	82·6	91·4 120*	94·1
o o o		1 040	223	70·1	392	74·4 141*	94·1

* Magnitude depends on phase rotation of balanced currents. The smaller value occurs when current in conductor nearest communication circuit leads current in intermediate conductor by 120°.

TABLE 2.

Transverse and Longitudinal Induction from Residual Voltage. Power and Telephone Conductors Non-Transposed. Idle Power Conductors Earthed.

Type of induction	Energized power conductors	Residual voltage,† volts	Induced voltage		Shielded / Unshielded
			Volts	Volts per volt	
Transverse	1	8 180	58·9	0·0072	0·97
Longitudinal	1	240	34·3	0·143	0·81
	2	238	23·8	0·100	0·71
	3	240	20·8	0·087	0·62

† Sum of voltages to earth of energized conductors only.

TEST RESULTS OBTAINED BY THE CALIFORNIAN RAILROAD COMMISSION INVESTIGATION.

A number of tests were carried out by the Californian Commission in the course of which the effects of shielding were observed.

In its Technical Report No. 54 an account of tests to determine the coefficients of longitudinal induction at 50 cycles is given. From measurements on induction due to residual voltages, earthing one of the telephone conductors of a telephone circuit supported on the power-line poles reduced the voltage induced in the other by 33 per cent, when all three power conductors were energized. If one power conductor is earthed, reduction amounts to 17 per cent; if two are earthed the value is 33 per cent. In the case of induction due to residual currents, the corresponding figures are 2 per cent, 28 per cent and 41 per cent. The larger values denoted by the latter two figures are due to the relatively low resistance of the power conductors compared with the smaller iron telephone conductors.

From Technical Report No. 56, in which coefficients of induction were determined over a short length of the parallel concerned in the tests in Technical Report No. 54, further figures are available. For induction due to residual voltages, Table 2 gives the shielding effect when the two idle power conductors are earthed. The effect on the transverse induction is seen to be small but increases to 19 to 38 per cent for longitudinal induction.

TABLE 3.

Shielding by Earthing Idle Power Conductors. Induction in Telephone Circuit from Residual Voltage.

Energized power conductor No.	Computed induced voltage					
	Longitudinal			Transverse		
	Volts per volt		$\frac{\text{Shielded}}{\text{Unshielded}}$	Volts per volt		$\frac{\text{Shielded}}{\text{Unshielded}}$
	Unshielded	Shielded		Unshielded	Shielded	
1	0·180	0·133	0·74	0·00858	0·00777	0·91
2	0·155	0·089	0·57	0·00482	0·00226	0·47
3	0·136	0·075	0·55	0·00296	0·00036	0·12

TABLE 4.

Shielding by Earthing Idle Power Conductors. Longitudinal Induction in Power Conductors from "Residual Current."

Power conductor number			Computed induced voltage		
Disturbing	Disturbed	Shielding	Volts per ampere		$\frac{\text{Shielded}}{\text{Unshielded}}$
			Unshielded	Shielded	
1	2	3	1·44	1·11	0·78
1	3	2	1·24	0·87	0·70
2	3	1	1·44	1·11	0·78
2	1	3	1·44	1·11	0·78
3	1	2	1·24	0·87	0·70
3	2	1	1·44	1·11	0·78

TABLE 5.

Comparison of Measured and Computed Shielding. Conductors Earthed. Induction in Telephone Circuit from Residual Voltage.

Energized power conductor No.	Induced voltage ratio $\frac{\text{Shielded}}{\text{Unshielded}}$			
	Longitudinal		Transverse	
	Measured	Computed	Measured	Computed
1	0·81	0·74	0·97	0·96
2	0·71	0·57	—	0·41
3	0·62	0·55	—	0·32

COMPARISON BETWEEN TEST AND CALCULATED FIGURES.

In the same report calculations were made in order to compare test and calculated figures. For the special cases of residual voltage and residual current with a single conductor of the power circuit energized, the shielding effects of earthing the idle power conductors were calculated. Tables 3 and 4 give the results obtained. Table 5 compares the shielding, measured and calculated for the case of induction from residual voltage, one power conductor being energized and the other two earthed. The calculated values for transverse induction take into account the capacitance out-of-balance of the telephone circuit.

OTHER PUBLISHED RESULTS.

Tests made on the Lancaster–Heysham section of the Midland Railway (21) showed a reduction of 15 per cent due to the shielding action of an earthed wire mid-way between the inducing and the induced circuits, combined with that of earthed telegraphs on the same poles as the circuit under test. The separation was of the order of 12 ft.

Tests on the Lake Coleridge (New Zealand) Transmission System (24) showed reduction factors varying from 55 per cent to 25 per cent due to the remaining five of a group of six communication conductors being earthed. The distance from the power line was about 26 ft.

The above tests only concern electric induction.

The opportunity of tests on induction between a h.t. system and German Imperial Telegraph and Telephone Lines (119) led Brauns to draw certain conclusions regarding the shielding effects of earthed wires. For a vertical configuration and separation varying from 7 to 10 metres he suggests a reduction factor varying from 30 to 60 per cent according to the position of the earthed wires.

In a later article (95) Brauns considered the shielding effect of neighbouring rows of trees by replacing them by an equivalent earthed conductor, the size of which is apparently arbitrarily chosen. The reduction factors so calculated vary from 80 per cent to 25 per cent depending on the position of the trees relative to the lines concerned. No test data is available in this connection.

Jäger in a more recent general article (88) apparently has summed up this question by stating that earthed objects, which include rows of trees and earthed wires, near either power or communication lines exert 25 per cent to 30 per cent protection on the electric induction. An earthed wire screen is stated to reduce the charging current in the protected wires to about one-third, i.e. a reduction factor of 33 per cent.

APPENDIX 6.

REMEDIES APPLICABLE TO TELEGRAPH CIRCUITS.

The information given in this Appendix is taken from a very comprehensive discussion by Devaux-Charbonnel (36) except where otherwise stated. The classification adopted for the various remedies is that given by Leboucher and Villeneuve (61).

APPARATUS FOR REDUCTION OF THE INDUCED CURRENT.

Increase of circuit impedance.—By the insertion of inductance in series with the apparatus, the disturbing a.c. is reduced. The value of the inductance is limited by the permissible time-constant of the apparatus—an important factor since it determines the limit of transmission speed.

Proceeding from the statement that the disturbing current should not exceed 20 per cent of the working current, it is shown that, for a maximum speed of 15 signals per second (say 70 words per minute), the maximum permissible value of an induced voltage at a frequency of $16\frac{2}{3}$ cycles per second is 60 per cent of the working d.c. voltage. For higher frequencies the permissible limit is increased.

Arrangements comprising an inductance placed at each end of the line, termed the Carat method, were in service over a year on lines paralleling the Midi Railway (then a single-phase system) and worked perfectly if the induced voltage did not exceed 100 volts.

Increase in impedance of apparatus due to eddy currents.—It had been suggested that by placing metal in the magnetic field the effective resistance of the apparatus to a.c. would be increased due to eddy currents. Drouet placed a copper ring for this purpose on a relay-type sounder. The relay has functioned correctly with 20 mA working current, when the disturbing current is 8 mA at a $16\frac{2}{3}$-cycle frequency and 12 mA at a 25-cycle frequency. The apparatus has the disadvantage that it is of a special type.

Insertion of a series rejector.—Latour and Bethenod suggested the insertion of a parallel resonant circuit in series on the line and tuned to the disturbing frequency so as to form a rejector for that frequency. This arrangement suffers from the disadvantage that resistance is inserted in the circuit. Leboucher and Villeneuve (61) state that Latour used this rejector in conjunction with a resonant shunt placed across the receiving apparatus, and with both circuits tuned to a frequency of $16\frac{2}{3}$ the arrangement was satisfactory with induced voltages up to 300.

APPARATUS SHUNTING THE INDUCED CURRENT.

Resonant shunt.—Latour's apparatus employs a resonant shunt connected between the line side of the receiving apparatus and earth. The usefulness of this arrangement is shown to be greatly increased by the insertion of series impedances on the line side and on the apparatus side of the connection to the shunt. Leboucher and Villeneuve mention a similar arrangement which was in service for 18 months on a line paralleling the Midi Railway. The method was found to be efficacious up to certain values of induction for high-speed telegraphs. Tests at Tarbes showed that Hughes' apparatus was working with an induced voltage of 100.

Bartholomew (32) states the greatest success has been achieved with resonant shunts and shows the connections for simplex and duplex circuits in this country, where apparently series impedances are not used in conjunction with the shunts. The design of the shunt is limited in both directions since a high capacity will seriously affect signals on certain types of circuits which are worked by condenser impulses, while a high inductance makes the shunt less effective due to its associated resistance. With automatic working it is pointed out that the protection afforded by the shunt fails when the speed of working (Wheatstone automatic being cited) results in alternations approaching the resonant frequency of the shunt or multiples thereof. In an actual case of a circuit fitted with a shunt, a disturbing pressure of 22 volts caused interference when working on a 50-volt battery. The figure corresponding to this case, as calculated from formulæ derived by Devaux-Charbonnel on certain assumptions, is of the order of 30 volts for the maximum permissible disturbing voltage. With series impedances in conjunction with the shunt and a battery voltage of 150 volts, the limit is given as 500 volts.

Bridge connections.—Brouquier has proposed a bridge connection with the receiving apparatus connected across two arms so that no disturbing current of the frequency for which the bridge is balanced passes through the receiver. This type of protection does not appear to have been developed.

APPARATUS COMPENSATING THE EFFECT OF THE INDUCED CURRENT.

Girousse apparatus.—This method involves the use of a relay with two equal windings differentially connected. One winding of the relay is connected to the line through an inductance and capacity in series arranged to be resonant at the frequency of the disturbing voltage; the other is connected to the line through a resistance equal to the equivalent resistance of the resonant part of the first path. The disturbing current then divides equally between the two windings and its effect is neutralized.

The relay works well if the disturbing current does not exceed 80 mA. Since the circuit impedance with apparatus in circuit is 2 500–3 000 ohms, this apparatus is useful for induced voltages up to 200–250 volts. It is stated to work well in certain departments of France, but was not maintained in the Midi region, partly because of the complication introduced.

The Latour apparatus, considered above, was preferred by the Midi Company. Leboucher and Villeneuve (engineers of the Midi Railway) state, however, that beyond about 150 volts protection is not given. Condenser discharges tend to distort signals. Girousse (56) states that this apparatus has given good results on lines paralleling the 10-kV Haute-Vienna and the 6·6-kV Maritime Alps tramways and the Pyrenées–Orientales Railway. Voisenat (51) deals with the disadvantages of this method.

Apparatus involving the use of a transformer.—The method involving the addition of a transformer, by means of which a current is induced in the receiver in opposition to the disturbing current in the line, is due in its simplest form to Delcamp, and has been modified by Brouquier. Tests have proved satisfactory but the apparatus is of a special type and the method has not been used. Arrangements using transformers have been proposed by Lavallée and Hébécourt, but are not of interest.

METHODS BASED ON MECHANICAL MODIFICATION OF RELAYS.

These methods have the disadvantages that special apparatus is required and they have not been adopted on this account. In addition, as Leboucher and Villeneuve point out, for a particular modification, such devices do not discharge the line (presumably in comparison with previous methods, considering magnetic induction). These modifications are therefore not described.

Effect of frequency variation.—Methods involving the use of resonance devices are most severely affected. In the case of the Girousse apparatus, a frequency variation of the fundamental to the extent of 1 cycle in $16\frac{2}{3}$ allowed 5 per cent of the disturbing current to pass in the particular case calculated. Hence with a permissible limit of 4 mA disturbing current through the relay the permissible induced voltage is approximately 170 volts.

The Latour apparatus using a resonant shunt is affected more since the effective resistance is small. With the same frequency variation, the permissible disturbing voltage is reduced to an amount of the order of one-third of the permissible value at resonance.

In the case of the method employing a series rejector the increase in impedance is of the order of 7 per cent with the above frequency variation and a time-constant of approximately 0·03, so that its effectiveness is not much impaired.

APPARATUS TO TRANSMIT AT A HIGHER VOLTAGE THAN THE INDUCED VOLTAGE.

Leblanc proposed an arrangement in which the signal impulses were transferred to the line by a 10/1 step-up transformer, and a special modified Baudot relay was used as the receiving apparatus. Results were satisfactory, but trouble was found due to static charges, since the impedance to earth of the apparatus was high (of the order of 100 000 ohms), while, due to the high voltage, leakage effects trouble the transmission.

APPARATUS TO TRANSMIT AT A HIGHER FREQUENCY THAN THE INDUCED FREQUENCY.

Magunna evolved a method in which a vibrating tuning fork produces vibrations at a frequency of 500 which are employed for signalling, a receiver being used which only responds to this frequency, according to Leboucher and Villeneuve. Results obtained are good, according to Devaux-Charbonnel, while up to 12 channels of communication are possible over one wire. The only disadvantage appears to be the necessity of altering existing apparatus and the method has not been applied. Leboucher and Villeneuve only state, however, that the apparatus is too complicated for small telegraph offices.

APPARATUS TO TRANSMIT A.C.

Leboucher and Villeneuve refer to tests made in 1914 by Gratzmüller in which a.c. was permanently transmitted, signals being sent by interrupting the a.c.

More definite information regarding transmission by a.c. is given in an article (115) in which a system, which has been in use on the Italian State Railways, is described. Spinelli-triplicators were used to supply the a.c. at a frequency of 126 or 150 which is relatively high compared with the traction fundamental frequency. Special receiving circuits were used. Tests made in service showed that communication was not affected on a line on which the induced voltage was more than 100 volts with maxima up to 250 volts, while on a normal circuit the relay armature vibrated continually.

The transmission voltage was 110 volts.

The conclusions drawn regarding this method are:—

(1) Ordinary working with normal apparatus is possible.
(2) Induction by the a.c. on other telegraph circuits has no influence on the working of Morse apparatus.
(3) Induction on metallic telephone circuits is, in the cases observed, of the same order as that produced by other telegraph circuits when a coil-type generator is used; it is quite insensible when a smooth wave is used.

The system might also be applied to high-speed apparatus such as the Hughes apparatus by employing suitable transmission frequencies.

This system has, apparently, been adopted for lines alongside railway routes which are being electrified.

APPENDIX 7.

REMEDIES APPLICABLE TO TELEPHONE CIRCUITS.

INTERFERENCE DUE TO TRANSIENT CONDITIONS ON THE POWER LINE.

Induction from short-circuits on the power line is apt to cause acoustic shock through the non-simultaneous operation of the over-voltage protectors connected to the telephone lines. Jäger (88), in an extensive summary of investigations carried out by the German Telegraph Administration and published in 1924, states that although attempts have been made to produce a protective device which will give simultaneous operation, e.g. the vacuum-tube protector with three electrodes, presumably one connected to each line and one earthed, a successful device has not been constructed. A British Patent Specification (99), taken out in 1922, describes an improved form of protective device which, it is claimed, considerably reduces the acoustic disturbance. If similar results to those claimed in the Specification have been obtained commercially, the protector will go a long way towards solving the problem of eliminating acoustic shock from transient conditions on the power line.

Apparatus shunting receiver.—The German Telegraph Administration has made extensive experiments with "rare gas" devices connected across the receiver to avoid noises, according to Jäger (88). A device consisting of a "cartridge" (presumably a tube) filled with argon at a pressure of 5 mm and provided with basket-formed electrodes containing potassium mixture meets the case if placed in parallel with the receiver. This "shunt" protector operates on the average at 150 volts. Operation is satisfactory when induction is due to transient conditions, but when acoustic shocks are due to normal induction this protector is no use. The protector continues acting and produces a crackling noise in the receiver.

Jäger also mentions that the most satisfactory devices are of the coherer type although they are not always reliable. These devices are shunted across the receiver similarly to the "rare gas" protector and operate with quite low voltages. This can easily be a disadvantage as they cannot be maintained permanently on the line, for they would short-circuit speech currents.

The same article states that experiments have been made to reduce acoustic shock by adopting a different receiver construction.

Jäger also points out that acoustic shocks could not originate if over-voltage protectors could be dispensed with, assuming perfect insulation so that a breakdown would not occur. He foresees that in the future German cable system there will be no over-voltage protection, and mentions a figure of 2 000 volts which the cable and telephone transformers should withstand. In the proposed French Rules (102) it is laid down that "if underground lines terminate on transformers and arresters between wires and earth are absent, the maximum values expressing danger in case of short-circuit are considered to be the breakdown voltage between cable conductors and sheath, between transformer windings and between transformer windings and their metallic covering."

REDUCTION OF EFFECTS DUE TO LONGITUDINAL INDUCTION.

Insulating transformers.—The use of insulating or telephone transformers in separating sections of a circuit with different degrees of unbalance has been mentioned in Section 6.

Drainage coils.—A drainage coil consists of a high-impedance coil connected across the conductors of the telephone circuit and earthed at its mid-point. The halves of the winding are so connected that the impedance to currents flowing from wires to earth is small, being the resistance of the coils only if the coil is perfectly balanced; at the same time the impedance between the telephone conductors is high. The use of such coils was mentioned by Schrottke (35), who pointed out that by connecting a regulating resistance across the halves of the coil, so arranged that the coil could be earthed at any point along the resistance, it would be possible to neutralize any unbalance in the telephone line due, say, to insulation faults. As Stein (*E.T.Z.*, 1912, pp. 844–847), however, shows, this regulating resistance is useless for this purpose, since the earth current through the coil due to electric induction is only slightly affected by the value of the earthing resistance. In addition, the unbalance may vary due to a sudden change in line resistance due to bad joints.

Jäger (118) mentions the results of connecting discharge coils to communication circuits. The most satisfactory results were obtained with coils with a low resistance of 22 ohms per winding which were applied to telephone lines carried on power-line poles. Coils with windings each having a resistance of 200 and 1 100 ohms were correspondingly less satisfactory. From measurements made of the impedances of the windings of these coils, differences of the order of 1 to 2 per cent were found between windings of the same coil.

Jäger points out that if the windings of a coil are unbalanced, a portion of the current to earth will flow round the apparatus. The unbalance of the telephone circuit also needs to be taken into account. Telephone lines carried on power-line poles have a fairly well-balanced insulation, as they are far from trees and are often insulated with h.t. insulators. In comparison, an unbalance of 5 to 10 per cent must be looked upon as an average figure, according to Jäger, for public service circuits in Germany. This figure takes into account all electrical constants, including the mutual unbalance with respect to the power line. It is then shown that the effect of connecting a discharge coil to a telephone circuit may result in a charging current through the receiver due to the circuit unbalance. Similarly, it is shown that when two discharge coils are connected to a circuit, unbalance currents will flow through the receivers due to magnetic induction.

In conclusion it is stated that discharge coils can, therefore, only be used for the purposes of the R.T.V. (German Imperial Telegraph Administration) in exceptional cases and should by no means be looked upon as sufficient protection for strongly influenced lines.

Kellogg (52) mentions that drainage coils practically eliminate noise from longitudinal induction due to insulation leakage, but sometimes increase the trouble due to defective joints. Increased susceptibility to noise from irregularities in the series impedances of a circuit is also pointed out by Warren (59). Telephone transmission efficiency is impaired also. Warren remarks that these coils are helpful for reducing electrostatic effects on power companies' lines carried near h.t. lines, but they have not proved to be adapted for general use on commercial systems. Leboucher and Villeneuve (61) confirm that attempts to allow for unbalance of the circuit by varying the relative number of turns in the windings of the coil were unsuccessful.

So far the use of discharge coils on public telephone lines in this country has not been found to be necessary.

It is shown from the above that discharge coils are not a general remedy for public service lines, but they may be used with good effect on strongly induced lines, such as private lines carried on power-line poles. Successful application is reported by Bennett (4) and Gillespie (104).

Latour system of transmission.—Costabel (84) gives an account of experience with this system in which the telephone current is amplified at the sending end and reduced at the receiving end. Disturbing effects are, therefore, reduced at the same time. Several circuit arrangements are given employing ordinary valve amplifiers.

Tests carried out on the Midi Railway showed that these arrangements overcome disturbances due to single-phase traction lines without a return feeder. The conclusion is drawn that this system is for circuits carried on power-line poles.

Bartholomew (32) points out that this system would be satisfactory on single-circuit routes, " but overhearing would occur on lines carrying two or more circuits owing to the greater power used."

Use of cabled circuits.—The consequence of earthing the lead sheath is to bring into play a compensating effect which reduces to some extent the longitudinal induced voltage. A number of writers have considered this effect in particular connection with induction due to single-phase railways. Amongst these are Kühle (6), Krause and Zastrow (116), Zastrow (80) and Jäger (88). It will be clear that short-circuit conditions on earthed power systems will produce similar effects to those present with single-phase traction systems. The vector diagram shown in Fig. 15 has been re-drawn from a similar diagram given by Jäger in order to cover both cases. Since the lead sheath is earthed at various points a sheath current flows due to the longitudinal voltage induced therein, and a partially compensating e.m.f. is induced in the cable conductor.

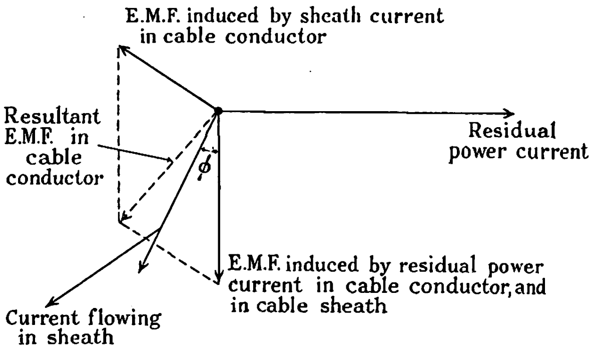

E.M.F. induced by sheath current in cable conductor
Resultant E.M.F. in cable conductor
ϕ
Residual power current
E.M.F. induced by residual power current in cable conductor, and in cable sheath
Current flowing in sheath

FIG. 15.

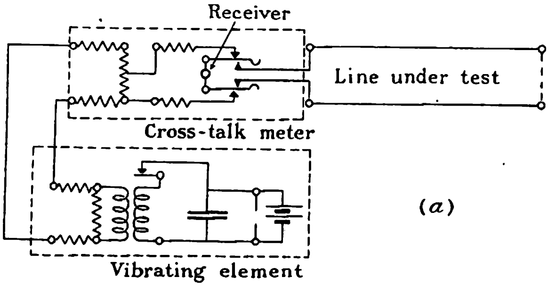
APPENDIX 8.

NOISE MEASUREMENTS.

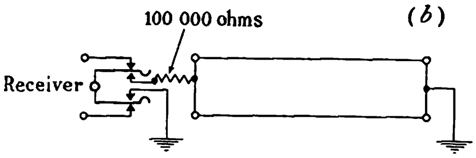
In interference problems, the deciding test as regards disturbance to telephonic transmission is the amount of noise produced in the subscriber's receiver.

The 1-*A* noise-measuring set has been developed in U.S.A. so that the noise on any circuit can be directly measured in terms of an arbitrary noise unit. A description of this apparatus is given in a paper by Erikson and Mack (*Journal I.E.E.*, vol. 62, 1924, pp. 653–687). The circuit of the noise-measuring set is given in Fig. 16. It is a portable instrument including a standardized vibrating element or noise standard generating a noise of comparatively low fundamental tone very rich in harmonics. The receiver is connected alternately to the circuit under test and to the standard and the potentiometer setting is adjusted until the noise in the receiver is judged to be the same in both cases as regards disturbance to conversation.

The noise-measuring circuit used in connection with the Californian Commission investigation has been superseded by the 1-*A* noise-measuring set.



(*a*) Measurement of line noise.



(*b*) Measurement of earth noise.

FIG. 16.—Circuit of noise-measuring set.

The 2-*A* noise-analysing set is another U.S.A. development which is used for determining the frequencies of the different tones in a noise. In conjunction with the 1-*A* noise-measuring set it may be used for obtaining an approximate estimate of the relative magnitudes of these tones. The circuit of the noise-analysing set consists of a resonant circuit with a receiver in series, which can be caused to resonate at any frequency between 150 and 2 500 cycles per second by varying the value of the condensers. Whenever resonance points occur the corresponding frequency can be read from a calibration chart.

It is stated in this paper that " the effect upon transmission efficiency of various amounts of noise has been closely studied, so that an estimate can now be made of the reduction in intelligibility in any given case due to the presence of a given amount of noise."

A flicker-type noise meter in which the unknown noise is balanced against a known sound from a current of definite frequency has been tried by the Post Office (32) but has been found unsatisfactory.

Another method, which was also being investigated, consists of amplifying the noise so that the current in the circuit can be measured and by means of a potentiometer comparison made between the amplified and line currents; thus the line noise can be expressed as a voltage. Filters are necessary to cut out frequencies outside the audible range to ensure that the current measured includes only that producing noise.

The vibrating element type has been widely employed in America and Europe, and is specified for use in the French Rules.

APPENDIX 9.

EFFECT OF PHASE-CHANGE AND ATTENUATION.

The effect of phase-change and attenuation has been discussed in Technical Report No. 66 of the Californian Investigation.

Considering a uniform exposure of a telephone conductor to a three-phase power circuit forming one

TABLE 1.

Unbalanced Exposures in a 24-Mile Parallel.

Different lengths and types of barrelling.

V = 144 000 miles per second; f = 1 000 cycles per second.

Barrels		Unbalanced exposure, miles				
		One barrel		Total unbalance		
Number	Length, miles	*ABC*	*CBA*	*C*	*H*	*H–R*
0	—	—	—	22·9	—	—
1	24	4·3	5·1	4·3	—	—
2	12	1·15	1·27	2·2	1·6	0·6
3	8	0·52	0·55	1·49	0·32	0·43
4	6	0·294	0·310	1·13	0·19	0·15
6	4	0·132	0·137	0·76	0·08	0·07
8	3	0·074	0·076	0·57	0·10	0·04

C = " Continuous " type barrels.
H = " Halting " type barrels.
H–R = " Halting-reversing " type barrels.

complete barrel, there are equal exposures of the three different phase arrangements. If it is assumed that no phase-change or attenuation occurs in the balanced voltages and currents along the power circuit, these components induce waves in the telephone conductor which are 120° apart in phase and at points one-third of the length of the barrel apart. These three waves would be at every point and the resultant would be zero if the waves travelled along the telephone conductor at an infinite speed. Since in the time for the waves to travel to a particular point a change of time-phase occurs, then considering a point at one end of the parallel the waves from points in the middle and further section one-third of the barrel length apart arrive there $120° + \phi$ and $240° + 2\phi$ out of phase with the wave from the first section. The change in time-phase ϕ is that occurring while a wave travels along one-third of the barrel length. It is shown in the above-mentioned report that the unbalance U is given approximately by

$$\frac{2\pi f L^2}{9V}\left[1 + 2/\underline{120 \pm \tfrac{1}{2}\phi}\right]$$

When ϕ is small, it is evident that the unbalance varies directly as the frequency, as the square of the length L of the barrel, and inversely as the wave-speed V. The alternative sign allows for the two possibilities, namely, whether the power transpositions cause a lead or a lag of 120°, depending on the point in the parallel considered.

It is shown from a consideration of a 6-mile barrel at 1 000 cycles that the effect of attenuation can be neglected for the range of frequencies and distances met with in practice, and that the approximate formula shown above is sufficiently accurate for all ordinary purposes. " For the rather extreme case of a 24-mile barrel at 1 500 cycles " this " equation indicates an unbalance of 6·5 miles which is about 6 per cent too high."

" The speed of propagation is generally from 170 000 to 180 000 miles per second in power circuits and in non-loaded metallic telephone circuits," open-wire circuits being considered.

Considering the phase-change of the waves also present in the power circuit, the effect on the unbalanced exposure may be either additive or subtractive with respect to the effect of the phase-change occurring in the telephone circuit, depending on the position chosen on the telephone line. Therefore, at one end of the telephone line the total effect of phase-change is zero assuming the same wave-speed in both circuits, while at the other end the total effect would be double that which would occur were there no phase-change along the power line.

Hence if the phase-change along the telephone circuit is alone considered, the average effect is obtained, although the worst effect will be roughly double this value.

Reflection of waves from the communication circuit is not considered in the above discussion.

In Technical Report No. 68 are shown some curves giving the unbalances for various frequencies and lengths of barrel. The curves show that unbalances of 0·1 mile occur as follows:—

Frequency, cycles per second	Length of barrel, miles
300	6·1
900	3·6
1 500	2·8

Owing to the large unbalance with long barrels it becomes necessary to use more than one barrel in long uniform parallels.

As mentioned in Section 7 of the *résumé*, where more than one barrel is necessary, three different arrangements may be used having barrels of equal length. Table 1 to this Appendix shows the unbalance for each of these three types of transposition in a 24-mile parallel when the frequency is 1 000 cycles per second.

The advantage of both types of halting barrels over continuous barrels is clearly shown. With " continuous " barrelling the unbalances of successive barrels add nearly in phase, while with " halting " and " halting-reversing " barrelling the unbalances nearly balance each other every three barrels and two barrels respectively.

Such arrangements enable the unbalances to be reduced " to a point beyond which it is probable that minor irregularities will control the result."

APPENDIX 10.

METHOD OF CALCULATION OF LENGTHS OF UNBALANCED EXPOSURE.

Since the method of obtaining the amounts of unbalanced exposures in an actual parallel is practically unknown to power engineers, the details of the procedure necessary for the calculation are given here as outlined in Appendix 1, Technical Report No. 66 of the Californian Investigation. The example considered is taken from this Appendix and involves telephone circuits transposed on the cross-over system. A diagram of the telephone transpositions showing the exposures of each circuit for a complete transposition section is required. In order to distinguish between the two possible positions of each circuit relative to the power circuit, the terms positive and negative exposures are used. Diagram 1 in Fig. 17 shows this diagram for the example to be considered. Another diagram, termed the " Transposition Distance Chart," is necessary, on which is shown the actual distances between successive telephone transposition poles and the distances from the nearest telephone transposition poles to all power transpositions and points of discontinuity. Diagram 2 on the same Fig. 17 shows such a chart for the example chosen. The parallel may be divided into a number of zones or uniform parallels and the unbalance exposure determined for each circuit in each zone or uniform parallel.

The three different phases of induction from a transposed three-phase circuit of uniform construction are termed A, B and C. B is assumed to lag by 120° behind A, and C to lead A by 120°. Transverse induction is positive or negative, depending on the position in the telephone transposition section.

The sample record sheet given below shows the type of form used, with figures entered for circuit 7–8, zone 2 being considered. The distances correspond to + *A* − *A*, + *B*, etc.; exposures are set down as shown and totalled. The sum of the positive *A* total and negative *A* total gives the longitudinal *A* exposure, while the difference of these totals gives the transverse unbalances. The *B* and *C* figures are treated in the same way. The transverse residual unbalance is given by the algebraic sum of the *A*, *B* and *C* transverse unbalances. The transverse and longitudinal unbalances to balanced components of currents and voltages are then obtained

Sample Record Sheet.

Lengths of Unbalanced Exposure.

Parallel: San Jose-Gilroy.

Remarks: Present transpositions.

Circuit No. 7–8 Zone No. 2

+A	−A	+B	−B	+C	−C
1 330	1 020	840	1 330	1 170	780
1 340	1 340	1 210	1 340	340	1 250
500	1 220	1 340	390	—	1 250
1 340	1 340	1 180	810	—	1 170
1 350	1 210	1 360	1 340	—	1 360
—	520	1 210	—	—	—
—	—	1 340	—	—	1 230
—	—	1 210	—	—	320
—	—	1 330	—	—	—
—	—	1 340	—	—	—
—	—	880	—	—	—
5 860	6 650	13 240	5 210	1 510	8 700
—	5 860	—	13 240	—	1 510
Longitudinal ..	12 510	—	18 450	—	10 210
Transverse	− 790	—	+ 8 030	—	− 7 190

Transverse Residual:

+	−
8 030	790
	7 190
8 030	
7 980	7 980

+ 50

Transverse-Balanced Longitudinal:

+ 8 030	B	18 450
− 7 190	C	10 210
840	$B + C$	28 660
− 790	A	12 510
− 420	$-\frac{1}{2}(B + C)$	− 14 330
− 1 210	$x = A - \frac{1}{2}(B + C)$	− 1 820
+ 15 220	$B - C$	+ 8 240
+ 13 180	$y = 0{\cdot}866(B - C)$	+ 7 140
13 240	$U = (x^2 + y^2)^{\frac{1}{2}}$	7 360

by adding vectorially the three transverse and longitudinal unbalances.

In order to combine the unbalance exposures in several zones, the relative magnitude of the induction per unit length and the phase difference must be calculated for each zone.

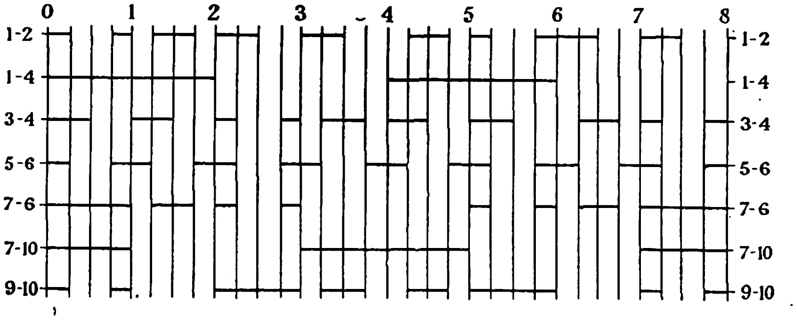


Diagram 1.—Telephone transposition diagram.

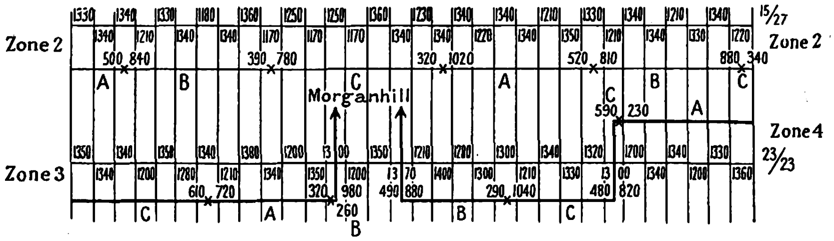


Diagram 2.—Transposition-distance chart. San Jose-Gilroy parallel.

FIG. 17.

For the example considered it is seen that the residual transverse unbalanced exposure is + 50 ft. while the balanced transverse and balanced longitudinal unbalanced exposures are 13 240 ft. and 7 360 ft. respectively, the length of the zone being 41 170 ft. (approximately 8 miles).

APPENDIX 11.

TELEPHONE TRANSPOSITION SCHEMES.

This Appendix gives a more complete description than is contained in the *résumé* of the special methods developed by the American Telephone and Telegraph Co. of transposing telephone lines exposed to induction from other circuits.

An outline of the methods of design involved is given by H. S. Osborne (78). A systematic consideration of all possible arrangements was necessary to obtain the maximum economy and efficiency.

THE "E" SECTION.

An endeavour was made to develop a new section having a nominal length of 8 miles (actually 8 miles or less), which should give balance within short lengths for all circuits for induction from balanced and residual components, and should properly co-ordinate with power barrels of several lengths.

"Investigation of $\frac{1}{2}$, $\frac{3}{4}$, 1, $1\frac{1}{2}$, 2, 3, 4 and 6-mile continuous barrels in relation to the 64 fundamental types of telephone transpositions indicated that economical telephone transposition systems could not be developed to co-ordinate with barrels other than those $\frac{1}{2}$, 3 and 6 miles in length."

Other variations of power barrels were also considered.

"The system evolved has the following characteristics:—

"Balance to non-transposed foreign circuits in each mile; balance to three-phase power circuits transposed for $\frac{1}{2}$ and 3-mile barrels (and to barrels the length of which is any multiple of 3 miles) in each mile." "The system of $\frac{1}{2}$-mile barrels, halting at mile points only, having five transpositions (with the same direction of rotation) between mile points, was chosen on account of the greater economy found to obtain therewith." From information given in Osborne's paper mentioned above, continuous barrels can be used for the 3-mile barrels.

For 4-cross-arm, 40-wire lines, 32 transposition poles per 8-mile section are required when physical circuits are alone present. When phantom circuits are present 64 transposition poles are required. Drawings showing the system of transpositions for these two cases are given in Technical Report No. 66. For further cross-arms, 64 transposition poles are required for physical circuits and the most commonly occurring phantom circuits.

The E section can be used for line lengths shorter than 8 miles, but below 4 miles it is more economical to use the L transposition section.

THE " L " SECTION.

This section was designed on the same general principles as the E section, but is arranged for a section length of 4 miles or less. This section has the following characteristics:—

Balance to non-transposed circuits in each mile.
Balance to three-phase power circuits transposed for 3-mile barrels.

" It is frequently possible to include points of discontinuity within sections by so placing the telephone transposition sections that the discontinuities occur at mile-points, which are neutral points with respect to external sources of induction." This statement applies to both E and L sections.

" It is desirable to use these transposition sections wherever possible in parallels on account of the combination of good cross-talk balance, frequent balance to foreign circuits and provision for co-ordination with power transpositions, and they are the normal means to be used where uniformity and length of parallel justify."

CONSECUTIVE " X " SECTIONS.

" Where parallels contain numerous points of discontinuity separated by short distances, and where short lengths intervene between ends of longer sections and points of discontinuity, consecutive X sections are very convenient."

An X section comprises a section $\frac{1}{2}$ mile or less in length containing three transposition poles at its quarter points. "The use of X sections in parallels often involves the use of several in succession, each X section having transpositions added so as to secure balance within itself to non-transposed parallel foreign circuits." " Junction points of sections are placed opposite power transpositions and points of discontinuity. It is not necessary, though desirable, that successive sections be of the same length." " Consecutive X sections are decidedly inferior to the E and L sections on account of the relatively poor cross-talk balance and the greater cost for a given length."

" WHOLE-LINE " TRANSPOSITIONS.

When physical circuits only are concerned, the cross-talk balance of the existing telephone transposition system is not disturbed by inserting transpositions in all the circuits at any point, that is, transposing the " whole-line." " It is thus possible in such cases to place extra transpositions wherever required to balance the exposures to power circuits."

This method may be employed in some cases, where phantom circuits are present on the telephone line, without increasing the cross-talk to excessive values.

" The best use of this method is obtained in very short parallels or in short portions of long parallels where it is inconvenient to use the exposed line sections and where otherwise a long section of line outside the parallel would have to be transposed.

" The method is a very simple and economical solution of the problem of co-ordination of transpositions, where it is applicable."

PRACTICAL APPLICATIONS.

In order to appreciate fully the foregoing information it is necessary to consider an actual parallel and work out a co-ordinated scheme of transpositions.

In actual cases " the length and character of transposition sections and barrels is usually determined by the location of the points of discontinuity." In a long uniform parallel, the length of power transpositions required to obtain adequate balance is limited by the unbalance arising due to phase-change.

Where there are several power barrels in succession, it is better to use barrels of either of the two " halting " types. Where the number of barrels is a multiple of three, " halting " type barrels should be used; and where the number is a multiple of two, " halting-reversing " type barrels are better.

It is considered in Technical Report No. 66 of the Californian Investigation that 3-mile barrels in a long parallel may be expected to give a degree of unbalance such that configuration irregularities will control the unbalances. " For large separations, usually giving small coefficients of induction and with good wave-form, 6-mile barrels should be sufficiently effective."

Griswold and Mastick (71) state that 6-mile barrels have been found satisfactory in some cases in practice. They consider that 3-mile barrels give a satisfactory solution, except under severe exposure conditions.

Both opinions date from 1916–1917.

APPENDIX 12.

MEASUREMENT OF HARMONICS.

Whenever interference problems arise, knowledge of the harmonics present is, in general, required. The desired extent and accuracy of this information will depend on the type of problem. When it is necessary to locate the origin of harmonics causing interference, exact measurements of the magnitudes of the harmonics will not be required so much as the determination of their frequencies. When the harmonic is traced to the apparatus producing it, a quantitative measurement is necessary to determine whether the magnitude of the harmonic is normal or excessive and, in consequence thereof, where to apply the remedy. Again, when it is necessary to test new apparatus in order to decide whether interference might arise when such is placed in service, it is probably desirable to measure the total effect of all the harmonics present. There is, therefore, a need for apparatus, which will give and give alone the particular information required.

OSCILLOGRAPH.

Where the fundamental is small and the harmonics are prominent, as is usually the case for oscillograms of residual voltages and currents, it is possible to make an accurate determination of the values of the harmonics. Where the fundamental is proportionally large, as in the case of line voltages and currents:

(i) The harmonics may be magnified,
(ii) The fundamental may be neutralized or otherwise suppressed, leaving as a residue the harmonics only.

Under method (i) a condenser may be used in series with the vibrator and will produce magnification in proportion approximately to the frequency of the harmonic, provided that the impedance of the remainder of the circuit is small in comparison with the impedance of the condenser. This arrangement was used, where necessary, during the Californian investigation for voltage-wave measurements. Distortion of harmonics in oscillograms of currents, particularly line currents, was obtained by the use of an inductance coil shunted across the vibrator in series with a condenser. With this arrangement a magnification greater than the square of the frequency is obtainable.

From the constants of the oscillograph circuit and the values of the harmonics obtained by analysis of the oscillogram, the magnitude of the harmonic in the circuit under test can be calculated. The circuit arrangements used in the above investigation are described in Technical Report No. 41.

Method (ii) was under consideration by the British Engineering Standards Association in 1920 and subsequently.*

RESONANCE METHODS.

These methods employ essentially a circuit comprising inductance and capacity in series which can be tuned to any particular frequency.

RESONANT SHUNT.

The method used during the Californian investigation embodied such a circuit with a low-impedance telephone receiver in series. When the shunt is tuned for the harmonic whose magnitude is to be measured, the sound in the receiver will be largely due to this harmonic. By connecting the receiver in turn to an auxiliary comparison circuit capable of supplying current of any desired frequency and adjusting its value until the same sound is heard at the particular frequency, the value of the current through the resonant shunt is obtained from the known circuit constants.

This method is useful for determining high harmonics of small amplitude for which the oscillograph is not suited. While the value of each harmonic has to be determined separately, the process is quicker than the oscillograph.

FREQUENCY ANALYSER.

An analyser has been developed in the Research Laboratories of the American Telephone and Telegraph Company and the Western Electric Company (89) in which a variable-tuned circuit is employed, the natural frequency of which may be altered continuously over the whole range. The current in the resonant circuit is amplified and recorded on a moving photographic strip. Two frequency ranges of 20–1 250 and 80–5 000 cycles respectively are provided, and it is stated that the record is delivered five minutes after the mechanism has been set in operation.

No details concerning the accuracy obtainable with this instrument are given in the description (89), but even if the error is considerable the possibility of obtaining a complete analysis in such time should be of great value.

DYNAMOMETER METHODS.

In a paper by Cockcroft, Coe, Tyacke and Miles Walker (*Journal I.E.E.*, vol. 63, 1925), a modified dynamometer method is described which has been developed in both laboratory and commercial forms, which will enable wave-forms to be analysed up to at least the 23rd harmonic with considerably greater accuracy than with the oscillograph. It is stated that it should be possible to analyse e.m.f. waves to within 2 per cent of the harmonic itself, and to detect harmonics of less than 1/1 000th of the amplitude of the fundamental, thus enabling the approximate amplitude of harmonics to be determined which are not visible on an oscillogram. A more recent modification of the dynamometer analyser in portable form is described in the *Journal of Scientific Instruments*, vol. v, No. 10, October 1928, page 320.

TELEPHONE-INTERFERENCE FACTOR METER.

The simplest method so far suggested of determining the deviation of a wave from the equivalent sine wave is by devising a network such that the current in one branch resulting from a complex voltage wave at the terminals of the network is an indication of the distortion of the voltage wave in question. The harmonics of the wave may be given a desired relative weighting by using a suitable network. Davis (11) suggested that the harmonic weighting should be proportional to the frequency by using a simple condenser as the network. The American I.E.E. Sub-Committee on Wave-Shape Standards considered the possibility of modifying the network to obtain a satisfactory standard, based on this method of measuring wave-shape, so that errors due to the impedance of the machine under test and of the measuring instrument would be negligible, and so that it would be possible to use standard condensers, coils and meters. " It was the conclusion of the Sub-Committee, based on a large amount of experimental work, that whatever form of network might be adopted it would need to be set up as a special piece of apparatus with the constants carefully specified." " It was also found necessary to use with the apparatus a highly sensitive indicating instrument, such as a vacuum thermocouple with a d.c. milliammeter or a very sensitive a.c. dynamometer milliammeter."

EXPERIMENTAL WORK.

In order to determine the detrimental effect on communication systems, experiments were carried out to determine the relative effect of harmonics of different frequencies in producing interference in telephone systems.

Two methods have been used. In each case currents of different frequencies were in turn injected into the telephone receiver of an ordinary telephone circuit.

Method 1.—Observers compared the reading of ordinary news matter over the noisy circuit and over a quiet circuit of greater length and indicated the better circuit.

Method 2.—Articulation tests were made wherein the excellence of transmission was measured by the percentage of syllables correctly understood.

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* One of the most practical ways of using this method is that which has been proposed by Belfils (see *Révue Générale de l'Electricité* of April 3, 1926, page 523).

The results give curves as shown in Fig. 18 which represent the relative variation with frequency of the combined sensitiveness of the telephone receiver and of the human ear, the shape of curves obtained being due, to a great extent, to the resonant diaphragm of the receiver. This receiver was typical of all receivers in general use in the U.S.A.

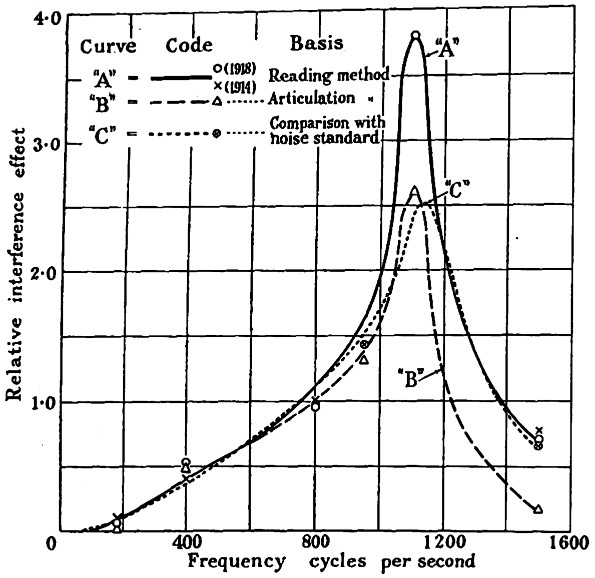


FIG. 18.—Relative interfering effect of single-frequency currents in a telephone receiver.

The difference shown by the curves of Fig. 18 between the results obtained by the two methods indicates that the factor of annoyance to the subscriber, which is not taken into account by the articulation tests, is included in the reading tests and becomes of more importance with high frequencies.

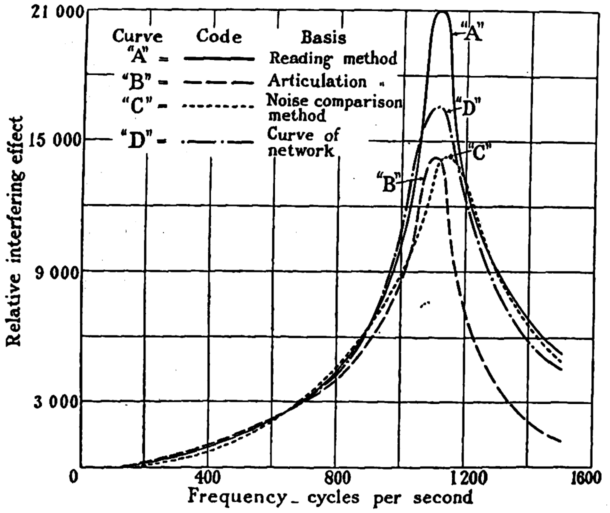


FIG. 19.—Comparison of frequency weighting curves.

These tests were carried out by the American Telephone and Telegraph Co. at different times, the first series of reading tests being made in 1914 at the request of the Californian Joint Committee.

DEVELOPMENT OF INTERFERENCE WAVE FACTOR FROM EXPERIMENTAL DATA.

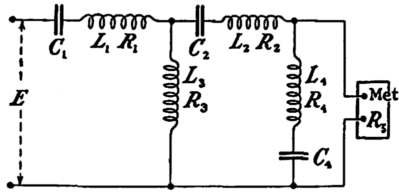
The relative amount of noise caused by generator voltages and currents of different frequencies depends on additional factors to that obtained by the above experiments. The frequency weighting curve for the interference wave-factor is given in Fig. 19, and is based on the sensitivity-frequency relations and, in addition, on the fact that the current induced in telephone circuits by magnetic or electric induction is approximately proportional to the frequency. It neglects the effects of:—

(*a*) The attenuation of the current harmonics along the power and telephone circuits varying with the frequency. This effect is usually relatively small.

(*b*) Some forms of telephone apparatus acting as filters or rejectors for certain harmonics, e.g. loaded lines, do not transmit currents above about 2 500 cycles, while with some forms of apparatus low frequencies are eliminated. Usually the effect on the noise volume of these frequencies is small.

A network was developed, as shown in Fig. 20, in which the ratio of the current through one branch of the network to the voltage applied at its terminals gives an indication of the telephone interference factor of a voltage wave, corresponding to the weighting curve. The measuring instrument of the apparatus consists of a vacuum thermocouple connected to a d.c. milliammeter. When a number of harmonics are present in the voltage wave applied to the apparatus a reading is given which is proportional to the square root of the sum of the squares of the effects of the individual harmonics (root-sum-square value). Data obtained on the summation law of a number of noises of various frequencies indicate that this law varies under different extreme conditions.

"It seems probable that the root-sum-square law best represents the average condition and it is far more practicable for use than any other law because of the characteristics of measuring instruments."



Network constants

C_1 = 0·9 *mf*	±0·5%	L_1 = 0·023 henry	±0·5%	R_1 = 5 ohms ±2%
C = 0·9 „		L_2 = 0·0205 „		R_2 = 12 „ ±2%
C = 7·5 „		L_3 = 0·068 „		R_3 = 73 „ ±1%
		L_4 = 0·019		R_4 = 22·5 „ ±2%
				R_5 = 43 „ ±1%

FIG. 20.—Network for measurement of interference wave factor.

Fig. 21 shows the relative interference to the telephone circuit per volt of harmonic in the power circuit for harmonics of different frequency.

It has been pointed out (18) that, since the effect of increased impedance and leakance of the line at the higher frequencies is neglected in determining the interference factor, the curve in Fig. 21 will give values too large when the interference is caused through magnetic induction. This effect only affects the usefulness of the T.I.F. meter when applied to machines not yet placed in service.

Since by definition the interference factor is the ratio of the root-sum-square of the weighted values of the harmonic components to the R.M.S. value of the wave, it is necessary to multiply the values given by the T.I.F. meter for voltage and current waves by the R.M.S. value of the wave in order to determine the degree of disturbance in the telephone receiver

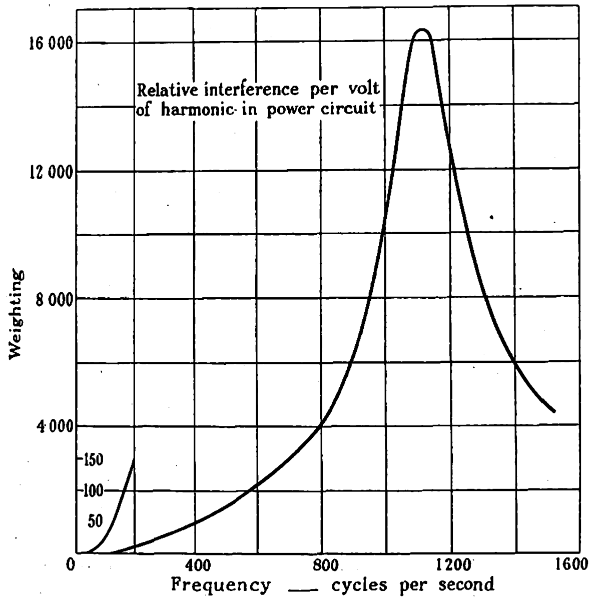


FIG. 21.—Frequency weighting curve for interference wave factor.

T.I.F. values have been obtained for a number of machines (9) and may serve as a basis for future work.

APPENDIX 13.

SOURCES OF HARMONICS.

The object of this Appendix is to present a brief general summary of the features which bear upon the production of harmonics in so far as they affect interference.

ROTATING MACHINERY.

The two groups of harmonics obtained in machines may be termed

(a) Spacing ripples or harmonics.
(b) Tooth ripples or harmonics.

SPACING HARMONICS.

Considering the special case of the smooth surface armature, the shape and content of the flux-curve is unvarying in time. With a non-sinusoidal distribution of the flux, the e.m.f. induced in a turn will, therefore, contain harmonics, the orders of which will be those present in the flux-space wave. The phase e.m.f. will be the sum of the e.m.f.'s induced in coils connected in series, modified by the distribution factor for each harmonic.

Effect of distribution factor and phase-spread.—The importance of the harmonics in the flux wave is determined by the values of the distribution factor for the various harmonics.

Table II, page 150 of the "Electromagnetic Machinery" section, Whittaker's Pocket Book (5th edition), gives values of this factor for uniformly distributed windings and various phase spreads. Fig. 474, vol. 3 of *The Dynamo*, 6th edition, shows a curve of distribution factors for uniform distribution over one-third of the pole-pitch.

Whole number of slots per pole.—With a whole number of slots g per pole, the distribution factor for the xth harmonic holds also for harmonics, the orders of which are any multiple of $2g \pm x$. Harmonics of the orders $2g \pm 1$ have the same value of distribution factor as the fundamental; similarly, harmonics of the orders $2g \pm 3$ and the third harmonic have the same distribution factor. Fig. 473, vol. 3 of *The Dynamo*, shows distribution factor curves for different numbers of slots per pole per phase for phase-spread $\sigma = \frac{1}{3}$.

For harmonics of the order $2g \pm 1$ in the flux wave, therefore, there is no reduction factor for the resulting harmonics in the phase e.m.f., and they will reappear with the same percentage value. Harmonics of the order $2g \pm 3$ reappear in the e.m.f. wave with a percentage value reduced by about one-third.

Relative importance of harmonics of the orders $2g \pm 1$ and $2g \pm 3$.—Since harmonics of the orders $2g \pm 3$ are triple harmonics, i.e. their order is an odd multiple of 3, their inductive effect is relatively more serious. They form a residual component which will appear in the line with a star-connected neutral earthed winding. On the other hand, harmonics of the orders $2g \pm 1$ do not suffer any reduction in their percentage value of the fundamental in the original flux-space curve, but their inductive effects are not normally so serious, since they form part of the balanced component of the line voltage.

Therefore, harmonics of the orders $2g \pm 3$ are specially undesirable and, in general, are most to be avoided.

Effect of coil-span factor.—While in single-layer windings the coil-span is equivalent to a full pole-pitch, in double-layer windings the coil-span may be any whole number of slots or winding spaces on the smooth armature. The phase e.m.f. is therefore modified by the coil-span factor. From the expression for the reduction factor due to the coil-pitch for the nth harmonic given on page 76, vol. 3 of *The Dynamo*, Table 1 has been worked out showing values of this factor for each harmonic for various values of coil-pitch for the case with 9 slots per pole.

C. C. Hawkins states (vol. 3, p. 51, *The Dynamo*) that the expression on which this statement is based is only strictly true for smooth armatures and is to be regarded "as a guide only when toothed armatures are in question." The values obtained upon the assumption that the flux curve is constant are, however, close to the truth until we come to harmonics of frequency connected with the presence of the teeth.

Hawkins shows (p. 77, vol. 3, *The Dynamo*) that if the coil-pitch = $2k/n$, where k is an integer, the pitch factor for the nth harmonic is zero; "on a smooth core a fractional pitch (as recommended by Prof. Comfort A. Adams, *Trans. A.I.E.E.*, vol. 28, p. 1077) of about 0·833, as given e.g. by 5 out of 6 slots or 10 out of 12 slots per pole, would, by the combined action of the coil-span and distribution factors, reduce the 5th, 7th, 17th and 19th harmonics to about one-quarter of their value in full-pitch coils. If the multiples of 3 are cared for by star-connection, the 11th and 13th are left as the most prominent harmonics."

TABLE 1.

Coil Reduction Factors for Various Values of Coil-Pitch for the Case with 9 Slots per Pole.

Coil-pitch ..	1	8/9	7/9	6/9
Order of harmonic n				
3	1	0·87	0·5	0
5	1	0·65	− 0·18	− 0·87
7	1	0·34	− 0·81	− 0·5
9	1	0	− 1·0	—
11	1	− 0·34	—	—
13	1	− 0·65	—	—

Fractional number of slots per pole per phase.—With a fractional number of slots per pole per phase in either single-layer or double-layer windings, the total reduction factors can be considered as nearly the same as for a uniformly distributed winding. When the number of slots per pole-pair $2g$ is an odd integer, harmonics of the order of multiples of $2g$ cannot appear in the phase e.m.f., due to the effect of the coil-span, when the armature is smooth, and they may be much reduced when the armature is slotted.

Effect of rotor slots.—Owing to the slotted rotor of non-salient pole turbo-generators, the distribution of flux over a pole-pitch does not follow a smooth curve. Ripples occur in the flux-density space curve, coinciding with the rotor slots, due to the spacing of the exciting winding. A second ripple due to variation of the gap reluctance also exists; but this is, in general, "negligible compared with that due to the spacing of the existing winding, since wide open slots without magnetic wedges are seldom used nowadays on the rotor."

Smith and Boulding have shown that since the amplitude of the ripple due to the concentration of the exciting winding can be assumed to fall off sinusoidally towards the centre of the pole, the spacing ripple can be replaced by two harmonics of the orders $2R \pm 1$, where R is the number of rotor slots per pole.

These harmonics will be greatly reduced in the phase e.m.f. due to the distribution factors, except when R is nearly equal to g. If $2R \pm 1 = 2g + 1$ or $2g - 1$, no diminution occurs when g represents a whole number of stator slots per pole. It should be pointed out that if one of the two harmonics is a triple harmonic, its distribution factor will be about 0·66. This may be of great importance, as already indicated.

TOOTH HARMONICS.

In connection with spacing ripples a fixed space-flux wave is assumed, but with a toothed armature such a fixed wave-shape of flux does not exist. It passes through a complete cycle of shapes as the poles move through a tooth-pitch relatively to a stationary armature or vice versa (see Fig. 487, vol. 3 of *The Dynamo*). "The e.m.f. induced in a loop is accordingly a complex phenomenon in the presence of teeth and slots."

It may be considered that two effects are present:—

(i) Due to the relative movement of the teeth under the pole the rate of change of linkages, i.e. the e.m.f. induced, in a loop fluctuates with time around the values which would occur if the armature were smooth. This effect is due to the differences in the permeances at the two ends of the pole-pitch according to the position of the teeth.

"The origin of tooth-ripples has often been assigned to 'flux-swing' upon the supposition that the weakening of the fringe at one edge of a pole and its strengthening at the other edge in the unsymmetrical positions of teeth and pole causes a corresponding amount of flux to travel backwards and forwards across the slots under the pole, cutting the conductors therein and virtually either increasing or reducing the normal rate of cutting such as would occur in an equivalent smooth armature with the same constant relative velocity of movement."

According to C. C. Hawkins, however, the growth and decay of the flux density in the teeth is to be regarded as occurring in the path along the direction of the flux without passage of any lines from the teeth across the slots; the phenomenon would not, therefore, appear to be so correctly explained by ascribing it to flux oscillating backwards and forwards in the above manner.

It is shown that the loop e.m.f. may have a crest of a ripple at its centre or a hollow, or any intermediate figure depending on the width of the interpolar gap; "but it must not be supposed that one will necessarily pass gradually into the other by gradual shortening of the polar width, although it is the case that as the curve of the flux per tooth-pitch becomes more rounded or sinusoidal, the less the amplitude of the tooth-ripple."

"The exact shape is dependent on *all* the circumstances, including the maximum density and reluctance of the teeth under the pole as compared with their almost negligible reluctance in the inter-polar gap." In fact no general rules or precise conditions for the pole width to contain a whole, even or uneven, number or a fractional number of tooth-pitches can be laid down as obviating tooth-ripples.

It has been shown by Smith and Boulding for the case when the basic flux-density space-wave is sinusoidal, that a ripple of frequency $2g$ is produced, the amplitude of which itself varies sinusoidally over the whole pole-pitch. This ripple can be analysed into two odd harmonics of the order $2g \pm 1$. This deduction holds in a general way for any flux distribution, "the condition presupposed implying a maximum tooth-ripple at the crest of the e.m.f. wave of the loop, is often fairly well reproduced in actual cases," according to Hawkins. Therefore, "in general, it may be said that harmonics of the orders $2g \pm 1$ may be expected to be pronounced in the toothed machine." Since the distribution factors for harmonics of the orders $2g \pm 1$ are the same as for the fundamental, the tooth-ripple occurs undiminished in the phase e.m.f.

(ii) Due to pulsation of the total flux or of the permeance of the pole-pitch during a tooth cycle, a loop e.m.f. is induced by transformer action which is a maximum when the loop e.m.f. due to cause (i) is zero. "The amplitude of the pulsation, even when undamped. will be found in all practical cases to be very small."

Effect of rotor slots.—The addition of rotor slots makes the consideration of tooth-ripples of still greater complexity.

Effect of damping bars in the shoes of salient poles.—Damping bars may cause ripples "if the number of '*amortisseur*' slots in the field bears a certain relation to or comes too close to the number of slots in the armature." Numerous tests have been made, chiefly by the General Electric Company of U.S.A., to remove the ripples due to d.c. machines and convertors. Information as to these is contained in the original digests (28), (39), (44), (46), which are filed at the offices of the Research Association.

STATIC TRANSFORMERS.

The theory of the cause of transformer harmonics has been treated by numerous writers. As pointed out in the *résumé* the distortion of the magnetizing component of the current wave, or of the induced e.m.f. wave if the current wave is sine shaped, is due to the variation in permeability of the iron at different flux densities.

Figures given by O. G. C. Dahl (90) for single-phase transformers at normal saturation show that—

The fundamental of the magnetizing current = 90 per cent of the equivalent sine wave.

The 3rd harmonic of the magnetizing current = 45 per cent of the equivalent sine wave.

The 5th harmonic of the magnetizing current = 15 per cent of the equivalent sine wave.

Other harmonics of the magnetizing current = 0–3 per cent of the equivalent sine wave.

Fig. 22 shows the variation of these figures with the flux density.

With transformers connected for three-phase working, a path may be provided enabling the necessary third harmonic of current to flow. Such paths may occur due to the type of connection chosen.

Stigant and Lacey have made a study of the conditions obtaining with different arrangements for 3-phase service (chap. 16, "The J. and P. Transformer Book"). Table 2 is taken from this book. The conclusions in this table apply to single-phase transformers of both shell and core-types and to three-phase shell-type transformers. With three-phase core-type transformers any third harmonic fluxes must find their return path outside the core. Such a path is of very high reluctance and consequently the third harmonics in the flux and induced pressure waves are very small. In modern rotary convertor transformer design, the magnetic shunts are so designed that their use does not lead to the production of any appreciable third-harmonic fluxes (see also F. P. WHITAKER, "Rotary Convertors, with Special Reference to Railway Electrification," *Journal I.E.E.*, 1922, pages 501–525 and 835–844).

The above remarks, which apply to third harmonics, also apply to other harmonics, which are odd multiples of three.

As regards harmonics other than triple harmonics, there is always an external path enabling corresponding currents to flow. The voltage harmonics remaining depend on the impedance of such paths.

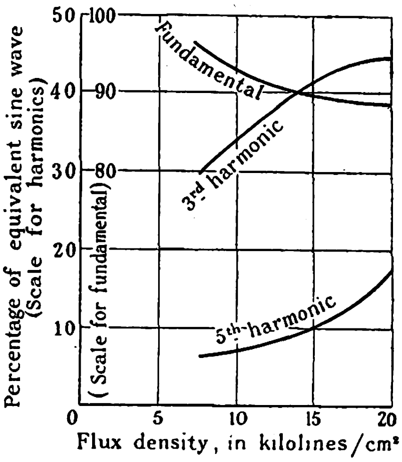


FIG. 22.—Components of magnetizing current of single-phase transformers.

The relation of triple-harmonic residuals to the magnetic-flux density is the subject of a technical report (No. 59) of the Californian Railroad Commission investigation, based on experimental and theoretical work. It is pointed out that, as shown by Nickolson and by Tackley (*Journal I.E.E.*, vol. 53, 1915, p. 248 and p. 521), at high densities the magnetization curve of iron can be represented by the equation $H = KB^m$. The tests in question showed that the B/H curve for the transformer iron could be represented fairly well by $H = KB^{10}$ above 13 000 gausses.

In this report one of the general conclusions states that "with increasing simple harmonic (i.e. sinusoidal) impressed voltage, the higher harmonics of the exciting current of a transformer increase at first more rapidly than the fundamental, but for high magnetic densities the wave-shape becomes constant." For modern transformer iron the ultimate value of the third harmonic is said to be about 54 per cent of the equivalent sine wave. Curves are given in this report which show that the magnitude of the harmonics increases very rapidly as the iron approaches magnetic saturation.

In the second edition of Vidmar's *Der Transformator* an exhaustive study is made of the harmonics produced by saturation of the transformer iron. The oscillating

TABLE 2.

Third Harmonics in Single-Phase Core and Shell-Type Transformers and in Three-Phase Shell-Type Transformers. Sine Wave of Voltage Applied.

No.	Connections	Primary				Flux	Secondary			
		Currents		Voltages			Currents		Voltages	
		No load	Line	Line	Phase		No load	Line	Line	Phase
1	Star I.N./Star I.N.	Sine	Sine	Sine	Contains 3rd H.	Contains 3rd H.	—	Sine	Sine	Contains 3rd H.
2	Star N. to G./Star I.N. ..	Contains 3rd H.*	Contains 3rd H.*	Sine	Contains 3rd H.*	Contains 3rd H.*	—	Sine	Sine	Contains 3rd H.*
3	Star I.N./Star 4 wire ..	Sine	Sine	Sine	Contains 3rd H.*	Contains 3rd H.*	Contains 3rd H.*	Contains 3rd H.*	Sine	Contains 3rd H.*
4	Star I.N. Tertiary Delta/Star I.N.	Sine in Star 3rd H. in Delta	Sine	Sine	Sine	Sine	—	Sine	Sine	Sine
5	Star I.N./Delta	Sine	Sine	Sine	Sine	Sine	Contains 3rd H.*	Sine	Sine	Sine
6	Star N. to G./Delta.. ..	Contains 3rd H.*	Contains 3rd H.*	Sine	Sine	Sine	Contains 3rd H.*	Sine	Sine	Sine
7	Star I.N./Interconnected Star I.N.	Sine	Sine	Sine	Contains 3rd H.	Contains 3rd H.	—	Sine	Sine	Sine
8	Star I.N./Interconnected Star, 4-wire	Sine	Sine	Sine	Contains 3rd H.	Contains 3rd H.	—	Sine	Sine	Sine
9	Delta/Star I.N.	Contains 3rd H.	Sine	Sine	Sine	Sine	—	Sine	Sine	Sine
10	Delta/Star, 4-wire	Contains 3rd H.	Sine	Sine	Sine	Sine	Contains 3rd H.	Contains 3rd H.	Sine	Sine
11	Delta/Delta	Contains 3rd H.	Sine	Sine	Sine	Sine	Contains 3rd H.	Sine	Sine	Sine

I.N. means " isolated neutral."

N. to G. means " transformer primary neutral connected to generator neutral."

* In all these cases the third-harmonic component is less than it otherwise would be if—
(*a*) The circulating third harmonic flowed through a closed delta winding only, or
(*b*) The neutral point were isolated.

potential of the neutral is one of the chief dangers to be feared in a star-connected three-wire system. This is eliminated with the delta connection.

MERCURY RECTIFIERS.

For ideal conditions D. C. Prince (*General Electric Review*, September 1924, pp. 608–615) has shown that the amplitude of the voltage pulsation harmonic of frequency mNf, where m is an integer, is

$$ln = \pm \frac{2}{N^2m^2 - 1} \text{(constant component } E\text{)}$$

Hence, for a six-phase rectifier, there will be present harmonics of frequencies 6, 12, 18 . . . times that of the supply frequency, and with amplitudes ± 5·7 per cent, ± 1·4 per cent, ± 0·6 per cent . . . respectively of the constant component E. A later contribution by L. B. W. Jolley (*Journal I.E.E.*, vol. 63, 1925, pp. 588–592) gives formulæ from which the above figures are also obtained. Figures given by Professor E. W. Marchant in an Appendix to a paper by Bartholomew (32), are about 70 per cent higher for the sixth harmonic. This increase may be due to harmonics in the a.c. supply voltage.

The actual figures obtained in this case for a 50-cycle supply were:—

6th harmonic	± 9·5 per cent
12th harmonic	± 2·5 per cent
18th harmonic	± 0·8 per cent
24th harmonic	± 0·83 per cent
30th harmonic	± 0·42 per cent

APPENDIX 14.

LEGAL ASPECTS.

This Appendix is intended to give an indication only of the legal questions relating to inductive interference.

GREAT BRITAIN.

The P.M.G. has very wide powers under Acts of Parliament. In practice, co-operation between supply authorities and the Post Office frequently enables satisfactory compromises to be arrived at.

With regard to the earthing of h.t. power systems:—

(i) In cases where the Electricity Commissioners deem earthing to be necessary for the safety of the public, authority can be given by them for such earthing without any reference to the P.M.G.

(ii) In cases where the Electricity Commissioners do not deem earthing to be necessary for the safety of the public, authority can be given by them for earthing, subject to the P.M.G.'s concurrence (see Section 10 of the Schedule to the Electric Lighting (Clauses) Act, 1899). "Permission has never been withheld to such earthing, subject to it being made at one point on each distinct circuit, and subject also to a proviso that the P.M.G.'s concurrence may be withdrawn at any time."

(iii) According to Section 69 of the 1899 Act it is made incumbent upon undertakers to arrange that their lines and works shall not harmfully affect the communication circuits of the P.M.G.

ABROAD.

The information we have found regarding legal aspects in countries abroad is contained in four articles, (55), (68), (69), (103), which refer entirely to the U.S.A. Beyer (68) indicated the general trend of the law relating to interference up to 1917. He summarized the question by stating that the various utilities are licensees of the public and priority does not give an exclusive privilege, but certain well-defined rights which must be respected, except by utilities connected with public travel. Presumably, priority to occupancy of roads is referred to here. The telephone is considered theoretically as a substitute for travel and has, therefore, greater fundamental rights than electric light and power lines.

Proceeding from the principle that the use of public highways is for travel, telephone companies have no remedies against tramways when negligence is not an issue. No supreme court has dealt with the question of who shall pay the cost of measures taken to avoid interference on prior-established lines and what relief may be granted for increased maintenance.

In a majority report of the Iowa Railroad Commission in 1917 (55) it was held that the Commission would not prohibit h.t. lines on roads where substantial interference could be eliminated by changing the location or the construction of the telephone lines at reasonable expense. If metallic circuits and transpositions or re-locations of the telephone lines be required the power company must pay the cost. If the telephone lines be in bad condition, the telephone company must pay the cost of putting them in order; or, in the case of re-location, or of conversion to metallic working, part of the reconstruction costs.

In the Homer inductive interference case (103), in which application was made to the Illinois Public Utilities Commission for permission to erect a h.t. power line serving property owners along a road on which local and long-distance telephone lines were prior occupants, the Commission stated that the growth of rural communities demanded that roads be used by other utilities and, therefore, all must operate so as to prevent undue interference one with the other.

With equal highway rights, the prior occupant cannot exclude others, but he may have superior rights which are limited to protection from interference, substantial in character. It was accordingly directed that the power line should be three-phase instead of single-phase and that a co-ordinated system of transpositions should be carried out on both systems. An opinion as to the allocation of the costs of such extra transpositions was not given.

DISCUSSION ON

"THE CAPACITY EFFECT AND NATURAL FREE PERIOD OF A D.C. ARMATURE."*

Prof. W. Cramp (*communicated*): The subject of this paper is of great interest, extending far beyond the limits to which the author has confined himself. Moreover, the mathematical expressions are here developed in a manner more lucid and thorough than that of previous investigators, and the experimental apparatus which the author has devised is original, ingenious and effective for teaching purposes. Since, however, some years ago a considerable amount of research work was carried out on somewhat similar lines in my laboratory, I wish to place on record some of those results and, in particular, to mention another experimental method of examining the same problem. Referring first to equations (6) and (7), the author's assumptions are not very explicit. Since E has disappeared from the equations it would seem that he is assuming a motor with constant separate field excitation whose armature, having been run up to a speed such that the counter e.m.f. exceeds the supply p.d., is then disconnected from the supply and short-circuited. If this is not his meaning, it is not clear why E is omitted. And if it is his meaning, then his solution shows that, if R is small enough, the armature will experience velocity oscillations as its average speed falls. This may be true, though no experimental proof is given. But then, if true, would this not happen whether the armature were "accelerated above its normal running speed" or not? On the other hand, if E be added to the left-hand side of equation (6) the system is still oscillatory (R being small) and my calculation of its period agrees with equation (8), even when a constant-load torque is added to the right hand of equation (7). I conclude from my analysis that generally the inherent value of L for a d.c. armature is too small to produce practical effects, but that if a separately excited armature were switched on to constant p.d. mains, with a large inductance in series, oscillation should result. This was confirmed by experiment on February 26th last year. Clearly, energy was alternately stored in the rotating armature and the series inductance, and this exchange between kinetic and magnetic energy lies at the root of all the author's work. There is a further more telling experiment which I occasionally show to students and which depends upon the author's equations (6) and (7). Choose a machine with small armature resistance and brush friction and separately excite it, having a large value of L placed across the armature with an ammeter in series. Then in the author's notation

$$aM\frac{d\theta}{dt} = L\frac{di}{dt}$$

or, if $\theta = 0$ when $t = 0$, $i = aM\theta/L$. In other words, if the armature be uniformly turned round, the ammeter needle will register the angle through which it has been turned. This generally causes surprise, since it seems so contrary to the ordinary dynamo equations, but it works well experimentally. For example, in one experiment, the armature having moved through 90°, the ammeter read 0·12 ampere, and after another 90° it read 0·22 ampere, and so on. The proportionality is not exact on account of unavoidable resistance, but the principle is the same as that of the Grassot fluxmeter. It is interesting to notice that on releasing the armature the stored energy in L is distinctly evident as a "restoring torque."

I turn now to the author's section on instability and can confirm his comments concerning the solution of equations (15) and (16), upon which I have spent many hours. Here, again, I included a constant-load torque, and, like the author, arrived at a solution by neglecting smaller quantities. My solution, however, is in terms of flux and current, and is not better than equation (18). The practical importance of this instance arises from a fact that the author does not mention. It is seldom that a motor or generator is differentially compounded, but interpole motors are frequently built with shunt speed-regulation. Now the author's equations (15) and (16), when armature reaction is taken into account, apply ultimately to all shunt motors, but oscillations are not usually experienced because the reaction is not sufficient at normal loads, unless the field is abnormally weak. When, however, interpoles are employed, it can be shown, both theoretically and by measurement, that the resultant field flux per pole, and therefore the induction factor, is of the form $(M-Ki)$ as given by the author for the differentially compounded machine. Therefore shunt interpole machines oscillate when the shunt field is weak and the speed high, especially if the brushes be given a small shift backward, though this is not essential. Fig. A shows the result of a test obtained by F. M. Aust, M.Sc., in my laboratory in March, 1924. The machine to which it refers was a 50-h.p. 4-pole shunt interpole motor, intended for a variable speed of 450 to 750 r.p.m. It has a wave-wound armature with 318 conductors, and the normal shunt currents for the above speeds are from 5 to 3 amperes. In order to make the machine oscillate, the brushes were given three segments backward lead and the field current was reduced to 1·1 amperes, the load torque (a friction brake) being 16·7 lb.-ft. The torque equation was obtained by separate tests and gave

$$\mathbf{T} = 0{\cdot}735 \times 10^{-6}\,\Phi_0 i - 0{\cdot}00353\,i^2$$

which corresponds to the author's equation (16). the values of $\mathbf{T}$ being in lb.-ft., and Φ_0 being the flux per pole corresponding to the shunt field amperes. This equation expresses, for different constant values of Φ_0, a family of curves each having two values of i for a given torque, except when $i = 104 \times 10^{-6}\,\Phi_0$, which is the maximum value of **T**, and in this instance $\mathbf{T} = 0\cdot00353\, i^2$. Such torque curves are common to all shunt motors, but for normal excitations the curve is approximately a straight line up to the safe limiting armature current. When the shunt current, however, is reduced, the value of Φ_0 falls, and at 1·1 amperes is nearly $1\cdot36 \times 10^6$. Thus for Fig. A, $\mathbf{T} = i - 0\cdot00353\, i^2$, having its maximum at $i = 142$ amperes. The figure shows the phase relationships between field current, field voltage, armature current, armature voltage, speed and acceleration. The periodic time is 8·5 seconds. A comparison of these results with the author's equations (17) and (18) suggests the following remarks:—

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* Paper by Mr. J. C. PRESCOTT (see page 185).

(1) Equation (17) seems to have a term missing, for the current does not oscillate about zero but about a value corresponding to the steady conditions, i.e. 47·2 amperes in Fig. A.

(2) The angle between current and speed is approximately 90°, which is the difference between the author's angles β and β'.

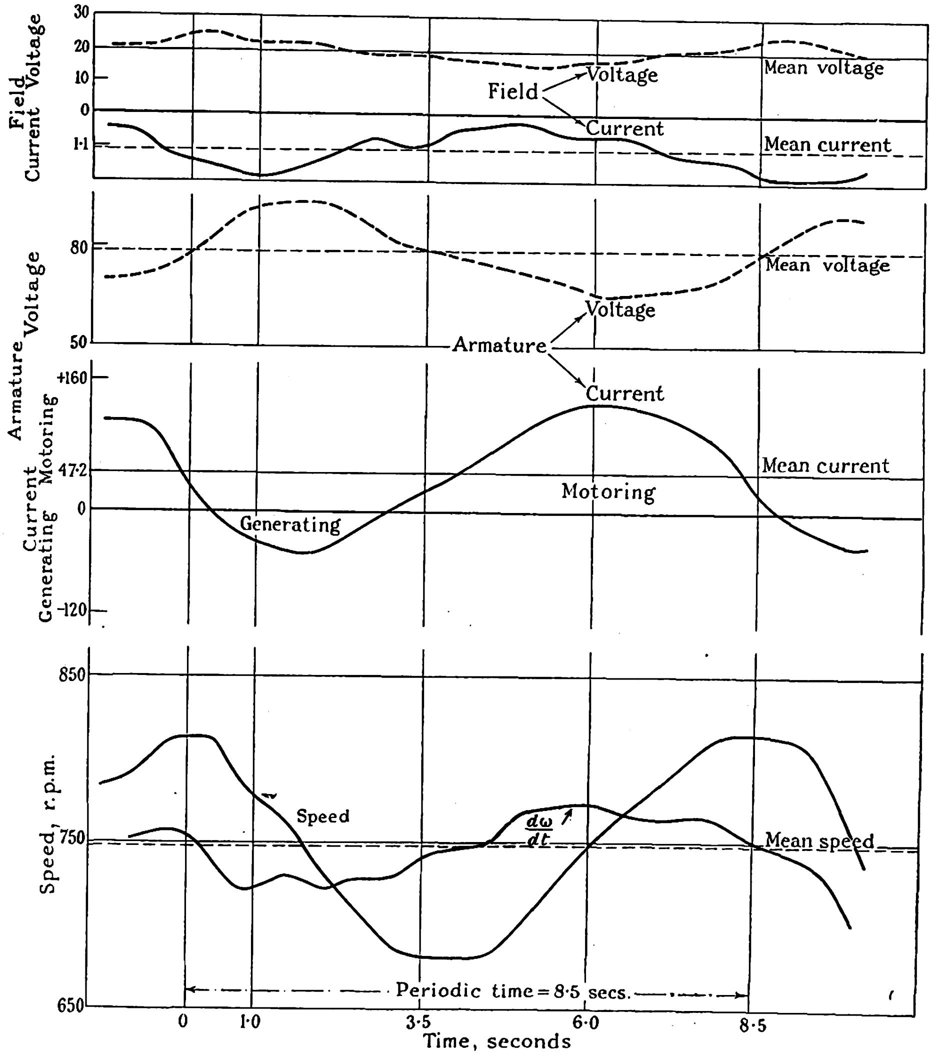

Fig. A.

(3) No. 2 is confirmed by the acceleration curve, which is shown to be in phase with the current.

(4) The armature voltage is not in phase with the speed, but nearly in phase with the current.

(5) Although the field was separately excited, a considerable variation was induced which is not in phase with current, voltage or speed.

The effect of the variation in the field is not referred to by the author, but it must modify equations (17) and (18). It may be of interest to explain the method by which the curves of Fig. A were obtained. It was desirable to record simultaneously the five quantities shown and also the readings of the spring balances for the torque arm. All were varying and no two were absolutely in phase. To obtain results even with one observer to each instrument proved impossible, and Mr. Aust finally adopted a kinematograph method. The instruments necessary for the measurements mentioned above and, in addition, a seconds clock were all fitted on a frame in the same plane. The machine having been set oscillating, films 1 in. by $\frac{3}{4}$ in. were exposed at about the rate of 12 per second. These, after development and fixing, were projected one by one on a screen by a stereopticon. The instrument pointers were then quite clear, but the finely divided scales were difficult to read; exact reproductions of the dials, therefore, were made and fixed to the screen, the stereopticon being adjusted until the image was the exact size of the dials. Thus the readings could be taken off as accurately as on a stationary instrument. These results were then plotted, as shown in Fig. A. This method may be recommended to any observer having a number of variables to record, as being convenient, accurate and inexpensive. It has already been remarked that the oscillations which are the subject of this paper are only one example of a large number, all of which depend upon certain general principles. Remembering that work or energy may always be divided into an intensity factor and a quantity factor, and that power may similarly be resolved into intensity and quantity per second, the first principle may be enunciated as follows:—

Where a system includes two alternatives for the storage of energy, a double energy transient will always arise if the natural characteristic intensity-quantity slope is negative and less than the corresponding slope of the supply system.

Besides the instability of electric motors, this principle covers organ pipes, violin strings, the shrieking of brakes, the swinging of a loose belt on a shaft and the oscillation of a pendulum fixed to the shaft of an induction motor. As regards the interchange of various forms of energy, the following principles are also of interest:

(*a*) In electrical and magnetic systems there are five possible variables, i.e. mass, elasticity, inductance, capacitance and resistance.

(*b*) Since in a given medium inductance and capacitance can only be changed by relative motion, self-sustaining oscillations supplied from a constant source of power cannot arise except by the intervention of mechanical motion—of these the synchronous motor is the standard example.

(*c*) Since change of resistance is not dependent upon mechanical displacement, self-sustaining oscillations, similar to those under (*b*), can arise without mechanical motion—the standard example is the oscillating arc.

Mr. J. C. Prescott (*in reply*): I am indebted to Prof. Cramp for his appreciation of my paper and for his criticism. As he points out, equations (6) and (7) are somewhat ambiguous. They are intended to express the oscillation of the angular velocity about the normal running speed of a motor, considered to have an induction factor M (which is constant, in accordance with the footnote on page 135), and operating on a constant e.m.f. The variation in angular velocity is, in these equations, expressed in terms of the resulting variation in armature current, but, as Prof. Cramp suggests, it would have been better to write the equations in the form

$$\left.\begin{aligned} E &= aM\frac{d\theta}{dt} + Ri + L\frac{di}{dt} \\ bMi &= \mathbf{I}\frac{d^2\theta}{dt^2} \end{aligned}\right\}$$

which will give as a solution, if $\dfrac{abM^2}{L\mathbf{I}} > \dfrac{R^2}{4L^2}$,

$$\theta = A\epsilon^{-Rt/2L}\sin\left[\left\{\frac{abM^2}{L\mathbf{I}} - \frac{R^2}{4L^2}\right\}^{\frac{1}{2}} t + a\right] + \frac{E}{aM}t + B$$

where A, B and α are constants. The experiment described by Prof. Cramp, in which an inductance is placed across a d.c. armature, is new to me and is of considerable interest as bringing out the fact that, whilst a d.c. armature connected across an ohmic resistance experiences a torque proportional to its velocity, when the same armature is connected across a pure inductance the torque is proportional to the angle by which the armature is displaced; for, neglecting resistance,

$$aM\frac{d\theta}{dt} = L\frac{di}{dt}$$

and i is therefore proportional to θ. Since the induction factor is constant, the torque is also proportional to i and therefore to θ.

The instability of uncompounded shunt motors with weak fields was known to me before I began the investigations described in the paper, and the reason why the fields of the motors used in the experiments were kept at nearly a normal value was that I wished to ascertain whether equations (15), (16) and (17) (which were evolved before the measurements were actually made) could be given a physical interpretation in a machine having the axis of its main field more or less rigidly fixed in space. The curves given by Prof. Cramp for the oscillation of a d.c. machine are very interesting and, speaking from my own experience, I should say that very careful adjustment of the circuit conditions would be necessary in order to obtain such excellent results, even with the method of recording used by Mr. Aust. With regard to the remarks of Prof. Cramp upon equation (17), here, again, the current specified is intended to be the extra current flowing due to the oscillation. Constant terms were omitted, with a view to simplifying the equation as much as possible.

DISCUSSION ON

"LOW-TEMPERATURE CARBONIZATION OF FUEL, WITH SPECIAL REFERENCE TO ITS COMBINATION WITH THE PRODUCTION OF ELECTRICITY." *

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 20TH JANUARY, 1930.

Mr. E. M. Hollingsworth: From the particulars given in the papers it is evident that the processes are technically successful, but little definite information is given as to the financial side of the question. In the paper dealing with the German process figures of the capital expenditure for stations with and without carbonization plant are given; apparently, the adoption of such plant almost doubles the expenditure and results in a high figure per kilowatt installed. At the World Power Conference in London in September 1928 reference was made to the high capital cost and probable short life of such plants. Mr. McEwen's experience shows that there is less difficulty in America than in this country in connection with the disposal of the gas produced. There also appears to be a more satisfactory market for the semi-coke for domestic and trade purposes in that country; this is an aspect which is not considered in the papers. With regard to the use of semi-coke on mechanical grates and for pulverized firing, I should like to know whether difficulty is experienced in grinding and burning this fuel. I have in mind the case of a large power station where good-quality coke breeze mixed with slack is fired on chain-grate stokers; experience shows that to obtain the best possible results the proportion of coke must not exceed 16 per cent.

Mr. R. E. Gibson: The gas industry is naturally interested in problems connected with the carbonization of coal, but it is something of a novelty to find that electrical supply companies are now concerned with problems of the same kind. Although I am glad to see that power engineers are giving some attention to carbonization I cannot understand why they should be interested in low-temperature processes. High-temperature carbonization is being ignored despite the fact that it is firmly established, commercially sound and of high thermal efficiency. In one of the papers reference is made to the fact that coke produced by high-temperature carbonization is not favoured as a fuel by power engineers. The reason for this is probably that the price of coke is, in general, considerably higher than that of slack. Gas coke has been successfully used, however, in several power stations where the boiler furnaces have been adapted for the purpose; this appears to be a suitable fuel, as it is smokeless, burns at a high temperature and has a substantial calorific value. Those responsible for the development of the gas industry have been accused of apathy and unwillingness to recognize the advantages of low-temperature systems, in spite of the fact that they are capable of exploiting them most easily. It should be understood, however, that they have been following closely the progress of low-temperature schemes and that these will be adopted as soon as it is clear that they have definite advantages. At the present time 6 of these plants are being tested in London gasworks and the records of their performance are awaited with much interest. In all these processes the yield of gas is less than half that which is obtained from high-temperature carbonization and, as this is the criterion with which the gas industry is primarily concerned, any process which reduces the output of gas is regarded with disfavour unless it can show compensating advantages. It is also feared that the special fuel and other liquid by-products may not realize prices sufficiently high to compensate for the loss of the gas and for the extra capital outlay. With regard to low-temperature carbonization as applied to electricity, Mr. McEwen states that, to make the process profitable, gas must be sold for town supply. Dr. Rosin agrees with this and also points out that unless the tar products and the gas are sold at prices sufficiently high to reduce the cost of the semi-coke below that of the fuel generally used in power stations, the scheme presents no financial advantage. The success of low-temperature processes for the production of domestic fuel has largely depended upon the ratio of the price of that fuel to the price of coal. It is difficult to see how any such process can be financially advantageous to the electrical industry unless it is worked in conjunction with a gas supply authority which is able to distribute the gas, dispose of the by-products, and perhaps sell a portion of the semi-coke at a comparatively high price. Messrs. Smythe and Weeks describe a system in which the gas is not sold but is burnt along with coke in the furnaces. They state that the proportion of volatile matter left in the coke must be 12 to 14 per cent to ensure ease of ignition. This seems to be a waste of good material, as coke with 3 to 5 per cent of volatile matter will ignite fairly easily. They emphasize the importance of the liquid by-products, which they value at 8s. 11d. per ton of coal carbonized. This is a high figure, and although it may be a correct estimate of the value under certain circumstances no statement is made as to the cost of installing and working the special plant necessary for refining the products. The quantity as well as the calorific and marketable values of the gas produced are not mentioned nor is any financial statement of the process as a whole included in the paper. I agree with the view expressed in the paper by Mr. McEwen, that low-temperature processes associated with the generation of electricity have a smaller margin of profit than similar processes applied to the production of high-grade fuel for domestic purposes. This is sold at a price in excess of that which supply companies can afford to pay. In view of his statement that the quality of gas with a calorific value of 275 to 300 B.Th.U. per cub. ft. is not high enough for use in a public service, it may interest Mr. McEwen to know that there is a town in England where gas of a lower calorific value is distributed. The paper describing German practice has rightly drawn attention to the problem of waste liquor disposal, a matter of some difficulty in this country. I agree that the large fluctuations in the prices of tar products and oils since the War have seriously affected the financial results of carbonization processes.

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* Introductory Papers by Mr. S. McEwen, Prof. P. Rosin, and Messrs. E. H. Smythe and E. G. Weeks (see pages 205–236).

Mr. J. Hamilton: The application of low-temperature carbonization seems to be attractive and practical, but we have to assume that it is economically sound. Messrs. Smythe and Weeks have told us that the semi-coke from their process has a heat value of 76 per cent of that of the coal treated, so that to get an equivalent heat value it would be necessary to treat approximately 1¼ tons of coal. This would cost, say, 13s. 9d.—an additional charge of 2s. 8d. The sum realized from the sale of by-products has therefore to exceed the capital charges on the plant plus the cost of production (including increased freight charges) by an amount sufficient to show a profit on the cost of the coal if burned untreated. Whilst it may be possible to attain such a result with coal at 11s. per ton, the prices ruling in this district would necessitate higher receipts from the by-products than those given in the paper. It would be interesting if the authors would indicate the financial results on the Dunston plant. A plant with a through-put of 160 tons per day is given as a typical example of modern practice, but such a plant would prove too small for modern boilers, in view of the need for a bunker reserve, where the process takes an appreciable time. Will the authors state their views on the relative merits of stoker and pulverized-fuel firing and their experience of arch settings and wear on pulverized mills with semi-coke? Is the stripped gas which is at present used in the boiler furnace suitable (possibly enriched) for supplying the combustion products to the retorts? From Mr. McEwen's paper it will be noted that in the American plant the process is accelerated by pulverizing the fuel at the outset. This is an advantage, but it would appear possible, in view of the percentage held on the 48-mesh, that further pulverizing might be necessary and this would increase the costs. Prof. Rosin's paper supplies figures as to the capital cost of German installations; the interest payable upon such costs would counterbalance any gain which might accrue from the adoption of the process. Reference has been made to the national aspect of the question and the need for more effective use of the constituent elements contained in coal. Messrs. Smythe and Weeks state that this should now be attempted by the electrical supply industry, in view of the co-ordination which is being effected by the Electricity Commissioners and the Central Electricity Board. If low-temperature carbonization is an economic success it should, in my opinion, be exploited by these authorities in certain districts, the semi-coke should be supplied as fuel to selected stations, and the profits derived from the process should be used to equalize freight charges. The selected stations would then be provided with raw material at the same price and competition in operating efficiency would result, with a beneficial effect upon the industry as a whole.

Mr. H. E. Stone: I am glad to find that the electrical industry is at last realizing the serious waste of our natural resources which is a consequence of their practice of burning raw coal. Destructive distillation and by-product recovery, as described in the papers, are obviously in the experimental stage and it is difficult to estimate their value on the small amount of evidence given. The paper on English practice is, I think, unduly optimistic for it gives the price of coal as 11s. per ton—a very low figure for fuel delivered to the plant. Further, the marketable value of the by-products is, in fact, not above 6s. per ton, compared with the figure of 8s. 11d. in the paper. The cost of working the tar would not be less than 3s. for the quantity mentioned, even with large-scale operation and up-to-date plant. This charge does not appear in the paper. The method of distillation used, that of internal heating, gives a low-grade gas heavily charged with inert constituents and is inefficient. I think that the process suffers by reason of the fact that one of the most profitable products of coal (gas) is eliminated. External heating would be more effective as it would provide gas of a saleable quality. It must be remembered that the high sulphur content of poor coal causes the sulphur content of the tar products and motor spirit also to be high. This point should receive careful consideration when the advisability of reducing the cost of the raw material is under discussion. I agree with the conclusion, arrived at in Mr. McEwen's paper, that gas and electricity undertakings must combine in order satisfactorily to solve the problem. The former fully understand the destructive distillation of coal and the working up of by-products. They have a good market for the gas and are themselves able to produce a large amount of cheap steam by the use of waste-heat boilers and coke-cooling plants. I believe that it would be quite possible for the gas industry to supply a coke or breeze suitable for combustion on boiler grates. Recent research work has shown that the reactivity and ignition temperature of coke are those of its most easily combustible constituent. A reactive coke could thus be produced by blending, and this would still leave the gas undertakings free to sell the larger coke for domestic and industrial purposes. Furthermore, if it can be demonstrated that low-temperature carbonization is a paying proposition the gas industry will certainly adopt it.

Mr. T. H. Byrom: The paper by Mr. McEwen shows, in Table 2, an item on the revenue side which allows $0·375 for the ammonium sulphate recovered. In low-temperature carbonization processes generally, however, it is doubtful whether the comparatively small yield of ammonia is worth recovery, in view of the present condition of the market. The disposal of the ammoniacal liquor may actually be a matter of some difficulty and cost owing to the restrictions upon stream and river pollution; I therefore consider that the value assigned to it should be diminished, if not ignored. On page 207 of the same paper a figure of 30 cents per 1 000 cub. ft. is given for the gas obtained in the process. Although this may be its value in America such a price could not be realized here; a certain coke-works in this country has agreed to supply coke-oven gas of a minimum calorific value of 520 B.Th.U. at 6½d. per 1 000 cub. ft., and this is not an isolated instance. In the paper by Messrs. Smythe and Weeks it is stated on page 220 that when coal is burnt in the boiler furnace no use is made of the "high-value" heat units contained in its volatile constituents. It is, however, very unlikely that these volatile constituents, which are driven off when the coal is first heated, can traverse the whole range of the heated zone under the boiler without undergoing at least partial combustion. On the same page it is stated that the optimum content of volatile matter in the semi-coke is from 12 to 14 per cent—a figure which is, in my opinion, unnecessarily high seeing that in many processes a volatile residue of 3 to 4 per cent is found to be satisfactory. It is noteworthy that the ash content amounts, in this case, to 16·4 per cent, so that the calorific value and combustibility of the coke will be low. This may explain why it is necessary to retain so high a percentage of the volatile constituents. With regard to the economic possibilities of low-temperature carbonization, there is no doubt that a market must be found for the tars and oils produced and that, even though certain products are recoverable from the former, they have to be sold at a price which is liable to considerable fluctuations. It is likely, however, that they may be utilized in hydrogenation processes and this appears to be a very promising outlet. In a paper on low-temperature carbonization, by Dr. Lander and Dr. Sinnatt, which was read at the World Power Conference in 1928, it was stated that the true commercial test of such processes could only be provided by plants which had been worked for a long period, throughout which the products had been sold on the open market and definite profits had been produced. Prof. Rosin's paper suggests that the product of low-temperature carbonization of brown coals is liable to spontaneous combustion unless suitably quenched. It is clear, therefore, that great care is necessary in cases where the product has to be stored for any length of time.

Mr. R. G. Devey: After inspecting the Dunston plant I came to the conclusion that low-temperature carbonization was a practical possibility and that it only remained to show it to be a commercial success. A paper * on this subject which was read some years ago drew attention to the fact that many types of pulverized-fuel systems exist; I am glad that only a few of the most practical of these have been described. American practice cannot but differ from that adopted in this country on account of the difference between the positions with regard to the supply of fuel oil. Whereas in the U.S.A. an abundance of the latter is provided by nature, England imports about 600 million gallons of spirit yearly and as she consumes, in addition, some 600 million tons of coal per annum the two countries must take widely different views of the commercial advantages of low-temperature carbonization. With regard to the paper on English practice, I should like to ask what percentage of coal is used and whether this is screened. Is the dust problem less serious as a result of the use of coke fires? I gather that less than 100 per cent of the fuel is distilled; it would be interesting to hear whether the quantity of sulphur, and the nuisance with which it is always associated, are at all reduced during the distillation process. Should not the plant which is used for this purpose be placed in a separate building near to the boiler house? That equipment would probably be subject to a good deal of corrosion arising out of the low-temperature conditions. What rate of depreciation on the capital charges would this involve? The authors' opinions as to whether coke firing, either by stoker or by pulverization, has been an entire success, would be of interest. As no statement of initial costs has been given, some indication of the capital charges on, for example, a distillation plant for 100 000 kW would be welcome.

Mr. E. W. Ashby: I notice a difference between the American and English systems in that in the former the coal is pulverized before treatment. It seems clear from the diagram that in the English system the coal is not crushed; I should have thought that this would not have been such an efficient process as low-temperature carbonization of coal which has been already pulverized.

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* "Pulverized Fuel and Efficient Steam Generation," *Journal I.E.E.*, 1924, vol. 62, p. 385.

THE AUTHORS' REPLIES TO THE LIVERPOOL DISCUSSION.

Mr. S. McEwen (*in reply*): It is natural that the question of general interest when considering the possible application of low-temperature carbonization of coal in conjunction with power generation should be a financial rather than a technical one. Mr. Hollingsworth gave expression to this in drawing attention to the fact that little definite information is given in the papers on the financial side of the question. In an industry, however, which is in process of development it is practically impossible to give definite financial figures which would be of any real value. The matter, in my opinion, has to be approached in an entirely different way. Thus, if it be accepted that by the carbonization of coal at low temperatures products of a considerably higher value than that of the coal from which they were extracted may be recovered, the procedure should be to apply the skill of engineers, chemists and financial experts to the study of the precise conditions which would obtain where a combined carbonization and power plant could be installed. The equipment could then be so planned as to secure profitable operation. Knowing the cost of the coal available for treatment and the minimum realizable values of the various products, it is possible to predetermine what amount of money may be expended as capital, what operating charges are permissible and what profit is essential in order to make the project worth while. This is the manner in which the installation at Milwaukee was undertaken. The revenue which could be obtained from a satisfactory gas and from the sale of the solid fuel was known. In the case of the revenue from the tar and light oil a minimum value could be fixed, but it was realized that, following careful investigation and research work, it would be possible to secure a higher rate of income. A prospective balance-sheet was prepared and it then remained for engineers to design the equipment, keeping within the limits of the estimated expenditure for capital and operation. At this early stage in the development of the industry it is inconceivable that figures relating to a plant erected in one district would apply with equal accuracy to a plant erected elsewhere. A careful study of local conditions will determine what financial results are possible, and it then remains for the combined effort of those skilled in engineering, chemistry and finance to convert into reality that which was shown to be possible.

The reference in my paper to the importance of securing an adequate revenue from the sale of gas was commented upon by several speakers, including Mr. Gibson and Mr. Byrom, it being pointed out that conditions for the sale of gas in America were obviously different from those which existed in England, but in this connection there is one point which is apt to be overlooked. A misapprehension has arisen with regard to the value of gas, as a result of the low prices which have in the past been realized for the surplus gas produced in high-temperature coke ovens. The cost of manufacturing the gas which is sold for supply to a town is well known (the figures are published every year), and it is apparent that there is little, if any, relation between the actual cost of manufacture of gas to a gas company and the price which such a company is willing to pay for surplus gas supplied from a high-temperature coke-oven plant. The justification for the low price paid lies in the fact that the gas company has the responsibility for public service and its supply must be available at all times, whereas the operation of the high-temperature coke-oven plant is dependent upon the fortunes of one industry. There is no guarantee of the continuity of the supply from the latter, and consequently the gas manufacturer must maintain his equipment, his staff and his whole organization in readiness to manufacture the gas in substitution for that purchased from the coke-oven plant should the latter supply fail. In considering the combination of carbonization with power generation, the question of continuity of supply does not arise; the electricity company is just as much a public service company as the gas company; the demand for electric power is not dependent upon the fortunes of any one industry, in fact the demands for electricity and gas bear a very definite relation through all the seasons of the year. Therefore, the value of the by-product gas should be represented by the actual cost of manufacture at the gasworks.

Mr. Byrom refers to an item on the revenue side of Table 2 in my paper, relating to the realizable value of the ammonium sulphate recovered. It will be seen, however, on further reference to Table 2, that the results given are not from low-temperature carbonization but from high-temperature carbonization. It is fully realized that in low-temperature carbonization the ammonium sulphate recoverable is of such small quantity as to make it valueless. In Table 4, which gives the revenue from low-temperature carbonization, no credit at all is given for ammonium sulphate. At the bottom of page 207 it is distinctly stated that no revenue is obtained from the sale of ammonium sulphate with low-temperature carbonization.

Mr. Devey asks for an expression of opinion as to whether coke firing by stoker or by pulverization has been an entire success. Presumably the question refers to semi-coke, and so far as combustion of semi-coke in pulverized form is concerned it has been very definitely established that combustion is entirely successful. Powdered semi-coke is very easy to ignite, it is sufficiently soft to prevent unusual wear in the handling equipment, the rate of combustion per cubic foot of furnace capacity is higher than with raw coal, and a very high percentage of CO_2 can be maintained.

Mr. Hamilton refers to the sizing test on the semi-coke resulting from carbonization at Milwaukee, and suggests that further pulverization might be necessary before combustion. In this connection, however, it is important to remember that rapidity and completeness of combustion are dependent upon the surface area exposed. A particle of semi-coke, although it fails to pass through a 48–mesh screen, can still expose as much surface for combustion (for its weight) as a very much finer particle of solid coal. The semi-coke particle is cellular, it is extremely reactive and it has been found in practice that relatively large particles delivered to a furnace by the standard pulverized-coal burner will burn completely and satisfactorily.

Dr. P. Rosin (*in reply*): I referred in my paper to the essential difference which exists between the carbonization of pit coal and of brown coal. The profit on the carbonization of pit coal must come from the higher price of the coke, which, however, the power stations will not pay, and for this reason I believe that there are no prospects in Germany for the combination of the carbonization of pit coal with the generation of electricity. Coke obtained from brown coal cannot be used in any great quantity for house fuel and has therefore a lower value. The sale of the tar and gas obtained from the carbonization of such coal is so profitable that coke is a cheaper fuel than raw coal for power stations. Therefore, in spite of the high capital charges associated with the carbonization of brown coal as compared with German pit coal, the process results in considerable economy.

Messrs. E. H. Smythe and **E. G. Weeks** (*in reply*): Replying to Mr. Hollingsworth, the paper dealing with the Babcock process is admittedly concerned with the technical side and no attempt has been made to give any detailed information as to finance. Such information would involve a hypothetical plant concerning which a number of assumptions would have to be made. We frankly consider that the Dunston distillation plant is on too small a scale to give a representative idea of the financial results to be obtained in large-scale working. Although the paper makes no mention of the production of semi-coke for household use, the process is well adapted for this purpose and in our opinion there is an even better market in this country than in America for the high-grade smokeless fuel, owing to the more general use in England of open fires and coke-fired domestic boilers. In America oil firing has now been extensively adopted for domestic heating installations.

No difficulties have been experienced in using semi-coke on chain-grate stokers. As far as our experiments have gone, the semi-coke has presented no difficulties either as regards grinding or burning in pulverized form, but we shall be in a position to give more information on this point when we have had some experience with the working of the new retort which has been purposely installed for the firing of a pulverized-fuel boiler. The possibility of having to blend coal with coke does not arise if semi-coke of the type made at Dunston is used, and this complication is therefore avoided. Semi-coke containing about 12 per cent of volatile constituents forms a very satisfactory boiler fuel.

Mr. Gibson mentions that the gas industries are naturally interested in coal carbonization, but as far as low-temperature distillation is concerned any practical interest they may have taken is of comparatively recent date; it is the result of endeavours made by those associated with certain low-temperature processes, or is due to Government assistance. Even so, the number of processes now under test by the gas companies is confined to only 3 or 4 large-scale plants in the London area, so that Mr. Gibson's estimate of half a dozen is rather too optimistic. On the other hand, the electrical industry has up to now taken no general interest in the problem except in the instance which forms the subject-matter of this paper. It is, however, a fact that the possibilities of combining low-temperature distillation with the production of power were first considered by electrical engineers about 12 years ago in some experiments which they instigated in order to discover a more economical method of utilizing our coal resources, combined with the home production of oils. High-temperature processes were not taken into consideration; firstly, because the gas industries make use of a different type of coal from that normally used for power-station work; secondly, because the coke produced is more expensive than coal and less suited for use in modern steam-raising plants; and thirdly, because high-temperature carbonization gives a lower yield of tar oils than that obtainable by low-temperature processes. Although it is reassuring to know that the gas companies are watching and will take advantage of the improvements in low-temperature carbonization, this is rather different from taking an active part in the work of development. Presumably they are content to leave the task to those already engaged upon it; this is encouraging, provided that their co-operative support is likely to be forthcoming in the commercial development of a method of carbonization with which their own industry is so closely allied. It is true, as Mr. Gibson says, that the production of gas from low-temperature distillation is considerably less than that from high-temperature carbonization, but at no time has it been claimed that one industry would supplant the other. Rather should one be complementary to the other, and while the gas industry may be primarily concerned with the production of gas it is also interested to a considerable extent in the sale of coke. For instance, some gas companies have of recent years devoted attention to the supply of a special type of coke suitable for use in domestic boilers. We hope, however, that they will soon recognize that low-temperature semi-coke is even more suitable for household purposes than high-temperature coke and that the production of this fuel should therefore be of immediate interest to them. The gas produced by the Babcock process could either be used to meet the heat requirements of the process, or else it could serve as a diluent for the rich gas produced by high-temperature retorts. As Mr. Gibson suggests, co-operation between gas and electricity undertakings on these lines would greatly facilitate developments, and it is our contention that the results already achieved at Dunston give a very fair indication of the possibilities. Mr. Gibson thinks that, from the gas-makers' point of view, it is wasteful to burn semi-coke containing 12 to 14 per cent of volatile material, but from the general economic point of view it is far less wasteful than the combustion of raw coal containing, say, 30 per cent of such material. In our experience, it is essential that the volatile content of the semi-coke should not be less than about 12 per cent and we do not agree that coke having 3 to 5 per cent of volatile matter is a fuel suitable for firing boilers. It is open to question as to whether it would support combustion when used as a pulverized fuel, apart from the fact that such coal is difficult to pulverize. It is altogether unsuitable for use as domestic fuel. The prices given for the by-products were obtained from actual sales figures of the products made at Dunston, and these prices compare very favourably with those quoted in the market at the time when the paper was written. This remark also refers to the point raised by Mr. Stone. We realize that by-product prices are liable to considerable fluctuations, but it is generally considered that these are at present exceptionally low. It is obviously necessary to install a refining plant in order to realize the full value of the by-products: this was carried out at Dunston in order also to obtain practical experience in refining low-temperature tar oils. As far as we were aware, no practical investigation into the commercial values of low-temperature tars had been carried out by the gas or the tar-refining industries. It was therefore necessary for us to do this work ourselves, with the result that we have been able to market the various products mentioned in the paper. The quantity of gas produced is about 33 000 cubic ft. per ton of coal treated, the calorific value being about 80 B.Th.U. per cubic ft. of gas. At Dunston, this gas is used in the boiler furnace and is therefore only valued at the same price per therm as the semi-coke supplied to the boilers.

In reply to Mr. Hamilton, we agree that it would be necessary to treat approximately 1⅓ tons of coal in order to obtain a ton of semi-coke, but this larger quantity treated would also proportionately increase the quantity of by-products available and, incidentally, if all industrial fuel were so treated considerable assistance would be given to the coal-mining industry. We agree with Mr. Hamilton that a plant with a through-put of 160 tons per day is too small for modern boilers, and for this reason we have evolved a design for a unit capable of handling 300 tons per day which will work on the same lines as the new 60-ton retort at Dunston. As regards the use of semi-coke on chain-grate stokers, the plant at Dunston has definitely proved that there are no difficulties and that the fuel is entirely suitable for this purpose. The brick arch required for the combustion of semi-coke may be made shorter and higher than is general with chain-grate stokers burning highly volatile raw coal, and thereby the first cost and maintenance of the brick arches is reduced. No special arrangements are required for draught regulation, beyond those usually provided on modern chain grates. Regarding the use of semi-coke in pulverized form, we shall be in a better position to give useful information after the new retort has been in operation for some time, but our preliminary experiments have not led us to anticipate any special difficulties in connection either with the grinding or the combustion of the pulverized semi-coke. It is for this reason that the new retort has been designed to work in conjunction with the pulverized-fuel boiler. The stripped gas from the retort could, as Mr. Hamilton suggests, be used for making the distilling medium and, incidentally, for pre-heating the coal. It is possible that it would be an advantage to enrich the gas if the foregoing arrangement were adopted. From the point of view of thermal efficiency, however, and in order to facilitate control of operation it is, in our opinion, preferable to utilize waste flue-gases from the boiler for pre-heating the coal and to have an independent source of heat for the retorts. The gas made in the latter can either be fed into the boiler furnace or sold for use as a diluent for gas of high calorific value. At Dunston, the gas from neighbouring coke ovens is used for producing the distilling medium, and this is the most economical method. A producer has also been installed as an alternative means of supply; this would come into action if for any reason the supply of gas from the coke ovens were cut off. Mr. Hamilton's suggestion that the Electricity Commissioners and the Central Electricity Board should investigate the possibilities of applying the process to selected stations is one which we warmly welcome: we have always maintained that power stations afford one of the best examples of correct application of the principle, owing to their continuity of operation and to the large quantity of coal which is utilized at one point.

We agree with Mr. Stone that the total of 8s. 11d. available per ton of coal from the sale of by-products has to cover interest on capital, maintenance, depreciation and operating expenses. With large-scale operation this figure is sufficient to show a profit on the process. In cases where coal is dearer, prices of by-products may be correspondingly more favourable. It is therefore clear that each application of the process must be accompanied by a careful study of the local conditions in regard to possible outlets for the products of the plant. Mr. Stone expresses the opinion that internal heating of the retort is inefficient owing to the amount of low-grade gas which it produces. We have already explained that, in this country at any rate, we do not think that great importance should be attached to low-temperature carbonization as a means of producing gas, at least as far as the requirements of gas undertakings are concerned. We therefore do not agree that external heating is preferable to the method we employ, firstly, because slow heat transference and the resultant losses greatly reduce its thermal efficiency, and secondly, because under this system it is difficult to treat large quantities of coal in one unit. This necessitates the use of a multiplicity of units. Many small retorts are therefore necessary and this increases the capital expenditure; in addition, the life of the retorts is not so great if they have to be subjected to high temperatures in order to effect complete carbonization. As an example of the effects of internal heating it may be mentioned that the walls of the new retorts at Dunston, which have now been in operation for 3 years, show no signs of deterioration or distortion. Mr. Stone believes that the gas industry could produce a type of coke suitable for boiler firing or for use as a domestic fuel, but the fact remains that hitherto the industry has not done so. Though this might be achieved by blending we doubt if the gas companies would be able to add this to their ordinary business of producing gas, and it therefore seems more reasonable to expect them to take an interest in low-temperature distillation, which will produce fuel suitable for both these purposes.

In reply to Mr. Byrom, we wish to explain that by high-value heat units we refer to those heat units available from the coal, which are more valuable when used in some other form than when they are burnt in the furnace. Thus, although it is certainly the case that in a boiler furnace the volatile constituents undergo combustion and add to the generation of heat, they would none the less be far more valuable in the form of motor spirit, creosote or some other liquid by-product. Our experience of boiler firing with coke containing only 3 to 5 per cent of volatile constituents has shown that this proportion is far too small for ordinary use, and we are certain that such coke would not be suitable as a pulverized fuel. We agree that the ash content of the coke is increased by distillation, but our avowed object is to treat the type of coal which is normally used in power stations. The fact remains that we are able to produce a semi-coke of equal calorific value, pound for pound, to that of the raw coal, without experiencing any difficulty in disposing of the ash. We note that Mr. Byrom agrees with our contention that the price obtainable in this country for gas produced by low-temperature plant is far lower than in America, and it should also be noted that in Great Britain a considerable number of gas companies are supplying gas of calorific value lower than 500 B.Th.U. per cubic ft. In this connection, there is the possibility of using the low-grade gas made by this process as the diluent for the rich gas made by high-temperature processes, and thus of creating another useful link between the two industries. As regards the quotation from Dr. Lander and Dr. Sinnatt's paper, we should like to know what period of working constitutes a true commercial test. The Dunston plant has now been in operation for 3 years and throughout that period the yield of by-products has been sold on the open market. This should be sufficiently long to show that the process is a practical proposition, though it must be admitted that the cost of developing and working a small-scale plant, such as the one at Dunston, gives no indication of the profit to be made from large-scale operation. As Dr. Lander points out, there are undoubtedly local conditions under which a plant can be expected to be a commercial success—it is only a matter of finding the right conditions in order to apply the process commercially. If time alone can tell how far low-temperature distillation can influence the utilization of coal, then it is high time that a start was made to show what can be done.

In reply to Mr. Ashby, the Babcock process is designed to treat ordinary small coal and to produce semi-coke either in lump form or as a pulverized fuel. The distillation of crushed coal is in a different category and is outside the scope of our investigations.

Mr. Devey aptly summarizes the essential differences between conditions in America and in this country from the point of view of low-temperature distillation, and we are in full agreement with what he says. In answer to his question, we would point out that the process described is not designed to treat duff and that it is preferred not to use coal with a proportion greater than about 20 per cent below ¼-in. sieve, so that to this extent screening may be necessary. The amount of sulphur present in the semi-coke is largely dependent upon whether the sulphur in the original coal was combustible. There are only isolated instances in which the amount of sulphur is reduced by distillation; in most cases the sulphur content of the semi-coke is equal to, or possibly greater than, that contained in the coal. Generally speaking, low-temperature distillation affords no solution of this problem. The distillation plant should, if possible, be housed in or alongside the boiler-house so as to make use of existing coal-bunkering arrangements, and also because the operation of the retorts can thus be controlled by the boiler-house staff. It should, however, be understood that the retorts will not be linked up direct to the boiler furnace, but will supply the semi-coke to separate bunkers for storage and subsequent use. In this connection, we have made some investigations which tend to show that the risk of spontaneous combustion is less with semi-coke than with coal. The distillation plant can be housed in a separate building, but this may necessitate the installation of separate coal-handling plant. The tar storage-tanks and any tar-refining plant should be at a convenient distance from the power station. Regarding Mr. Devey's remaining questions, we have already referred in previous replies to the fact that there is no difficulty in firing boilers with semi-coke, at any rate so far as the use of chain-grate stokers is concerned; we hope to prove by continuous working that pulverized semi-coke is equally satisfactory. We have also previously referred to the almost complete absence of corrosion; and the fact that the temperature in any part of the plant is no higher than 500 to 600° C. accounts for the good condition of the retort walls after 3 years of continuous operation. We consider that 5 per cent would be an ample figure to allow for depreciation.

ANNUAL DINNER, 1930.

The Annual Dinner of the Institution was held at the Hotel Cecil on Thursday, 6th February, 1930, when the President, Col. Sir Thomas F. Purves, O.B.E., presided over a gathering numbering 651 persons. Among those present were: Mr. G. M. Gillett, M.P. (*Secretary, Department of Overseas Trade*); The Rt. Hon. The Earl of Bective; The Rt. Hon. The Viscount Falmouth; The Rt. Hon. Lord Monk Bretton, C.B., D.L. (*Chairman, London County Council*); The Hon. Sir C. A. Parsons, O.M., K.C.B., F.R.S. (*Honorary Member*); Sir George Sutton, Bart.; Sir R. T. Glazebrook, K.C.B., D.Sc., F.R.S. (*Past-President; Honorary Member*); Sir G. Evelyn P. Murray, K.C.B. (*Secretary, General Post Office*); Sir John Rose Bradford, K.C.M.G., C.B., C.B.E., M.D., F.R.S. (*President, Royal College of Physicians*); Col. Sir Charles Close, K.B.E., C.B., C.M.G., F.R.S. (*President, Royal Geographical Society*); Sir Arnold B. Gridley, K.B.E.; Sir Cyril W. Hurcomb, K.B.E., C.B. (*Permanent Secretary, Ministry of Transport*); Sir Joseph E. Petavel, K.B.E., D.Sc., F.R.S. (*Director, National Physical Laboratory*); Sir J. R. Brooke, C.B. (*Electricity Commissioner*); Sir Ambrose Fleming, M.A., D.Sc., F.R.S. (*Honorary Member*); Sir H. Haward (*Vice-Chairman, Electricity Commission*); Sir J. H. Jeans, D.Sc., LL.D., F.R.S.; Sir David Milne-Watson, LL.D., D.L. (*President, Institute of Fuel*); Sir Archibald Page (*Past-President*); Sir Walter Raine, J.P. (*President, Association of British Chambers of Commerce*); Sir Ernest Rutherford, O.M., P.R.S. (*President, Royal Society; I.E.E. Faraday Medallist*); Mr. C. T. Allan (*Hon. Secretary, Western Centre*); Mr. H. V. Ashley (*Vice-President, Royal Institute of British Architects*); Mr. Ll. B. Atkinson (*Past-President, I.E.E.; Chairman, Royal Society of Arts*); Mr. G. Balfour, M.P.; Mr. J. R. Beard, M.Sc. (*Member of Council*); Capt. J. F. C. Bennett, J.P. (*Mayor of Westminster*); Major B. Binyon, O.B.E., M.A. (*Member of Council*); Mr. J. K. Brydges (*President, Incorporated Municipal Electrical Association*); Mr. R. A. Chattock (*Past-President*); Mr. A. E. L. Chorlton, C.B.E. (*Vice-President, Institution of Mechanical Engineers*); Col. D. S. Collins, D.S.O. (*Asst. Director of Works, War Office*); Mr. A. R. Cooper (*Member of Council*); Col. R. E. Crompton, C.B., R.E. (*Past-President; Honorary Member*); Mr. W. Cullen, LL.D. (*President, Institution of Mining and Metallurgy*); Mr. W. R. Davies, C.B. (*Principal Asst. Secretary, Technical Branch, Board of Education*); Capt. J. M. Donaldson, M.C. (*Vice-President*); Dr. C. V. Drysdale, O.B.E., F.R.S.E. (*Director of Scientific Research, Admiralty*); Mr. R. N. Eaton (*Hon. Secretary, Irish Centre*); Dr. W. H. Eccles, F.R.S. (*Past-President,* *I.E.E.; President, Institute of Physics; President, Physical Society of London*); Lieut.-Col. K. Edgcumbe, T.D., R.E.T. (Ret.) (*Past-President*); Mr. H. Cecil Fraser (*Hon. Secretary, North Midland Centre*); Mr. N. G. Gedye, O.B.E. (*Chairman, Association of Consulting Engineers*); Mr. T. G. N. Haldane, M.A. (*Member of Council*); Mr. S. Harcombe, M.A., B.Sc. (*Member of Council*); Mr. T. E. Herbert (*Chairman, North-Western Centre*); Mr. J. S. Highfield (*Past-President*); Mr. F. S. G. Hinings (*Past-Chairman, North Midland Centre*); Mr. H. Hooper (*Hon. Secretary, South Midland Centre*); Mr. P. V. Hunter, C.B.E. (*Vice-President*); Mr. J. M. Kennedy (*Member of Council*); Mr. L. J. Kettle (*Past-Chairman, Irish Centre*); Mr. J. E. Kingsbury; Prof. T. M. Lowry, F.R.S. (*President, Faraday Society*); Mr. W. McClelland, C.B., O.B.E.; Mr. H. Marryat (*Member of Council*); Mr. C. H. Merz; Col. R. K. Morcom, C.B.E. (*Member of Council*); Mr. W. M. Mordey (*Past-President*); Brig.-Gen. Magnus Mowat, C.B.E. (*Secretary, Institution of Mechanical Engineers*); The Very Rev. W. Foxley Norris, C.V.O., M.A., D.D. (*Dean of Westminster*); Col. William Parker, D.S.O., T.D. (*President, Chartered Institute of Secretaries*); Mr. H. Parodi (*President, Société Française des Electriciens*); Mr. C. C. Paterson, O.B.E. (*Member of Council*); Mr. R. W. Paul (*Chairman, British Electrical and Allied Industries Research Association*); Mr. F. W. Purse (*Member of Council*); Dr. A. H. Railing (*Vice-President*); Mr. B. A. Robinson (*Chairman, North-Eastern Centre*); Mr. T. Roles (*Chairman, North Midland Centre*); Dr. A. Russell, M.A., LL.D., F.R.S. (*Past-President*); Mr. E. E. Sharp (*Member of Council*); Mr. E. H. Shaughnessy, O.B.E. (*Member of Council*); Dr. F. E. Smith, C.B., C.B.E., F.R.S. (*Secretary, Department of Scientific and Industrial Research; Secretary, Royal Society*); Mr. Roger T. Smith (*Past-President*); Mr. James Swinburne, F.R.S. (*Past-President*); Prof. J. F. Thorpe, C.B.E., D.Sc., F.R.S. (*President, Chemical Society*); Mr. H. T. Tizard, C.B., F.R.S. (*Rector, Imperial College of Science and Technology*); Mr. V. Watlington, M.B.E. (*Chairman, British Electrical and Allied Manufacturers' Association*); Mr. R. S. Whipple (*Member of Council*); Mr. J. Harcourt Williams (*Past-Chairman, North-Western Centre*); Mr. T. P. Wilmshurst, M.B.E. (*Electricity Commissioner*); Prof. E. Wilson (*Member of Council*); Mr. M. F. G. Wilson (*Chairman, British Engineering Standards Association*); Mr. W. B. Woodhouse (*Past-President*); Mr. H. T. Young (*Member of Council*); and Mr. P. F. Rowell (*Secretary*).

The toasts of "His Majesty the King" and "Her Majesty the Queen, His Royal Highness the Prince of Wales, and the other members of the Royal Family," were proposed by the President and loyally received.

Sir James H. Jeans, D.Sc., LL.D., F.R.S., in proposing the toast of "The Institution of Electrical Engineers," said: "I suppose we all feel that electrical science occupies at the present time a very special and peculiar position both in the scientific life and in the technical life of this country. I remember once trying to imagine what would have been the impression of visitors from another planet, if they had visited us at intervals of a century to report on our world and its habits. For many thousands of years during the Stone Age the changes would have been slight. In the century which ended in 1830 they would find more to report on, but that would be nothing compared with the changes which have taken place in the century between 1830 and 1930. Now when we look for the causes of the great change which has taken place in our habits of life during the last century, I suppose that the largest single item would be Faraday's discovery of electromagnetic induction, made just 99 years ago. Such small practical use was at first made of that discovery that when your Institution was founded 40 years later it did not begin as a society of electricians but as the Society of Telegraph Engineers. I think I am right in saying that in 1870 nobody imagined that electromagnetic induction could have anything to do with telegraphy as then understood. Ten years later, in 1880—just half a century ago—your Institution took electromagnetic induction and similar subjects under its wing, and became the Society of Telegraph Engineers and Electricians. Until then the electromagnetic side had, I think, been in charge of the societies concerned with pure science—the Royal Society, the Physical Society, and so on. From that time development has been rapid and one might fairly say that, as the result of the development of electromagnetism alone, human life has changed more in the last half-century than throughout the whole duration of the Stone Age. I think it may fairly be said that all the developments of electrotechnics have been for the good of the human race: one cannot make that statement about all sciences. On the purely scientific side the science of electricity has developed, I suppose, at a greater rate than any other pure science, largely under the guidance of great men of science who have specialized in electricity and all of whom have, I think, been connected in some way with your Institution. Partly as a result of this, your Institution has always been in very close touch with pure science, and we on the purely scientific side are extremely glad of this. For one thing, it gives the pure scientist a very strong argument when asked to justify the expenditure of money, time and energy on research in pure science. All he has to say is, 'Think of the financial value to the country of Faraday's discovery of electromagnetic induction.' In a sense your Institution has been obliged to keep in touch with abstract science and theory. A man may be a very clever civil engineer or a very clever mechanical engineer without knowing very much about the differential calculus, but he cannot be a good electrical engineer without knowing something both about the differential calculus and about pure science. If he thinks that he can, he is making a great mistake, for which he will have to pay very heavily in his profession. At the same time, it has been a great satisfaction to pure scientists that there has been this close contact between pure science and applied science. One of the real honours which has come to me during my scientific career was the invitation from your Council some years ago to deliver the Kelvin Lecture. I remember that on that occasion I was requested not to deal with technical matters but to talk about one of the most abstract branches of mathematical physics. The Council showed extreme breadth of view in suggesting the subject for the Kelvin Lecture; and that attitude has characterized the history of your Institution and, to my mind, accounts for a very large part of its greatness and success. I am much impressed by a remark made by Mr. C. F. Varley in 1872 at one of the earliest meetings of your Institution, before its title had been changed, when he boldly prophesied that electricity would take within its purview the whole of nature. It was really the concept of the electrical structure of matter which brought the whole of nature within the scope of electrical science, yet that idea did not come until later. In 1872 even the electromagnetic theory of light was not established; Clerk Maxwell was discussing it, but had not at that time published the first edition of his work " Electricity and Magnetism," and there was no reason in 1872, apart from pure insight and breadth of view, for supposing that the whole of nature would ultimately come within the purview of electricity. Yet Varley used those words, which have since been justified by the advance of science. Again, to come to more modern times, I was more than ever impressed by the breadth of knowledge of the electrical engineer when this year I read the address of your President, Sir Thomas Purves. Before I read that address I should not have imagined that abstract mathematical astronomy and electrical engineering could have anything in common, and yet I found your President dealing with abstract ideas about the galactic system and the number of possible universes, and such numbers as 10^{177}, which I had hitherto looked on as the special preserve of astronomers. It made me wish that I could invade your realm of electrical engineering with the same facility as your President invaded the realm of abstract astronomy. It gives me great pleasure to propose the toast of 'The Institution of Electrical Engineers,' and to couple with it the name of your President."

The President, in responding, said: "It is a pleasure and an honour to respond to the toast of this Institution, which has been so graciously and so pleasantly proposed to us by Sir James Jeans. I feel that to give anything like an adequate reply for the great groups of the electrical industry which the Institution represents would be a very considerable task; but I think that I am absolved from one of the duties which, I understand, sometimes devolves on the individual who has to reply to a toast of this kind—the duty of gracefully calling attention to various nice things about the subject of the toast that the proposer may have unfortunately omitted to mention. There is no need for me to do that; Sir James has done us full justice in a thoroughly comprehensive way. I am rather glad he has done so, because I must confess that the professional activities of some of the members of this Institution are still rather mysterious to me, in spite of the fact that I have already had the pleasure of attending a good many dinners of its Local Centres up and down the country, and have in this way had the advantage of listening to a very fine selection of speeches on the subject—speeches of the kind which, I believe, are often the main sources of information from which Presidents of great organizations such as this learn things about them that they ought to have known before. I shall not attempt, therefore, to stand here as an expert dispensing information. I have heard an expert defined as merely an ordinary man away from home, so here at our headquarters I am not able to put up even that claim. Besides, I once heard Sir Oliver Lodge remark, in one of those delightful conversational soliloquies with which he sometimes entertains his friends, that experts in one's own line of business require to be placated rather than informed. At all events if I should ever feel inclined to pose as an authority on the great subject of electrical engineering it would certainly not be in the presence of an audience such as I have the honour of addressing to-night, an audience so much more fully informed on all aspects of the subject than I am, or can ever hope to be. Occasions after dinner are not, perhaps, the best occasions on which to speak in any detail of the work and of the manifold functions of this great Institution, and yet one feels it appropriate to make a brief reference to some of its aims and activities. It exists to serve an industry which already covers a very wide and diverse field, and one which is continually developing and reaching out into new spheres of action; and it has deliberately adopted the policy of standing for, and endeavouring to cater for, the whole of that industry. Other great engineering institutions have in some cases adopted the alternative policy of allowing more or less specialized groups of interests, coming within their ambit, to form themselves into separate institutions or societies, in some cases affiliated to the parent body but with an independent constitution and a separate government. We, on the other hand, have thought that a profession based upon electrical research and electrical knowledge, however wide and varied its interests may be, is capable of being treated from this point of view as one profession. We think it will reap advantages from keeping together and that the general public interest, as well as the interests of the electrical industry and of its professional *esprit de corps*, will be better served by one powerful Institution of a national character than by a number of separate electrical societies. From this standpoint we have had to sectionalize our membership, and we have tried to do it in such a way that members who are interested in the same special subjects may be able to meet and act together for the advancement of their sectional interests, with as much effect and, for all practical purposes, with as much freedom as if they were independent bodies. So far as I have been able to judge, this system is working well and is giving satisfaction. Our constitution has so far proved to be sufficiently flexible to provide both the necessary freedom and the necessary government, and I think that the main body of opinion in the Institution favours the continuance of development along those lines. Our policy is, therefore, to offer the ægis of the Institution to any distinctive group of qualified workers in the electrical field who wish to act together for the advancement of their science and art, in a wider sense than the interests of one particular firm or concern, and I think I might describe our idea of the status that such a special section should hold in the Institution by saying that it corresponds more or less to what we know as Dominion status within the British Empire. Up to the present we have not evolved a satisfactory system of caring for the whole of the natural adherents of such groups. I have been very much impressed by the fact that electrical societies which have transformed themselves into sections of the Institution have been called upon to make the very great sacrifice involved in shedding the large proportion of their membership not individually qualified by professional education and experience for membership of the Institution. Any relaxation of the standard of qualification required for corporate membership is of course quite out of the question; the movement of the future is much more likely to be in the opposite direction. But I feel sure that we shall, in due time, devise methods of meeting this difficulty which will enable the Institution to extend its usefulness among the classes which have at present to stand outside it, in ways which will not only benefit those immediately concerned but will react to the benefit of the electrical industry as a whole, and to the benefit of the nation. As Sir James Jeans has very pointedly put it to us, anything which tends to spread and to make more universal the ideals of science and engineering is an object worthy of support. As he says, we are living in a great age. I do not suppose that ever since this world began has any generation of men witnessed such a panorama of scientific progress as that which has unrolled itself before our eyes during the past 30 or 40 years, and which has led to developments entering intimately into the whole social and commercial structure of the world. Many of us can remember the days when there was no electric light or electrical machinery, no Parsons steam turbines, no internal-combustion engines or motor-cars, no phonographs, no cinematographs, no radio, no flying machines, and I might add —though perhaps this may be counted as a blessing— no telephones! And this wonderful technical progress has been accompanied by a kind of lifting and widening of the whole intellectual horizon of mankind; a real mental revolution accomplished by science and by the exercise of the scientific spirit, the significance of which has yet been seen and appreciated only by relatively few. Science is, of course, the spear-head of engineering, and there is no more pressing material need to-day than the increase of science, and the inculcation of the methods of science and engineering in the education of the nation as a whole. What, after all, is engineering but the optimum use of available means to secure the desired end? What is the constructive statesman or the director of a great business but an engineer? What is Rutherford, sitting here with us to-night—our Faraday Medallist of this year—the man who first began to take atoms to pieces in order to show us how they are made, and who, with Dr. Jeans and others here, has carried the banner of English science into the very highest places of the world's honour—what is he but an engineer? Every true engineer is a builder, and I think that the converse is equally true: every man who builds for the future, with a just appreciation of permanent values, is a true engineer. There is urgent need for great numbers of men with the scientific and engineering turn of mind to come forward and take their places in industry, and to give industrial leading. Fortunately, their capacity to do it is becoming more and more widely accepted as time goes on, and I hope that such mentality and training will before long be looked upon as essential for the efficient direction of British effort. One could no doubt enlarge on that theme, but I must leave it and return to my more immediate objective, the subject of this Institution and of the graceful and generous way in which the toast of its success has been put before us to-night. Once more I thank Sir James Jeans most sincerely—and I know that in doing so I speak for every individual here—I thank him for the kind way in which he has presented the toast, and I thank you all, my lords and gentlemen, for the very hearty manner in which you have responded to it."

Captain J. M. Donaldson, M.C., (Vice-President) then proposed the toast of "Our Guests," to which **Sir John Brooke, C.B.,** (Electricity Commissioner), responded.

A reunion was subsequently held in the Victoria Hall of the Hotel.

INSTITUTION NOTES.

Professional Engineers' Act (Queensland).

Corporate membership of the Institution is one of the qualifications entitling to registration as a Professional Engineer under the above Act.

The Benevolent Fund.

The Committee of Management of the Benevolent Fund desire to draw the attention of the members to the last page of the cover of this issue of the *Journal*, on which will be found particulars of certain publications, etc., which are offered for sale on behalf of the Fund.

Elections and Transfers of Members.

At the Ordinary Meeting held on the 13th February, 1930, the following elections and transfers were effected :—

ELECTIONS.

Member.

Arendt, Otto.

Associate Members.

Cameron, Charles James.
Campbell, Harold Gordon, B.Sc.
Cunningham, Bertram Tweedale.
Damant, Eric Louis B.
Hunter, Francis Grant, Lieut.-Commander R.N.
Jolley, Ernest Harris.
Maxwell, Robert Gibson, B.Sc.(Eng.).
Nowacki, Friedrich-August.
Pallot, Charles Frederick.
Pullan, Arthur Hubert.
Saunders, Norman Clement J.
Symonds, Alfred Edward J.
Tudball, Fergus Campbell, B.Sc.
Washington, Albert Bryan, B.Sc.
Wheatley, Mervyn Savile.

Companion.

Gray, Robert Cochran, M.A., D.Sc.

Associates.

Cater, Clinton.
Chapman, Gerald Sidney.
Narayanan, Kannanur, B.A.
Stave, Cecil Herbert.

Graduates.

Adley, Arthur George, B.A.
Burke, Anthony, B.E.
Clifford, Cecil Frank, B.Sc.
Crowe, Henry Eyre.
Evans, Trevor.
Floyd, Geoffrey.
Guha, Hem Chandra, B.Sc.
Lambert, Austin Edmund, B.E.
Robson, Oswald Murray, B.A.
Rossler, Albert.
Smail, George Grey, B.Sc.
Whiteley, Joseph William, B.Sc.Tech.

Students.

Allen William Kenneth.
Arnott, Arthur Walter.
Ashworth, James Lewis.
Balean, John Hermann.
Barker, Harold.
Barr, James.
Beaton, Robert Frederick.
Bedil, Shams Din.

Students—continued.

Bilton, Stanley Maurice.
Blair, David Charles.
Blewett, Harold Stuart.
Bowie, Sydney Herbert.
Brewer, Sydney Roy B.
Bridge, Hugh John.
Bridger, William.
Brooks, John Frederick.
Burton, John Shepherd.
Caddy, Bernard Charles.
Carte, Humphrey John C.
Combridge, John Hayden.
Cook, Arthur.
Cooper, Lawrence Henry H.
Creasey, Frank Raymond.
Damany, Lax Michand Mansingbhai.
de Lestang, Marie Clement, R.
Dreyfus, Henry Benfey.
Farren, Leslie Ivan.
Fitzer, Herbert Clyde.
Forster, Edward.
Freebody, John William H.
Gadkari, Narayan Laxman.
Gatehouse, Harry William C.
Groom, Leonard William.
Hadlow, Loris Ivor.
Harris, Thomas Alfred.
Hartley, Alfred William E.
Harvey, John Philip.
Haslam, John Robert.
Hedley, John Arthur J.
Higgins, Stanley George.
Hodges, Philip George L.
Holt-Jones, Cecil.
Hughes, Claude Samuel G.
Inglis, Felix Stevens.
James, David Edward.
Jarvis, Charles McKechnie.
Jewsbury, Thomas.
Jobling, Hugh Beresford.
Kelly, Richard Gould.
Kennedy, Philip William.
Khosla, R. D.
Knott, Harry Cleal.
Lacey, Ronald Edgar.
Lewis, Hexell Arthur.
Lissimore, John Philip.
Little, James.
Lucas, John Harold.
McIlvride, Keith Jack A.
MacKenzie, Murdo.
McKinlay, John Finlay.
MacMaster, Ian James.
Mansell, Frederick Raymond W. K.
Marshall, Philip Henry.
Mathur, Suraj Jang B.
Meeres, Alfred Shirley.
Miller, Andrew Hugh.
Miller, Henry Arthur.
Moore Frederick George.
Nasib, Mohd.
Naylor, Arthur Edgar.
Newsam, Harold, B.Sc. (Eng.).
Onslow, William George.
O'Sullivan, Barry Joseph C.
Pafford, Wilfred Clive.
Page, Harold.
Parshad, Sital.
Patel, Natverlal Lalaji.
Pathak, Chun Chun.
Peak, Charles Harrison.
Pinto, David Joseph, B.Sc.
Ramana, Jagdhir Singh, B.A., B.Sc.(Eng.).
Randell, Wilbur Horatio.
Reeve, John Polden.
Richardson, Dennis Eric O.
Ritchie, David Findlay.
Roddan, Robert Alexander
Rousell, Sydney Michael E.
Rowe, Ernest George.
Searby, Norman Halifax.
Sherwood, George Eliot C.
Shuttleworth, Harry.
Stephens, William Henry.
Strathmann, Robert Christian.
Thadani, Shamdas Tharumal, B.Sc.
Tucker, Edward William.
Underwood, Leonard Edwin.
Vernon, John Russell D.
Wakeford, Robert.
Walker, Alexander Frederick.
Walker, Frederick Alfred S.
Watkins, Thomas Peter.
Winstanley, Kenneth Charles.
Young, James Ernest.
Young, Robert Eric.

TRANSFERS.

Associate Member to Member.

Platt, Frank Cuthbert.
Roxburgh, Andrew Kean.
Sarsfield, Leslie Gerald H., M.Sc.(Eng.).

Graduate to Associate Member.

Anderson, Frank Cordue K.
Beaufoy, Samuel, B.Sc. (Eng.).
Beynon, John Henry.
Brook, Salomon.
Buckley, Cornelius Francis.
Charlton, Thomas Hadwen.
Davies, Edgar Wilfred.
Evans, Alan Wainwright, B.Eng.
Fleming, David Crawford, B.Eng.
Geernaert, Sidney Glorieux.
Grundy, Geoffrey Earnshaw.
Komarow, Alexander.
Mather, Frank.
Prickett, John Howard.
Richards, Ernest Montgomery, B.Sc.(Eng.).
Sahgal, Amar Chand, B.A., B.Sc.Tech.
Stahl, Henry Cecil.
Taylor, John Russell, B.Sc.
Templeton, William, B.Sc.
Thomas, Horace Augustus, M.Sc.
Uglow, John Curtice, B.Sc.

Student to Associate Member.

Preston, Geoffrey William.
Watkins, Donald John, B.Sc.(Eng.).

Student to Graduate.

Kirsten, Kenneth Haenart, B.Sc.

The following transfers have also been effected by the Council under the provisions of Bye-Laws 14, 15 and 18:—

TRANSFERS.

Graduate to Associate.

Adams, Herbert Leslie.
Ashton, Thomas James.
Atkins, James Walter.
Buckley, John Stanley.
Bulow, Vincent Alfred M.
Butler, John Henry.
Carrott, Herbert Edward.
Cope, William John L.
Durrell, William Henry.
Evans, Alfred Charles.
Galloway, James.
Gough, Howard Butler.
Grant, David Leslie.
Guthrie, Ernest Alfred.
Halliday, Harold Robertson.
Hambleton, Charles Ernest.
Hunter, Thomas Chalmers.
Jackson, Frederick Stanley.
Lash, Alfred Reeves.
Lewis, David.
McPherson, Angus.
Mittra, Binay Kumar.
Mukerjee, Nanigopal.
Patterson, William Herbert.
Pittaway, Kenneth.
Price, Arthur John.
Rac, N. Srinivas.
Sleigh, Charles Crofton.
Smith, John Albert.
Stonehill, David Hareven.
Sundar, Padma Malla.
Tandon, Ch. Parkash Laull.
Tydd, George Allan.
Vogel, Theodore Mathieu.
Wellingham, Herbert John.
Wheeler, Edmund Frank.
Wills, Maurice Alan.

Associate to Graduate.

Black, Richard Henry.
Clark, Ernest Cameron, B.Sc.
McKechnie, Alan Francis.
Phillips, John Douglas N.

Student to Graduate.

Batra, Rajindra Nath.
Beaumont, George Harold.
Bevan, Percy Archibald T.
Bickerstaffe, John, B.Eng.
Brickell, Robert Patrick.
Brockbank, John Bowman.
Brookes, Samuel Ernest.
Brown, James Connell, B.Sc.
Brown, James John.

Student to Graduate—continued.

Brown, William John.
Buchanan, Donald Geoffrey, B.Sc.(Eng.).
Calwell, James Edmonston M., B.E.
Castellan, Guy Edward.
Cheryan, Paruthiparambil B.Sc.(Eng.).
Christy, Geoffrey, B.Sc. (Eng.).
Collins, Wilfred John.
Cowlishaw, Alwyn.
Crofton, Robert Denis, B.Sc.(Eng.).
Daines, Sidney Arthur.
Dannenbaum, Arthur, B.Sc.
De Larue, Serge.
Dingwall, Ronald.
Dransfield, Tom.
Edwards, George William.
Ellwood, Percy.
Emery, Edward Thomas G.
Fielder, Cecil Redvers.
Fielding, Alfred Leslie.
Fitzpayne, Eric Richard L., B.Sc.
Flint, Ernest Frederick.
Gardiner, Stephen Maurice, B.Sc.
Gartside, Arnold.
Goodchild, Ronald Frank.
Gould, Charles Thomas.
Heath, Frederick Ernest.
Heyes, Clifford.
Hocking, Russell Charles, B.Sc.
Hollingsworth, John Edward R.
Horlock, Robert Pasifull, B.Sc.(Eng.).
Humphriss, Eric Allan, B.Sc.(Eng.).
Jephson, Peter Douglas.
Johnstone, Andrew Wauchope, B.Sc.(Eng.).
Jones, Harold Edward.
Just, Ernest James.
Kay, Edward John R., B.Sc.(Eng.).
Kelly, William.
Langley, Arthur Henry, B.Eng.
Laredo, Edward, B.Eng.
Lloyd, John Leslie.
Lusty, Harold Higson.
Marchant, Albert Edward, B.Sc.Tech.
Mare, Arthur John.
Matthey, Henry Albert.
Mildner, Raymond Charles, B.Sc.(Eng.).
Millward, Gerald Richard.
Mittra, Madan Gopal, B.Sc.
Mole, Franklin Henry.
Moore, William Herbert, B.Sc.
Morley, Cyril George L.
Moss, John Lawrence.
Mukerjee, Hemendra Nath.
Murdoch, James Barclay B., B.Sc.
Newton, John Burgess.
Olson, Andrew Hugh, B.Sc. (Eng.).
Page, Thomas Henry D.
Painter, William James A.
Palmer, Edward Barry.
Paterson, Allan, B.Sc.
Pearce, Donald John, B.Sc.
Phillips, John Waldron.
Pilfold, Charles William.
Pratt, Alan Anderson.
Raybould, Sidney.
Robertson, Alan Stuart.
Rose, Victor Reginald.
Rushton, James.
Sainsbury, Frederick Walter J.
Scriven, Vernon Colin.
Sears, Herbert William.
Sims, Robert Frank, B.Sc. (Eng.).
Snelling, Charles Arthur.
Stephens, Maurice Norman B.
Stewart, Ian, B.Sc.
Vickers, Harold Edwin.
Vine, Harry Albert E.
Vyas, Baldevbhai Motiram.
Wadhera, Chaman Lal.
Wallace, Leslie Macquestin, B.Sc.(Eng.).
Walters, Frederick.
Watthews, Herbert Thomas.
Watts, John Lea.
Whitworth, Gerald, B.Sc. (Eng.).
Willard, Leslie Albert.
Williams, Alan Cyril O.
Wilson, Kenneth Ellerby.
Woodroffe, Daniel Norman.
Young, Frederick Joseph, B.Sc.(Eng.).

Associate to Student.

Dinsmore, Harry.
Hall, Percival Henry G.
Hami, Mehemed Behaeddin.
Keay, Edmund McLaren.
Staddon, Edward Charles.

THE HEATING OF BUILDINGS ELECTRICALLY BY MEANS OF THERMAL STORAGE.

By Lieut.-Col. S. E. Monkhouse, R.E. (T.R.), and L. C. Grant, Members.

(*Paper first received* 11*th December*, 1928, *and in final form* 19*th September*, 1929; *read before* The Institution 19*th December*, *before the* North-Eastern Centre 11*th November*, *before the* North-Western Centre 26*th November*, *before the* Mersey and North Wales (Liverpool) Centre 9*th December*, *and before the* North Midland Centre 10*th December*, 1929; *also before the* Scottish Centre 14*th January*, *the* Irish Centre (Dublin) 23*rd January*, *and before the* South Midland Centre 3*rd March*, 1930.)

Summary.

Considerable progress has been made with electrical heating in recent years. The higher cost of electrical energy as compared with the cost of solid or liquid fuels is compensated by the advantages of cleanliness, convenience and efficiency.

The authors advocate the more extended use of electrical heating by adopting thermal storage, thus enabling energy to be used during off-peak hours. They contend that such a system is economical to operate, and they show that, for large buildings, electrical heating can compete with systems employing other forms of fuel.

Introduction.

During the past few years there has been considerable development in the electric heating of buildings, in which radiators and other types of direct heating appliances have played the principal part; but as the energy supplied for such apparatus must be unrestricted and must always be available for use, it follows that the price charged for such supplies is governed largely by the same factors as apply to any ordinary supply of electricity.

Continuous availability necessitates that any such supply must bear its proper proportion of the overhead charges of the power system, and as these are usually largely influenced by the shape of the supply undertaking's load curve and by the load factor of the system, it seems logical to conclude that, for supplies of constant load taken regularly each day but confined to off-peak hours only, there could be an appreciable reduction in the prices charged. It is the main purpose of this paper to describe means whereby advantage may be taken of these conditions, by making use of an off-peak supply for the heating of buildings.

The inherent low load factor and thermal efficiency of steam-driven electricity generating stations necessitate that if heat units from such a source are to be sold at a price which can compete with that of heat units derived from coke or coal burnt in a central heating plant, then full credit must be allowed for the improvement in the load factor of the system which would result from the sale of such units, just in the same way as discrimination is shown in the allocation of capital charges when tariffs are designed for lighting, power and other supplies of widely divergent characters.

Factors Influencing Cost of Current.

The practice of allocating to supplies for power or heating by radiator the same proportion of capital charges as is allocated to a lighting supply, is one which would be discountenanced by most supply engineers, as such a course, if followed, would throttle further development. Similarly, when supplying off-peak load, provided it is taken regularly throughout a certain portion of the year, the overhead charges should be lower for at least three reasons, namely :—

(1) The supply makes use of available power-station and system capacity at a time when it would not otherwise be producing revenue.

(2) The amount of energy consumed by such apparatus is large in relation to the capacity of the apparatus connected.

(3) The night load for heating being regular in character and a known quantity to the supply undertakings, it is possible for them so to arrange the conditions of night operation that a smaller proportion of stand-by plant than usual is retained in use, which in turn results in an improvement of the plant load factor and in the general efficiency.

In spite of the manifest difficulties of supplying current at a competitive price for direct heating, e.g. by the use of radiators and convectors, considerable development has taken place, largely on account of the ease of installation and convenience and cleanliness in operation, but as most electrical methods of heating have similar advantages, irrespective of the size of the installation, it is evident that, with the energy supplied at a cost which should be possible with off-peak thermal storage, considerable developments in electric heating may be expected.

The subject of what should be charged for electricity supplied under these restricted-hour conditions is one on which there will naturally be a great diversity of opinion, as this charge must depend largely upon local conditions, cost of coal, method of production and relationship of generating and system capacity to sales; and the authors feel it to be a matter altogether beyond the scope of this paper.

For these reasons they have refrained from making any definite statement on this subject, being content, in giving data in regard to the cost of operating the electrical equipments they have described, to indicate the maximum cost of current at which it would be economical for the user to adopt electric heating for each scheme, leaving it to the suppliers to decide whether it would be economical to sell energy at a figure which would be competitive with local prices for other forms of fuel.

The authors would like, however, to express the opinion that, if proper allowance be made by the supply undertakings for the appreciable value attached to any load which assists to fill the valleys of the load curve, there should be neither difficulty nor hesitation on their part in quoting prices which would give rise to the extensive adoption of equipments such as those described in this paper.

It is important to recognize that the supply of electrical energy for a heating system means, fundamentally, the supplying of heat units, and it should be borne in mind that it is liable to be compared (perhaps erroneously) by the user, purely on a heat basis when in competition with the fuels generally used, such as oil or coke.

OFF-PEAK STORAGE.

To make use of off-peak supplies a system of storage is necessary, as usually the off-peak hours are the few hours on either side of midnight when the ordinary public services are not generally required.

A cheap and economical method now employed of storing heat from off-peak electrical energy is to heat water during the off-peak hours and to store it in tanks suitably lagged so as to enable them to retain the heat for use when required during the remainder of the 24 hours.

Systems operating upon this principle have the important advantage over systems making use of solid or liquid fuels, that flues and smoke stacks are dispensed with. This, particularly with a new building, is a point of considerable importance, and results in an appreciable saving in the first cost of the building and its subsequent cost of maintenance. It has also an appreciable value in making available, for office or other accommodation, additional space with possibly an increased rental value.

The operation wages costs for electrical installations such as are described in this paper can be eliminated by the adoption of automatic working, while the annual overhaul and renewal charges are almost negligible.

In spite of much propaganda the value of the smokeless city is still but little appreciated in this country. With a better appreciation of the value of a pure atmosphere, the scope of the electrical thermal-storage system of heating should be much enlarged.

STORAGE MEDIA.

Heat can be stored conveniently in many substances, e.g. water, iron and oil. Water has several advantages, not the least important being its relatively low cost compared with that of other storage media.

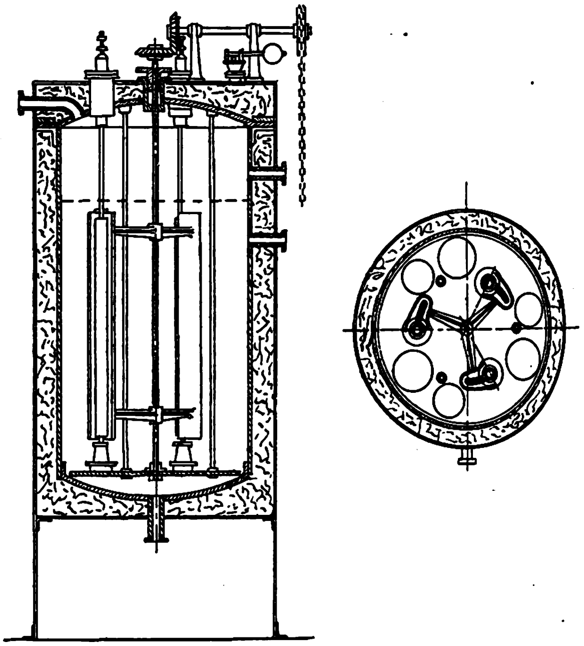

FIG. 1.—Electrode method of direct water-heating.

Water.—The specific heat of water is 1·0 and its specific gravity is also 1·0. It can be loaded under pressure to store heat up to 280° F. without boiling, thus giving a working range of 280° F.-120° F.

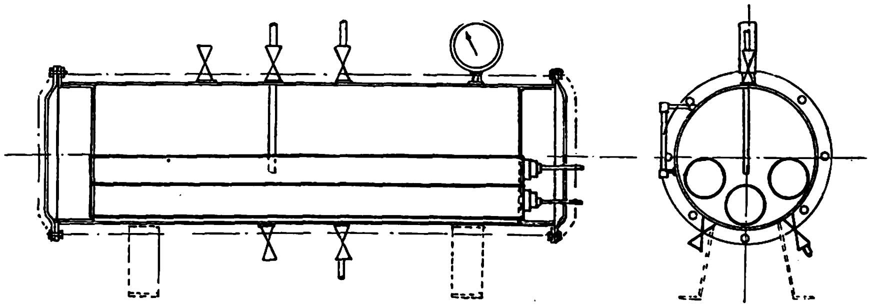

FIG. 2A.—Immersion-heater installation (large).

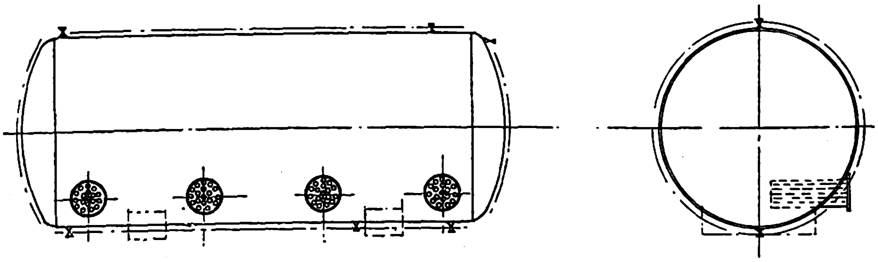

FIG. 2B.—Immersion-heater installation (small).

= 160° deg. F., which enables 160 B.Th.U. per lb. to be stored, or 160 × 62·5 = 10 000 B.Th.U. per cub. ft. The cost of water per 10 000 B.Th.U. stored is about 0·1d. with water at 1s. 4d. per 1 000 gallons.

Iron.—This material has a specific gravity of 7·2, but its specific heat is 0·13. It can be heated to a temperature of about 700° F., but cannot be worked much below 200° F., which gives an available temperature range of 700° F.–200° F. = 500 deg. F., giving 65 B.Th.U. per lb. or 65 × 62·5 × 7·2 = 29 800 B.Th.U. per cub. ft., i.e. considerably more than could be stored in water in a similar space. The heat-flow through iron is, however, such that it is rather difficult to secure the heat distribution desirable, and this, coupled with the fact that at the temperature mentioned the material would be working on the glow point and would necessitate expensive heat insulation, makes it doubtful whether the temperature range mentioned could be maintained economically under working conditions. The cost of iron castings at £14 per ton is approximately 18·8s. per 10 000 B.Th.U. stored.

Oil.—A suitable oil has a specific heat of 0·4 and a specific gravity of 0·92. It can be heated to a maximum temperature of 500° F., the working range thus being 500° F.–120° F. = 380 deg. F., giving 152 B.Th.U. per lb., or 152 × 62·5 × 0·92 = 8 753 B.Th.U. per cub. ft. The capital cost of oil per 10 000 B.Th.U. stored is thus 7·2s. with oil at 1s. per gallon.

Turning then to a consideration of heat storage in water, there are two ways of converting the electrical energy into heat, namely, by means of (*a*) electric water heaters, which are not, strictly speaking, boilers, and (*b*) electric steam boilers in which steam is produced and is subsequently utilized as a medium for transferring the heat to the storage system proper.

Both water heating and steam raising can be accomplished by means of either (*a*) equipment wherein the current is supplied to electrodes immersed in the water into which the current is led and in which heat is produced in proportion to the resistance of the water and to the current passed through it, or (*b*) resistance heaters, wherein the current is used to heat wire-wound or other forms of resistors which in turn heat the water.

Fig. 1 shows diagrammatically the electrode method of direct water-heating and steam-raising, while Figs. 2A and 2B show the resistance method similarly applied.

BOILERS OR WATER HEATERS EMPLOYING ELECTRODES.

In boilers or water heaters of the electrode type the loading of the equipment is determined by the area of electrode and the hardness of the water, care being necessary in the design of the electrodes to ensure that the current density is kept low, in order to avoid internal arcing between electrodes. Commercially pure water, that is, water of less than 1 degree of hardness, when used in an electrode boiler of 1 000 kW capacity passes a current of about 1 or 2 amperes at 6 000 volts. On the other hand, commercial town main water is frequently of 15 to 20 degrees of hardness, which results in something approaching a short-circuit in the boiler. Therefore, the water hardness must be adjusted to approximately 6 to 10 degrees, so as to pass full load at about half electrode immersion.

Various methods of load regulation are made use of. Messrs. Sulzer Brothers use movable deflectors which are hydraulically raised or lowered to the required degree of immersion, while Messrs. Siemens use movable electrodes which are kept at approximately earth potential.

In the Reyrolle electrode boiler, fixed electrodes are used and the load is regulated by varying the rate of feed. This method obviates the necessity for an awkward electric-cum-steam gland and enables the terminals to be completely encased in metal, a particularly important point in a boiler house.

The Oerlikon Co. use fixed electrodes and regulate the load by controlling the water-level in the boiler, but, owing to the variation in storage capacity which would result, this method is practicable only where the boiler is separated from the storage cylinder.

As electrode boilers are frequently of the 3-phase type, care must be taken to avoid phase unbalancing and the consequent neutral or earth current, though trouble from this source can be avoided by careful electrode adjustment.

It is an advantage in favour of the electrode boiler that it can be designed almost equally well for either high or low voltage, but the electrodes for the low-voltage boiler must naturally be correspondingly larger for a given load rating than for the high-voltage pattern, and it is worth noting that the extra electrode area for low-voltage work sometimes necessitates a complicated arrangement of electrodes which tends to increase the cost. It is on this account, therefore, and because of the somewhat greater difficulty of *applying* low-voltage electrode boilers to a low-voltage earthed-neutral system that the resistance heater method is frequently preferred when only a low-voltage supply is available (because the resistance heaters are completely insulated from earth and consequently avoid the formation of a short-circuit through earth to the network neutral).

RESISTANCE HEATERS.

These usually embody the storage cylinder and " boiler " in one unit, and the storage system usually takes the form of a horizontal drum with the resistance heaters placed along a horizontal axis.

In order to obtain the best circulation, the heaters should be fixed at a low level in the cylinder, as the water should be put into circulation in order to obtain an even temperature throughout the cylinder. If this were not done, there would be a temperature gradient throughout the water at the time of greatest storage, and this would result in a loss of heat-storage capacity.

With the object of improving the heat distribution in the cylinder it has on some occasions been considered an advantage to place some of the heating elements at different levels throughout the storage cylinder, or, as an alternative, to accelerate the circulation by means of a pump during the water-heating period so as to ensure a good circulation and an even temperature throughout the storage cylinder.

For medium-sized and large installations heater units are mounted in groups each of which has a capacity of about 50 kW. Heaters so arranged can be conveniently operated by means of thermostats and contactors so that the load taken during the water-heating period can be automatically controlled.

ATMOSPHERIC TEMPERATURE RANGE OF STORAGE CYLINDER.

The storage of heat in water depends upon the weight of water and the temperature attained, and as the atmospheric temperature of the water stored must not exceed atmospheric boiling point the upper temperature limit under these conditions is fixed at about 210° F. "Panel" heating installations require a normal circulating temperature of 120° F., therefore for such duty the temperature range is fixed at 210° F.–120° F. = 90 deg. F., and accordingly under atmospheric pressure 90 B.Th.U. can be stored per lb. of water. (Radiator systems generally require a higher circulating temperature.)

Storage under Pressure.—The heat storage for a given space can, however, be considerably increased by putting the storage cylinder under pressure, and a pressure of the order of 60 lb. per sq. in. (corresponding to 138 ft. of height) is often obtainable in modern buildings. It can be simply applied by mounting a small tank on the top of the building and piping it to the storage cylinder, thus stabilizing the head and consequently the boiling point, but it is advisable to keep the upper temperature limit rather below the boiling point, otherwise trouble with water vapour and steam formation may be experienced.

The boiling point at a pressure of 60 lb. per sq. in. is 292° F., so that the upper limit of temperature can be made as high as 285° F., the available temperature range thus becoming 285° F.–120° F. = 165 deg. F., or an increase of 75 × 100/90 = 83 per cent over that available at atmospheric pressure.

Large installations are now working in this country at atmospheric pressure and at higher pressures, actual examples of the latter being 30, 50 and 70 lb. per sq. in. Some of the smaller plants have been arranged to work at atmospheric pressure in order to avoid complication or because of the lack of a convenient method of obtaining the required head.

Heat Loss during Storage.—It is essential that efficient lagging should be used in order that the daily heat loss from the storage cylinder should not be excessive. A good commercial lagging of about 2 in. thickness is capable of limiting the heat loss to about 40 B.Th.U. per sq. ft. per hour with a temperature gradient of 145 deg. F. With carbonate of magnesia of 6 in. thickness, the loss can be reduced to about 15 B.Th.U. per hour and it is possible to reduce this loss to 5 B.Th.U. per hour if a heavier lagging be applied. About 12 to 15 B.Th.U. radiation per sq. ft. per hour seems to be the most economical figure for the majority of installations, taking a reasonable balance between the cost of lagging material and the cost of the B.Th.U. radiated.

There appears to be need for further development in laggings; the following table shows that the usual plastic boiler covering could be improved upon, particularly for low temperatures, by the adoption of some other form of heat insulation, although the first three materials shown in the table are considerably more expensive for a given weight. Cellular metallic laggings are promising in some respects.

*Relative Value of Heat-Insulating Materials.**

Material	Relative heat-insulating value, with wool felt = 1·0
Loose wool	3·35
Lampblack	1·12
Cotton (corded)	1·0
Fossil meal	0·7
Carbonate of magnesia ..	0·7
Paper	0·5 to 0·7
Cork	0·7
Sawdust	0·65
Loam	0·55
Asbestos paper	0·47
Air space	0·14 to 0·22
Sand	0·17

* From *Machinery* "Handbook."

ARRANGEMENT OF APPARATUS.

Combined Storage and Heater System.—The combined arrangement usually consists of one or more cylinders fitted with immersion heaters either of the withdrawable pattern or otherwise, the cylinder or cylinders being fitted with flanges for the circulating pipes, the filling and emptying pipes, the pressure tank and vent pipes, and also with thermometer and thermostat pockets. The circulating system is coupled to the top of the cylinder. A constant proportion of hot water is drawn off and added to the water in the circulating system, while an equal amount of cold water is returned from the circulating system to the cylinder, the relative proportions of water re-circulated and that drawn from the storage cylinder being regulated by means of suitably placed valves. In small installations these valves are sometimes arranged for hand control, but in large installations it is desirable to adopt servo-motor operated valves which are controlled automatically by a thermostat in the main flow pipe.

Thermo-siphon circulation can be used if great simplicity is of importance, but with automatic mixing a small pump has advantages and the cost is usually offset by the reduction which can be effected in the diameter of the pipework (see Fig. 3).

Separate Unit Scheme.—This arrangement, which makes use of a heater separate from the storage system, usually means that a steam-raising boiler will have advantages over a water heater, on account of its greater flexibility in operation. The use of such a boiler necessitates the introduction of a calorifier bank between the boiler and storage system.

The calorifier generally takes the form of a cast-iron drum tubed from end to end after the manner of a surface condenser, with a steam space outside the tubes. The steam from the boilers is passed into the outer space between the tubes, while through the latter the water from the storage cylinder is pumped and so warmed by contact with the steam-heated tubes. During this process the steam becomes condensed and passes from the calorifier through a trap system, thence to a feed or make-up tank to be re-pumped to the boiler.

A pressure-retaining valve is necessary between the boiler and the calorifier in order to control the steam flow; otherwise, if the boilers were connected direct to the calorifiers, excessive condensation would occur in these, priming would be set up in the boilers, and generally the system would become unstable in operation. The pressure-retaining valve may be worked by actual difference in pressure or by setting it for a minimum boiler pressure. Another method which may sometimes have advantages is to control the valve by an electric link so arranged that the steam output and electrical input just balance.

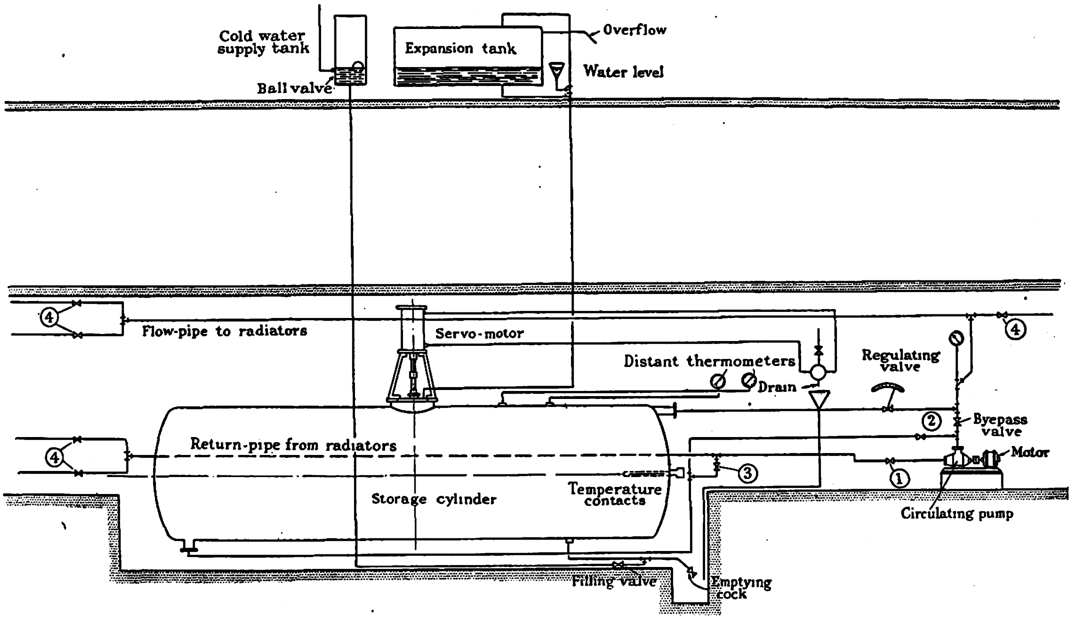

FIG. 3.—Pipe lay-out of electrode water-heater system.

ARRANGEMENT OF APPARATUS IN PRACTICE.

A description of some of the installations now in operation may be of interest and will show how the size of building, the location of apparatus and other considerations influence the general form of the heating installation.

Banca Commerciale Italiana di Roma.—In Italy, a large electro-thermal heating system was installed some 6 years ago at the Banca Commerciale Italiana di Roma, a building which occupies a ground area of 28 500 sq. ft. and has a total volume of 1 175 000 cub. ft. This installation, which was probably the first of its size and type in the world, consists of four Mascarini single-phase, 50-cycle boilers working at 450 volts. Current is taken during the period from 11 p.m. to 7 a.m., and the consumption during the first winter of operation was 0·08 watt-hour per cub. ft. per deg. F. rise in temperature. The cost of a set of 3 single-phase boilers suitable for this installation is about £1 200, plus £400 for one single-phase boiler to act as a stand-by.

Newcastle Motor Depot.—This plant, which was installed early in the year 1925, is believed to be the first of its kind to be used in Great Britain, and consists of a combined storage cylinder and " boiler," the latter being of the electrode type fed at 6 000 volts direct from a 40-cycle, 3-phase system. The normal load current is 20 amperes (equivalent to a load of approximately 200 kW), and the cylinder, which is under atmospheric pressure only, has a water-storage capacity of 6 000 gallons, giving a thermal-storage capacity of about 6 million B.Th.U. of useful heat.

The building has a capacity of 500 000 cub. ft. and is a difficult one to deal with from a heating point of view, because there are five large doors, each measuring 13 ft. by 10 ft., in frequent use, and a motor-driven ventilation system which is used to clear the building of carbon monoxide. Heat is supplied to the building continuously day and night for 7 days per week and about 8 months per annum. The building absorbs 210 000 kWh per annum, current being consumed only between the hours of 7 p.m. and 7 a.m.

There are no labour charges incurred in running this plant, as the only labour involved is the daily operation of closing the high-tension switch, which is opened automatically when the required amount of heat has been added to the storage cylinder.

Maintenance is practically negligible, as it consists only of opening the cylinder manhole once per annum for the ordinary annual inspection. It is expected that even this small item of cost will be reduced, as it would appear from the inspections already carried out that there is little object in having them so frequently.

The only other item of maintenance cost so far incurred has been the replacement of electrodes, and although one new set has been fitted as a precaution it was observed that only slight wear had taken place and the replacement was not really necessary.*

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* For statement of costs see Appendix 1.

Carliol House Installation.

Heating System.—The authors believe that this installation is the largest of its kind in use in the world.

Separate boilers and storage cylinders are used with intermediate calorifiers. There are two 3-phase boilers each capable of dissipating approximately 1 200 kW at full load, and these are supplied with current at 6 000 volts from a 3-phase, 40-cycle system, each boiler taking approximately 120 amperes per phase.

The boilers deliver steam at 55 lb. per sq. in., the steam production being controlled by an electric regulating-valve system which balances the water input against the electrical input, in addition to which there is a pressure-retaining valve which maintains a fixed steam pressure on the boilers and opens only to pass steam to the calorifiers when the pressure exceeds this value.

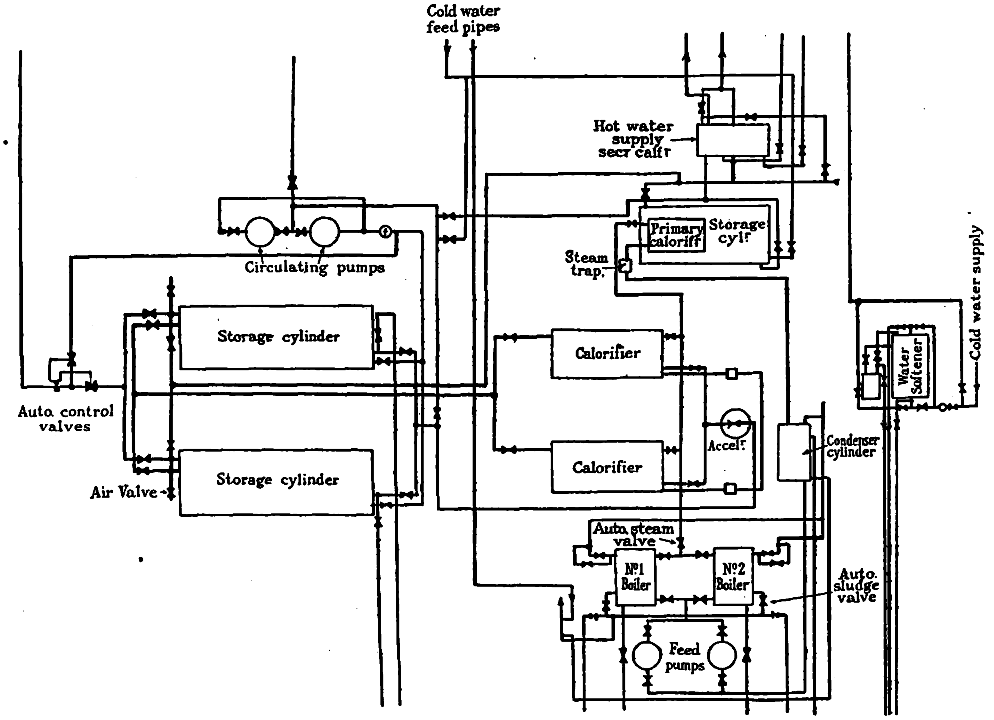

FIG. 4.—Skeleton pipework diagram of Carliol House installation.

The calorifiers, of which there are two, so arranged that either or both can be used in conjunction with each of the boilers, are each capable of handling an average steam output equivalent to 650 kW dissipation and, as already described, are somewhat similar to surface condensers in arrangement. The steam passes over a series of tubes, the water from the storage cylinders being pumped through these tubes and so warmed by contact with them, the steam and condensate being passed through traps to the feed tank and returned to the boilers.

All the water in the boiler-calorifier-feedtank circuit is initially passed through a softener and reduced in hardness from about 16 degrees to approximately 8 degrees, thus enabling the water-level in the boilers to be adjusted to about one-half or three-quarters water gauge at full load.

It has been found that there is a tendency for the hardness of the water in the boiler system to fluctuate, but this condition is satisfactorily compensated by the provision of a trickling draw-off valve which takes water from a predetermined level. Thus if the water tends to become harder, water is drawn from near the boiler bottom, while a tendency to soften is corrected by drawing off from a higher level. The heat loss involved in this process is so small as to be almost negligible. Even this small loss is further reduced, as the hot water is passed through a simple form of tubular feed-heater on its way to the drains—a precaution which also meets any local by-law that may be opposed to the passing of hot water into the town's drains. The cost of the water thus run off is negligible.

The two storage cylinders each measure 34 ft. in length and 9 ft. 6 in. in diameter, and enclose a total water volume of approximately 4 800 cub. ft. or 30 000 gallons under a pressure of 48 lb. per sq. in. Hence at storage temperature (i.e. 230° F.) there are contained in this volume of water approximately 60 million B.Th.U., of which about 50 million are available for ordinary use, the balance representing the heat first expended in raising the temperature of the town main water from 50° F. to 100° F.

Panel Heating System.—The system of radiators installed in the building is of the panel type. Each panel consists of a grid of $\frac{1}{2}$ in. internal diameter mild steel tubing sunk into the concrete ceilings and covered with a thin layer of high-grade plaster supported on scrim cloth. The normal dissipation of each panel is

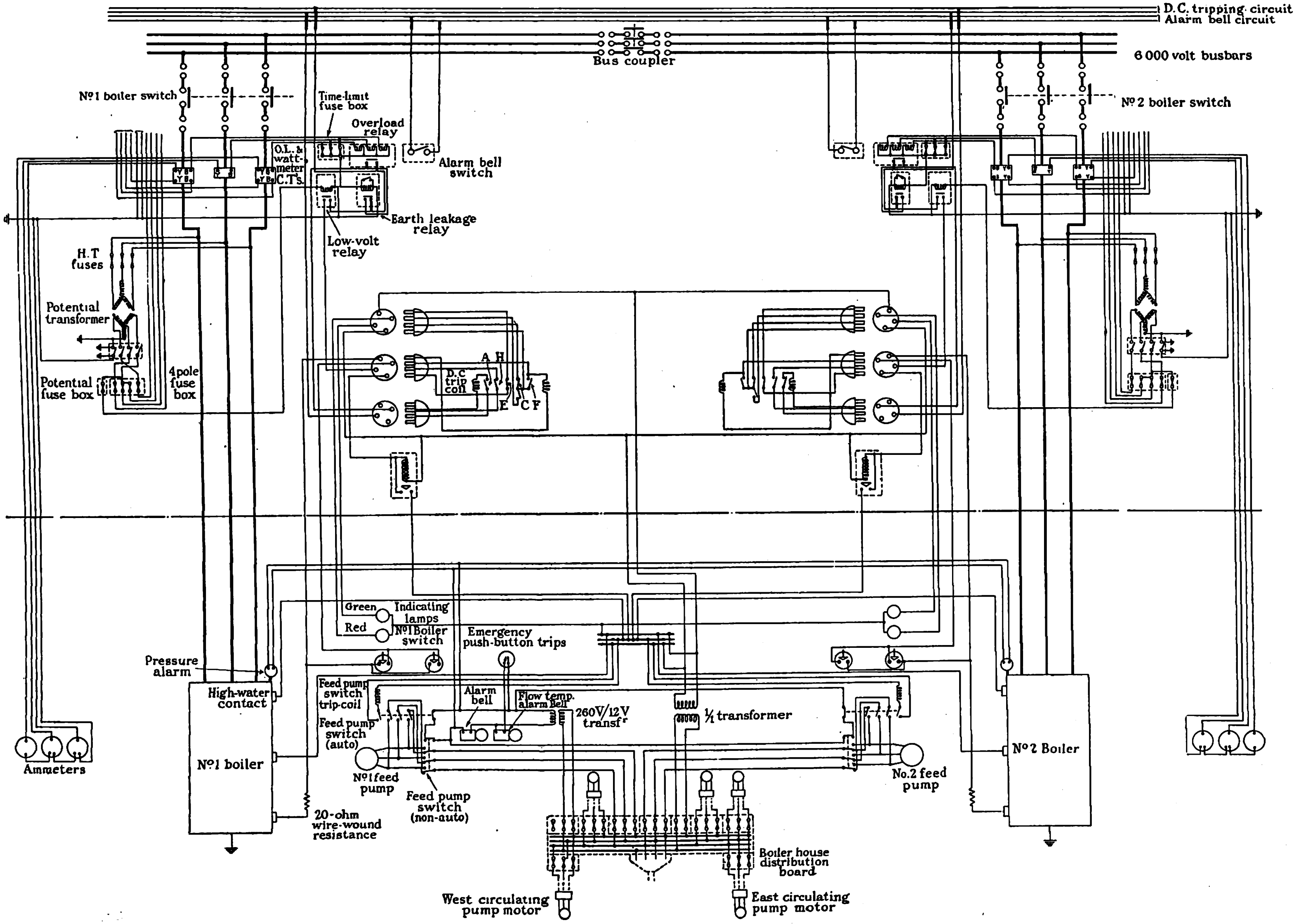
D.C. tripping circuit
Alarm bell circuit
6 000 volt busbars
Bus coupler
Nº1 boiler switch
Nº2 boiler switch
Time-limit fuse box
Overload relay
Alarm bell switch
O.L. & watt-meter C.T's.
Earth leakage relay
Low-volt relay
H.T fuses
Potential transformer
Potential fuse box
4 pole fuse box
D.C trip coil
A
H
E
C
F
Green
Red
Indicating lamps
Nº1 Boiler switch
Emergency push-button trips
Pressure alarm
High-water contact
Nº1 boiler
Ammeters
Feed pump switch trip-coil
Feed pump switch (auto)
Alarm bell
Flow temp. alarm Bell
260V/12V transfʳ
½ transformer
Nº1 feed pump
Feed pump switch (non-auto)
20-ohm wire-wound resistance
No.2 feed pump
Nº2 Boiler
Boiler house distribution board
West circulating pump motor
East circulating pump motor

FIG. 5.—Skeleton diagram of electrical connections of Carliol House installation.

about 8 000 B.Th.U. per hour, those on the north side of the building having a slightly greater pipe length and panel surface than those on the south.

Temperature Regulation.—The temperature of the water supplying the central heating system is regulated automatically by means of a relay valve system hydraulically operated and controlled by means of a thermostat in the main hot-water flow pipe, so adjusted as to maintain a normal circulating temperature of 110° F. to 120° F., which corresponds to a temperature of 63° F. at all points throughout the building, under all weather conditions. The arrangements are such that the temperature of the circulating water can be raised to 130° F. for quick heating or emergency conditions.

Consumption.—The building as so far erected is incomplete, but that portion which is in use and has been occupied for two heating seasons has an approximate content of 1¾ million cub. ft., and is therefore of such a size that any data so far obtained may be taken as being representative of the figures that will apply when the building is complete.

During the last complete heating period, which was of great severity, the building required an average daily input of 5 300 kWh, i.e. 18 million B.Th.U. The average outside temperature during this period was 44·3° F., and the air in the building was maintained at a temperature of 63° F.

The electrical consumption per office of 2 000 cub. ft. capacity (i.e. suitable for accommodating three or four persons, including its proportion of corridors, entrance hall, staircases, landings, lavatories, etc.) was 46 kWh per week, which at 0·3d. per kWh represents a weekly cost of about 1s. 1d.

The consumption of current in all cases was confined to the period 7 p.m. to 7 a.m.

On the question of maintenance charges there is little to be said. Beyond opening out the boilers for annual inspection, which occupies two days, the only expenditure that has been incurred has been the provision of one set of electrodes at a cost of £5. Fig. 4 shows a skeleton lay-out diagram of the system, while Fig. 5 shows the electrical connections.

Hot-water Service System.—In addition to the central heating system there is a separate storage cylinder of 1 000 cub. ft. capacity, working under a pressure of 48 lb. per sq. in., to supply the domestic hot-water requirements of the building.

This cylinder has a total heat-storage capacity of 15 million B.Th.U., of which approximately 11 million are available for use. This cylinder derives its heat from the boiler main steam-range, but it differs from the other storage cylinders in that it is fitted with a calorifier forming an integral part of it, the calorifier nevertheless being so designed as to be interchangeable with the two calorifiers of the main heating system.

The water in the storage cylinder is connected by means of a closed system to a secondary calorifier through which town main water is drawn and heated to a constant temperature before being passed to the building. There is, therefore, no draw-off from the storage system.

OTHER INSTALLATIONS.

A Newcastle-upon-Tyne Block of Offices and Showrooms.—This consists of a new building comprising a block of offices and showrooms, the cubical contents being 300 000 cub. ft.

The storage installation is arranged as a single unit and consists of a combined storage cylinder and water-heating equipment. The cylinder is 20 ft. long and 8 ft. diameter, and contains 6 600 gallons of water under a pressure of 30 lb. per sq. in., thus storing 7 million B.Th.U. of useful heat.

The electrical heating elements are of sufficient capacity to heat the whole volume of storage water under conditions of heaviest load, in addition to heating the building direct during the storage cylinder heating-period, and are of the wound resistance type formed into a bank of four heaters, each with a full-load rating of 50 kW. Thus the maximum electrical load is 200 kW. The resistor units are so connected as to be suitable for 500-volt working and are controlled in banks by means of a time switch and thermostat, the former switching on and the latter switching off.

The temperature of the water circulated through the building is regulated automatically in much the same way as in the Carliol House plant.

London Underground Railways Offices.—In some respects this installation, which has to heat a building of 2¼ million cub. ft., requiring 8 000 kWh per day (average) heating, is different from those so far described, the principal difference being that the plant is required to work on short charging cycles instead of continuously throughout the usual nightly off-peak period. The supply in this instance is available for use at any time other than the 4-hour morning peak and the 4-hour evening peak of the traction load of the Underground system, hence a smaller storage system than usual is installed.

There are four storage cylinders each 10 ft. high and 9 ft. in diameter. Each cylinder is fitted with three 100-kW 3-phase immersion heaters operating at 380 volts, being fed through transformers from the 11 000-volt distribution system. The cylinders are arranged to work under a pressure of 50 lb. per sq. in. and are capable together of storing some 20 million B.Th.U. of useful heat.

CAPITAL COST.

Capital cost has an important bearing upon the extent to which electricity will be used for central heating systems in the future, for it is evident that if a comparison on a heat basis shows electricity at a disadvantage, the electrical scheme must be able to claim credit on other counts if its use is to be extended.

The saving in the cost of building by the avoidance of flues, stacks, etc., is clearly in its favour, just in the same way as the saving in labour and maintenance charges may be set against the actual extra cost of electrical heat production; but although these items of cost are to be placed on the credit side of the balance sheet there are instances where the balance remains in favour of the scheme making use of solid fuel.

The saving effected by the avoidance of flues and chimney stack, and the value of the extra space that becomes available, are appreciable in the case of larger buildings, an interesting example of this being a building where the owners allowed £2 000 as the value of the stack and flues and calculated the value of their increased rent roll to be £300 to £400.

APPENDIX 1.

Newcastle Motor Depot.

	Coke	Electric
Capital charges.		
	£	£ s. d.
Additional cost of electric scheme as compared with that of coke-fired scheme (£350)	—	—
Less amount saved in building due to absence of flues (£80), leaving net extra cost of £270	—	270 0 0
Running costs.		
Coke (estimated).		
Fuel—90 tons at 27s. ..	121	—
Capital and depreciation charges on additional cost, at 11 per cent ..	—	29 14 0
Labour and ash removal (estimated)	130	—
Estimated additional maintenance of coke plant ..	40	—
Electricity.		
216 000 kWh at 0·3d. ..	—	270 0 0
Total ..	£291	£299 14 0

APPENDIX 2.

Carliol House Plant.

	Coke	Electric
Capital charges.		
	£	
Cost of whole scheme, including domestic hot-water apparatus	3 600	5 600
Estimated annual charges (normal winter).		
Energy—1 100 000 kWh at 0·3d.	—	1 375
Fuel—500 tons coke at 26s...	650	—
Interest on plant at 6 per cent	216	330
Depreciation fund on boiler-house plant:		
Coke—10 years at 7·95 per cent per annum ..	286	—
Electric—20 years at 3·02 per cent per annum ..	—	169
Maintenance and renewals ..	150	30
Attendance	550	—
Ash removal	30	—
Total ..	£1 882	£1 904

Notes: (*a*) These figures do not include the saving on flues and chimneys, which would have cost approximately £2 000.

(*b*) The capital cost of the electrical installation is high, for the reason that in this case duplication of plant is complete.

(*c*) At the present time, certain labour charges are incurred with the electrical equipment. These will shortly be eliminated when the complete automatic apparatus has been installed.

[The discussion on this paper will be found on page 676.]

THE HEAT PUMP—AN ECONOMICAL METHOD OF PRODUCING LOW-GRADE HEAT FROM ELECTRICITY.

By T. G. N. HALDANE, M.A., Associate Member.

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SUMMARY.

The paper deals with a method—which so far has not received the attention of engineers—of converting electrical energy into heat energy. The method is based on the general principle that the efficiency of the heat engine working in the normal cycle is given by $(T_1 - T_2)/T_1$, where T_1 is the high temperature and T_2 the low, and that the heating efficiency of a reversed-cycle heat engine is given by $T_1/(T_1 - T_2)$. The reversed-cycle heat engine (or heat pump) is described, and it is shown both from theoretical considerations and from practical tests on refrigerating plant that where heat at a comparatively low temperature is required, heating efficiencies of the order of from 300 to 500 per cent or even more may be obtained, the heating efficiency being defined as the ratio of the heat produced by the heat pump to the heat equivalent of the electrical energy consumed.

The application of this principle to the heating of buildings and for such purposes as the heating of public baths is discussed, and estimated figures for a public-bath installation are given. The paper concludes with a description of experiments which the author has been carrying out during the past 2 years, and which have demonstrated the soundness of the general principles on which the heat pump is based.

ELECTRICITY AS A HEATING AGENT.

Electrical energy and mechanical energy are readily interchangeable, and it is due to the ease, simplicity and efficiency of this convertibility, combined with the high efficiency of transmission, that the great developments in the electrical supply industry have taken place. Like mechanical energy, electrical energy can also be converted very easily into heat energy, and wherever there is a flow of electrical energy this process is always present to a greater or lesser extent. With properly designed plant, such, for instance, as the electrode boiler, the conversion of electricity into stored heat energy can be carried out with an efficiency closely approaching 100 per cent. Although the processes of conversion of electrical and mechanical energy into heat energy are simple and efficient, the reverse processes can only be carried out with a much lower efficiency; i.e. we cannot utilize the stored heat energy to drive a steam engine and dynamo so as to produce as much electrical energy as was originally put into the boiler. Such a process always involves the rejection of a large proportion of the heat energy in the form of warm condensing water or exhaust steam. Even in the most efficient power stations where the similar process of conversion of the heat energy of coal into electrical energy is effected under the best possible conditions, the highest thermal efficiencies at present attained do not exceed about 25 per cent, and are generally lower. It is necessary, therefore, to burn at least 4 lb. of coal in the power station in order to produce the thermal equivalent of 1 lb. of coal in the form of electrical energy. The consequence of this elementary fact is that the cost per British thermal unit (B.Th.U.) of electrical energy produced from fuel is generally high compared with that of coal and, in most cases, of gas. For many purposes this high cost does not prevent the direct use of electricity as a heating agent, particularly where simplicity of operation, exactitude of control and cleanliness are of primary importance. The same is true where radiant heat or very high temperatures are essential, and in all these fields the electrical industry has already to a large and increasing extent captured the market.

Where heat has to be supplied at ordinary temperatures and in large quantities, and where extreme exactitude of regulation or ease of operation is not essential, it is a much more difficult matter to justify the use of electricity. To a large extent this difficulty has been met by the cheap supply of electricity during the off-peak periods when power can be supplied at the bare operating costs, but even so this cost necessarily includes the cost of burning at least 4 lb. of coal for every 1 lb. equivalent in the form of electrical energy, and unless coal can be obtained at a much cheaper price by the power station than by the consumer, e.g. where low-grade coal can be used by the power station but not by the consumer, the economic difficulties are apt to be considerable. When coal is consumed in hot-water boilers, between 50 and 80 per cent of the total thermal content of the coal can, under favourable conditions, be extracted, the exact percentage depending on the size of the boiler. In actual operation under practical conditions the percentage is generally much lower but would exceed the figure of 25 per cent applying to electrical energy. In the case of gas the process of manufacture involves the loss of some 20 per cent of the calorific value of the coal and when, for instance, gas is consumed for the production of hot water the efficiency of conversion is probably of the order of from 60 to 80 per cent. Thus the overall efficiency of heat supplied through the medium of gas is about 50 to 65 per cent.

ECONOMY OF INDIRECT CONVERSION OF ELECTRICAL ENERGY INTO HEAT ENERGY.

Because of these facts many people, including some electrical engineers, are of the opinion that electrical energy can never be used economically for producing large quantities of heat under ordinary conditions. Such opinions are, of course, based on the assumption that the consumption of 1 kWh can at the best produce about 3 400 B.Th.U. It may therefore come as a surprise to many electrical engineers to learn that this assumption is by no means justified. It is, in fact, possible to produce a very much larger number of B.Th.U. by the consumption of this amount of electrical energy, provided it is converted first into mechanical energy and then used on the Carnot principle to pump heat from a low to a higher temperature. The theoretical justification of this statement follows directly from the principles embodied in the Carnot cycle. Carnot showed in 1824, and Kelvin and others made more explicit at a later date, that if we imagine a perfect reversible heat engine operating by taking heat from a source at a high temperature T_1 and rejecting it at a lower temperature T_2, so producing mechanical energy, the efficiency, i.e. the ratio of the mechanical work produced to the mechanical equivalent of the heat taken in, is $(T_1 - T_2)/T_1$. Carnot showed also that this is the greatest possible efficiency for any type of heat engine working between these temperature-limits. It is, of course, on this fundamental principle that the design of power stations is based, though no power station yet built has ever attained the efficiency which Carnot showed to be theoretically possible. However, he was not concerned with the practical difficulties of designing a perfect heat engine, but rightly argued that because such a machine was conceivable the theoretical consequences which he deduced must necessarily be true.

If we imagine the Carnot engine reversed—that is to say, supplied with mechanical energy and made to pump heat from a low to a higher temperature—the heating efficiency [*] is $T_1/(T_1 - T_2)$. It can therefore be seen that if $(T_1 - T_2)$ be small compared with T_1, a small amount of mechanical work supplied will allow a very much larger amount of heat to be pumped from the one source to the other. In practice the source of the low-temperature heat T_2 would normally be the unlimited heat of the surroundings.

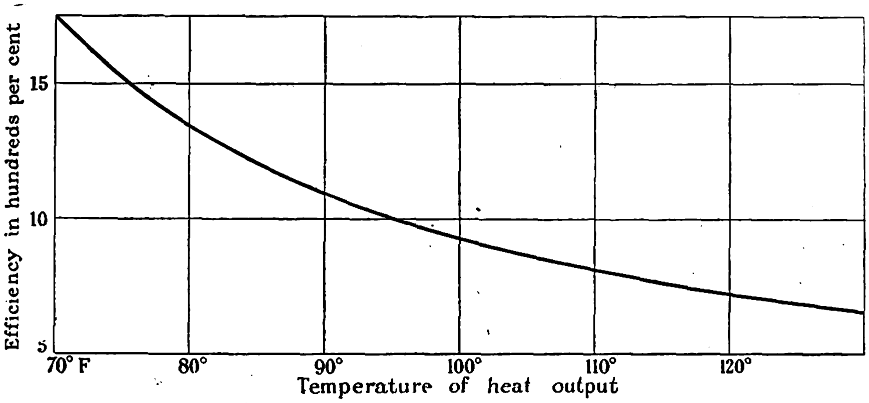

Fig. 1.—Theoretical heating efficiency of heat pump, taking in heat at 40° F.

Fig. 1 shows the heating efficiency theoretically obtainable from the perfect reversed heat engine for such ranges of temperature as might normally be required. It will be seen from the curve that if heat is delivered at 100° F. (560° abs.) and taken in from the atmosphere at 40° F. (500° abs.) the efficiency is 9·33, i.e. 560/(560 — 500). That is to say, for every B.Th.U. of electrical energy put into the heat pump 9·33 B.Th.U. will be delivered at a temperature of 100° F., and as each B.Th.U. of electrical energy may have required the consumption of some 5 B.Th.U. at the power station, the remarkable fact is revealed that it is at least theoretically possible for the consumer of the electrical energy produced at the generating station to obtain very considerably more heat than was required to produce the electrical energy which he consumes. In other words there is an economy in fuel consumption as compared with direct conversion if the fuel is first consumed in a power station, converted into electrical energy and then used to produce heat by means of a heat pump.

In the above example the economy is $(9 \cdot 33 - 5)/9 \cdot 33 = 46 \cdot 5$ per cent, but it must be noted that this economy only exists if the heat required is comparatively low-grade, i.e. low-temperature heat. The economy becomes greater as the temperature range is decreased, and reaches a very high value indeed when the range of temperature through which the heat is to be pumped is only a few degrees. The general principle of the above process was first pointed out by Lord Kelvin in 1852, and a description will be found in his "Collected Papers," vol. 1, p. 515.

OPERATION OF HEAT PUMP.

The reversible heat engine has so far been treated simply as a heat pump, and it is now desirable to describe its operation in more detail. The most familiar type of heat pump is the refrigerator. In the design of refrigerating plant the primary object is the production of cold rather than heat, but the two operations are, of course, complementary. The process of producing cold is simply that of pumping heat from a relatively cold to a relatively hot source, but in this process particular attention is paid to the prevention of the leakage of heat into the cold source, whereas no attempt is made to prevent the escape of heat from the hot source; in fact it is of assistance to the refrigerating process that the heat removed from the cold source should be allowed to escape in every possible way. If a refrigerating plant were to be treated as a heat pump in which the primary product is the heat rejected to the hot source, the order of importance would be reversed and every opportunity would be given for the leakage of heat into the cold source and every precaution taken to prevent leakage of heat from the hot source. Apart from this and minor differences in the temperature ranges over which the plant would work, a refrigerator is precisely the type of heat pump which, for the purposes of this paper, it is desired to consider.

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[*] In what follows the term "heating efficiency" as applied to the heat pump denotes the ratio, measured in hundreds per cent, of the heat produced to the heat equivalent of the electrical energy supplied. Although this is not the true efficiency from a thermodynamic point of view it is the efficiency from the standpoint of this paper, i.e. the production of heat by the consumption of electrical energy.

REFRIGERATING PLANT.

Refrigerating plant is divided broadly into two classes. The first of these is the absorption type of refrigerator, in which the refrigerating process takes place generally without the application of mechanical work. The simplest form of absorption machine is that in which a volatile liquid is allowed to evaporate, so cooling its surroundings, and is then removed by passing into solution in some suitable liquid. This process can only be made continuous either by a continuous supply of the volatile liquid or by some process whereby the solvent in the solution is driven off and the volatile liquid so returned to its original state. It is not proposed to consider this type of refrigerator at any length because it is necessarily a comparatively inefficient process owing to the fact that, in general, as much heat has to be supplied to evaporate the solvent as is absorbed by the volatile liquid during the process of evaporation.

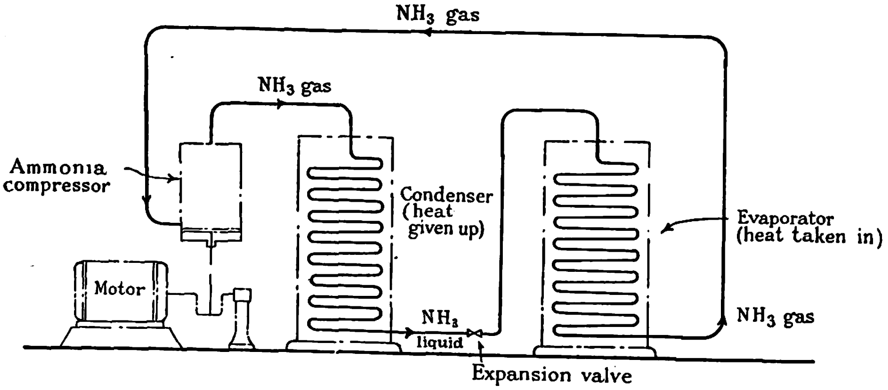

FIG. 2.

The second type of refrigerator is that in which a gas is subjected to a continuous cycle of compression and expansion by means of a compressor. During the process of expansion, heat is taken in from the cold source, and during the process of compression heat is given up to the hot source. This type of refrigerator corresponds to the perfect reversible heat engine of the Carnot cycle. The compression type of refrigerator can be made much less bulky, and consequently more efficient, if a condensable gas is employed so as to absorb heat during the process of evaporation and to deliver heat during the process of condensation. Such a gas is used in all modern types of compression machine; those most commonly employed are ammonia, carbon dioxide and sulphur dioxide, and of these three ammonia is generally recognized as being on the whole most suitable for large installations on land. Carbon dioxide is frequently used for marine plant, but owing to its low critical temperature it would not be suitable for use with a heat pump working at comparatively high condensing temperatures.

Fig. 2 shows the general arrangement of a compression type of heat pump. It will be seen that the plant consists of four essential parts:—

(1) The electric motor,
(2) The compressor,
(3) The evaporator, and
(4) The condenser.

The cycle of operations is as follows. The compressor sucks in gas from the evaporator and compresses it to a pressure corresponding to a saturation temperature slightly higher than that of the required heat. From the compressor the compressed gas passes to the condenser where it is cooled and condensed, so giving up a large quantity of heat to the water or other substance which it is desired to heat. The condensed gas then passes through the expansion valve, where a sudden reduction of pressure takes place. This reduction of pressure lowers the boiling point of the liquid, which therefore vaporizes and takes in heat from the medium surrounding the evaporator. After evaporation the gas passes on to the compressor and the cycle is completed.

It will be noted that the above process differs from that of the ideal heat engine of the Carnot cycle because there is no expansion cylinder, and therefore no use is made of the work available during the expansion from the condenser pressure to the evaporator pressure. The loss due to this cause is, however, comparatively small, and the prevention of this loss would not compensate for the complication of an expansion cylinder.

COMPARISON OF THEORETICAL AND ACTUAL HEAT-PUMP EFFICIENCIES.

It is now necessary to consider the effect of the losses which must inevitably occur in practice in plant of this type. These losses are due mainly to two causes, the first being the inefficiency of the electric motor and the second the inefficiency of the compressor. In addition to these and various other minor sources of loss, there is a loss of efficiency due to the differences of temperature which must necessarily exist between the hot condensing gas and the water being heated, and between the cold evaporating liquid and the source from which heat is being drawn. This temperature difference involves operating the plant for a range of temperature somewhat greater than that through which the heat is actually pumped, but the difference can be kept comparatively small by using an evaporator and condenser with as large a surface area as possible.

In large installations of, say, 100 kW it is quite possible to obtain an efficiency of at least 90 per cent in the electric motor and about 80 per cent in the compressor, so giving an overall efficiency of over 70 per cent. Other losses, such as absence of expansion cylinder, gas friction, heat leakage, etc., may be assumed in a large installation to amount to an additional loss of not more than 15 per cent. Thus the heating efficiencies which could actually be obtained would be at least 55 per cent of the ideal heating efficiencies shown in Fig. 1. Assuming that in cold weather the evaporation temperature is 20° F., the curve of reduced efficiencies which may be expected in such circumstances is shown by the dotted curve in Fig 3.

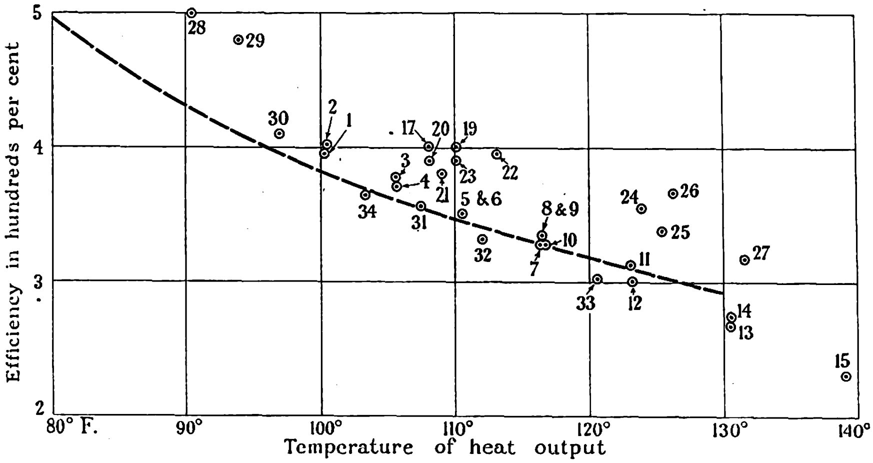

Fig. 3.—Heating efficiencies obtainable in practice, assuming 20° F. evaporation temperature.

Numbered points refer to the actual test results given in Table 1. Dotted curve shows estimated efficiency obtainable in practice.

Efficiencies Obtained in Actual Test.

To the best of the author's knowledge no detailed experiments other than those carried out by him, which will be described later, have ever been made on a refrigerator used primarily as a heat pump. There have, however, been many detailed tests carried out on refrigerating plant from which the desired heating efficiency can be obtained. With this object in view the author has analysed some such detailed experiments carried out on refrigerating plant. Owing to the fact that in refrigerating plant no attempt is made to lag either the hot pipe coming from the compressor or the shell of the condenser, the heating efficiencies tend to be slightly lower than those which would be obtained in practice with a machine designed primarily as a heat pump. Table 1 shows the results of an analysis of a number of accurate and detailed tests on refrigerating plant. The results are also expressed in this table as a percentage of the ideal heating efficiency. It will be seen that the evaporating temperatures are considerably lower than those which would normally occur in a heat pump extracting heat from the atmosphere, and in order to reduce the results to a comparable basis they have been plotted in Fig. 3 according to the range of temperature shown in Table 1, and for an assumed evaporation temperature of 20° F. Although this method of interpolating the results is not strictly accurate, the error involved is very slight, and has the effect of slightly reducing the true heating efficiencies. All the test results are plotted in Fig. 3 except No. 16, which lies outside the range of temperature shown. It will be seen both from Table 1 and Fig. 3 that the estimated efficiencies shown by the dotted curve in Fig. 3 are conservative, particularly when it is remembered that the machines tested were designed to produce cold rather than heat.

The evaporation temperature of 20° F. has been chosen because, assuming that heat is taken in from external sources, this temperature represents what would normally be the lowest evaporation temperature required during the winter months in this country. For the greater part of the winter the evaporation temperature could be considerably higher and the heating efficiency correspondingly greater.

Application of Heat Pump to Central Heating of Buildings.

The circumstances under which the heat-pump system can be applied most favourably to the central heating of buildings are:—

(*a*) Where the heating system in the building is designed to operate at a comparatively low temperature (e.g. panel heating);

(*b*) Where there is available a large supply of water for the evaporator (e.g. a building near a river or canal).

As regards condition (*a*) the temperature of the hot water supplied from the heat-pump system would, with a suitable size of condenser, be equal to, or only a few degrees lower than, the condensing temperature of the gas, particularly as the latter is normally superheated after compression and is therefore at a temperature considerably above the condensing temperature. Where condition (*b*) obtains, the evaporation temperature would normally be considerably higher than the assumed 20° F. and the heating efficiency therefore much greater than that shown in Fig. 3. When condition (*b*) does not hold it is possible to use an air-heated evaporator, but the size and cost of the evaporator would, in general, be considerably increased.

Fig. 4 shows an arrangement which might be adopted for heating a large building by means of a heat pump. In this arrangement the evaporator would be supplied with cold water which would be further cooled before being discharged. The hot water for the radiator system would be circulated through the condenser, where heat would be received from the condensing ammonia.

TABLE 1.

Summary of Tests.

Particulars of test	Test No. (see Fig. 3)	Evaporating temperature	Condensing temperature	Range	Actual heating efficiency	Ideal Carnot heating efficiency	Actual efficiency as percentage of ideal efficiency
		deg. F.	deg. F.	deg. F.			per cent
L. H. Jenks, New York, 1926 * (kW of machine, 110–130)	1	+ 5·3	85·6	80·3	3·95	6·81	58
	2	+ 5·3	85·8	80·5	4·02	6·80	59·2
	3	+ 5·3	90·9	85·6	3·78	6·44	58·8
	4	+ 5·3	91·0	85·7	3·72	6·44	57·9
	5	+ 5·3	95·8	90·5	3·51	6·15	57·1
	6	+ 5·3	95·8	90·5	3·51	6·15	57·1
	7	+ 5·3	101·7	96·4	3·28	5·84	56·2
	8	+ 5·3	101·8	96·5	3·35	5·83	57·5
	9	+ 5·3	101·5	96·6	3·35	5·81	57·6
	10	+ 5·16	101·9	96·7	3·28	5·81	56·5
	11	− 1·1	101·9	103·0	3·13	5·45	57·5
	12	− 1·2	101·9	103·1	3·07	5·45	56·4
	13	− 8·6	101·9	110·5	2·68	5·09	52·8
	14	− 8·6	101·9	110·5	2·75	5·09	54·1
	15	− 17·18	101·9	119·1	2·31	4·71	49·0
	16	− 27·9	101·9	129·9	1·99	4·34	45·9
Eastman Kodak tests, 1908 † (kW of machine, 40–80)	17	+ 6·6	95·4	88·8	4·04	6·26	64·4
	18	+ 6·2	96·4	90·2	—	6·17	—
	19	+ 6·0	96·3	90·3	4·04	6·16	65·5
	20	+ 6·5	95·4	88·9	3·90	6·26	62·1
	21	+ 6·3	95·5	89·2	3·82	6·24	61·4
	22	+ 3·4	96·6	93·2	3·97	5·98	66·4
	23	+ 6·5	96·8	90·3	3·91	6·17	63·4
G. A. Horne, Merchants Refrigerating Co., New York, 1922 ‡ (kW of machine, 300–350)	24	− 11·0	92·9	103·9	3·55	5·33	66·7
	25	− 12·21	93·2	105·4	3·385	5·24	64·7
	26	− 11·5	94·7	106·2	3·67	5·21	70·4
	27	− 22·9	88·7	111·6	3·18	4·91	64·6
Denton tests, 1891 § (kW of machine, 45–70)	28	+ 14	84·5	70·5	5·0	7·71	64·9
	29	+ 14	88	74	4·80	7·40	64·9
	30	− 11	66	77	4·10	6·84	60·0
	31	− 5	82·5	87·5	3·47	6·20	56·0
	32	− 8	84	92	3·32	5·90	56·4
	33	− 22	78·5	100·5	3·02	5·35	56·5
Fry's factory, Bristol ‖ (kW of machine, 49)	34	+ 2·5	85·8	83·3	3·65	6·58	55·6

* See *Refrigerating Engineer*, March, 1926.

† See *York Manufacturing Co. Bulletin*, No. 40.

‡ See *Ice and Refrigeration*, January, 1929.

§ See *Transactions of the American Society of Mechanical Engineers*, 1892, vol. 22, p. 336.

‖ See *Proceedings of the British Association of Refrigeration*, 1927, vol. 23, p. 33.

An alternative method of using the heat pump for heating large buildings, and one very well adapted to the characteristics of the heat pump, would be to supply heat directly to air blown into the building through a series of ducts. This air would be heated by passing over the hot condenser coils and the exhaust air would be sucked out by a fan and passed over the evaporator coils, where it would give up its heat before being passed out of the building. With this system it would probably be possible to work at lower temperatures than those assumed for the panel-heating hot-water system, with a corresponding gain in heating efficiency.

COOLING OF BUILDINGS IN SUMMER.

In Fig. 4 an arrangement of cross-over connections is shown which would enable the system to be reversed and the building cooled in hot weather. Such cooling could, however, be effected more easily with the air-duct system suggested in the last paragraph. Although in this country the periods during which it might be desirable to cool a building are comparatively short, there is no doubt that the possibility of such cooling would be a valuable asset. Any refrigeration which might be required if, for instance, the building were a large hotel could be supplied very simply.

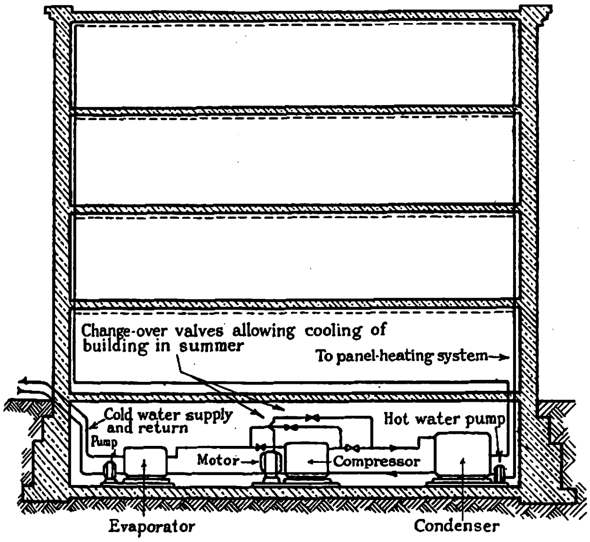
Change-over valves allowing cooling of building in summer
To panel-heating system
Cold water supply and return
Pump
Hot water pump
Motor
Compressor
Evaporator
Condenser

FIG. 4.

PANEL-HEATING SYSTEM.

In applying the heat pump to the central heating of buildings it is desirable to operate with as low a temperature as possible in the radiator system, and therefore the modern panel-heating system is peculiarly adapted for this purpose because it can be operated at a considerably lower temperature than that of the ordinary radiator system. The panel-heating system can, in fact, be operated with water supplied at temperatures between 110 and 120° F. or possibly, with an increased amount of panel pipe, at temperatures even lower than this.

COMPARISON OF HEAT-PUMP AND THERMAL-STORAGE SYSTEMS.

In connection with the suggested use of the heat pump for heating installations it is interesting to note that Carliol House, the new headquarters of the Newcastle-upon-Tyne Electric Supply Co. and one of the largest buildings in the North of England, is being heated by means of an electric thermal-storage system. In this case the water for the central heating system is heated electrically during the off-peak hours when electricity can be supplied at very low cost. Although a similar heat-pump installation would not obtain power entirely during off-peak hours, it would not be difficult to avoid running the plant during the worst hour of peak load, so obtaining a supply of power at a comparatively low cost for this reason. With heating efficiencies of between 3 and 4, which might be obtained in practice with the heat pump, the cost per 3 400 B.Th.U. would be considerably less than the cost of a unit of electricity taken during off-peak hours. If, for instance, the cost of electricity taken during off-peak hours for the thermal-storage system were 0·25d. per unit, and the corresponding cost of the heat-pump plant 0·5d. per unit, the cost of 3 412 B.Th.U. supplied by the heat pump would be between 0·167d. and 0·125d., a reduction of from 30 to 50 per cent.

PRODUCTION OF ICE.

In comparing the heat-pump plant with other methods of central heating, allowance should be made for the possibility in certain cases of combining the heating function of the heat pump with the production of ice on a commercial scale. The demand for ice in summer is rapidly growing, and therefore the introduction of a freezing tank into the lay-out would admit of very profitable use being made of the plant during the summer months when the more usual forms of heating apparatus are lying idle. In this way a large proportion of the capital charges of the installation might be paid.

SWIMMING-BATH HEATING.

The heating of large buildings is not, of course, the only purpose for which the heat pump can be used, nor is it the purpose for which it can be employed with the greatest advantage. As has already been pointed out, the heating efficiency increases rapidly as the temperature difference between the heat taken in and the heat given out decreases. An ideal application is therefore to be found either where water at comparatively low temperatures is required or where it is necessary to transfer heat through a small range of temperature from waste water to clean water. The most obvious case of this sort is the heating of swimming baths. Water for swimming baths is required normally at a temperature of between 70 and 80° F., and this range of temperature is easily within that of the condensing water of the ordinary refrigerator. Consequently, not only would an extremely high heating efficiency be obtained in the heating of swimming baths, but an ordinary type of refrigerating plant could be used for this purpose with practically no modifications. It will be seen from Fig. 3 that a heating efficiency of over 5 can be obtained, assuming that heat is taken in from air at 20° F. The efficiency can, however, be increased very considerably if, instead of absorbing heat from the air, heat is taken in from the water discharged from the swimming bath. Under such conditions the heat pump is simply transferring heat from the outgoing water to the incoming clean water, and after making the necessary allowance for the thermal heads in both evaporator and condenser it is probable that a heating efficiency of about 7 could be obtained.

In many swimming-bath installations it is, however, usual to install a comparatively elaborate system of filters so as to avoid the cost of heating up the fresh cold water from the supply mains. A heat-pump installation could be run either with or without the filter system. In the latter case the capital and operating

TABLE 2.

Comparison of Costs of Coal-fired and Heat-Pump Installations for Public Baths.

Coal-fired		Electric	
	(a) Particulars of installation.		
Number of boilers	3	Number of machines	1
Average efficiency	30 per cent	Size of motor	100 kW
Consumption of coal for swimming bath	2 tons per week	Stand-by immersion heaters	150 kW*
		Size of hot-water storage tank	2 000 gals.
Consumption of coal for slipper baths	8 tons per week	Size of waste-water storage tank	2 000 gals.
Total coal consumption	10 tons per week	Heat supplied to swimming bath	2 300 000 B.Th.U. per day
Heat supplied to swimming bath	2 300 000 B.Th.U. per day	Average heating efficiency	5
Heat supplied to slipper baths and laundry	9 220 000 B.Th.U. per day	Energy consumed	135 kWh
		Heat supplied to slipper baths and laundry	9 220 000 B.Th.U. per day
Calorific value of coal	12 000 B.Th.U. per lb.	Average heating efficiency	4·5
Cost of coal	£1·75 per ton	Energy consumed	600 kWh
Temperature of swimming bath	74° F.	Energy consumed for steam and scalding water, say	100 kWh
Temperature of slipper baths	100° F.		
Staff employed:		Total energy per day	835 kWh
Mechanic	1	Cost of energy	0·5d. per kWh
Stokers	3	Staff employed:	
		Mechanic	1
		Assistant	1
	(b) Capital cost.		
Cost of boilers (3 at £300)	£900	Cost of heat-pump installation	£2 000
Cost of flues, brickwork and chimney	£750	Cost of piping	£250
Cost of piping, etc.	£250	Cost of storage tanks	£200
		Cost of stand-by immersion heaters*	£250
Total capital cost	£1 900	Total capital cost	£2 700
	(c) Annual charges.		
10 tons of coal per week at £1·75 per ton	£910 per annum	835 kWh per day at 0·5d. per kWh	£635 per annum
Wages (1 skilled mechanic, 3 stokers)	£716 per annum	Wages (1 skilled mechanic, 1 assistant)	£387 per annum
Total operating charges	£1 626	Total operating charges	£1 022
Capital charges on £1 900 at 9 per cent	£171	Capital charges on £2 700 at 9 per cent	£243
Repairs and maintenance	£25	Repairs and maintenance	£25
Total annual charges	£1 822	Total annual charges	£1 290

Saving with heat-pump installation: £532 per annum, or 30 per cent.

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* This figure assumes that the stand-by heaters could, if necessary, operate throughout the whole 24 hours, whereas the heat pump would normally run for some 7 hours per day.

costs of the filter system would be avoided and absolutely clean water, instead of partially clean filtered water, supplied to the swimming bath. It is probable, however, that in general it would remain cheaper, as in the case of coal-fired installations, to use a filter. Most swimming baths are run in conjunction with slipper baths and it is therefore possible, by means of the heat pump, to utilize the waste warm water coming from the slipper baths for supplying the heat required to maintain the swimming bath at its proper temperature. Under such circumstances the heating efficiencies obtainable would be high.

In order to examine the economics of the electrical heating of public baths, a balance sheet has been prepared, based as far as possible on particulars obtained of the annual cost of one of the large London public baths. This is shown in Table 2.

The scheme on which Table 2 is based is shown diagrammatically in Fig. 5. In order to provide a stand-by to the heat-pump installation, allowance is made for the installation of 150 kW of immersion heaters. The comparison assumes that a filtration system is used both with the coal-fired and with the electrical systems, and the heat supplied to the swimming bath is therefore only that required to balance the losses due to radiation and conduction. In the electrical system the waste water from the slipper baths is passed through the evaporator of the heat pump, and thus the bulk of the heat in this water, which would otherwise be lost, is saved. The net annual saving (after allowing for capital charges) amounts to £532 per annum, or approximately 30 per cent of the total annual cost with a coal-fired system.

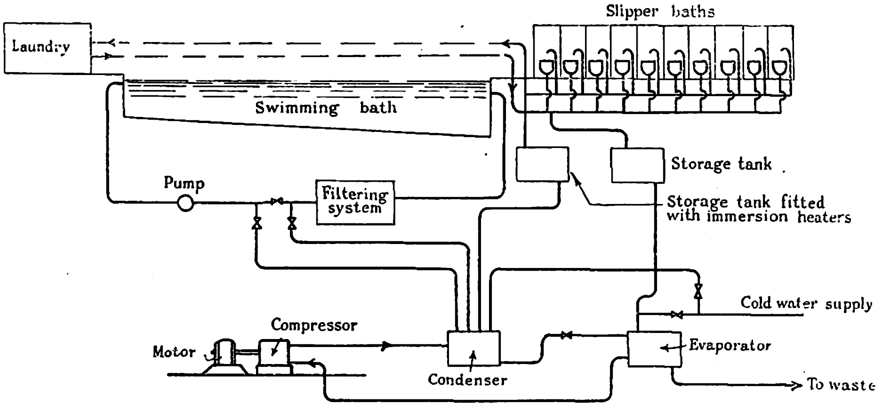

FIG. 5.—Electrical heating of public baths by means of heat-pump system.

EXPERIMENTAL HEAT-PUMP INSTALLATION.

Reference has already been made to experiments which the author has made on a heat-pump installation. After some preliminary experiments had been carried out in London, a small heat pump was installed in the author's home in Scotland and was used for operating the central heating system and for the production of a supply of hot water for domestic purposes. The arrangement of the apparatus is shown in Fig. 6, and it will be noticed that heat can be drawn either from the outside air or from a supply of cold water from the mains, or from both sources together. The compressor employed is a small ammonia machine manufactured for ordinary refrigerating purposes, and the supply of electric power (unfortunately somewhat limited in amount) is obtained from a hydro-electric installation which also supplies the cooking and lighting requirements of the house and the power and lighting on two neighbouring farms. The water from the central heating system is circulated, by means of a small centrifugal pump, through the tank forming the condenser and hence through the house. A simple and reliable automatic device is fitted whereby the motor driving the compressor is switched off if the pressure rises above a certain figure, and with this precaution there is no difficulty in allowing the compressor to run unattended for prolonged periods. Connected to the central heating system is a large storage tank which can act as a by-pass to the central heating system and so allow the hot water to be stored for domestic purposes without operating the central heating system. During the winter the plant has been used both to supply the domestic hot water and for the central heating system; during the summer it has been run only at night and used to give a supply of hot water for domestic purposes and also a supply of ice. The latter is formed in the evaporator tank, on the surface of the coils immersed therein.

In warm weather it is unnecessary to run water through the evaporator tank because sufficient heat can be taken in by the coils exposed to the air, but in cold weather the supply of heat taken from the air is augmented by heat taken in from cold water flowing through the evaporator tank. Difficulty has occasionally been experienced owing to the formation of so much ice round the coils in the evaporator tank that the flow of heat from the water to the coils is impeded. This difficulty has not been sufficiently serious to necessitate any alteration in the arrangement, but it could no doubt be overcome by forcing the water to circulate more vigorously in the evaporator tank.

As has already been mentioned, the compressor used is a small one intended for ordinary refrigeration work and is not suited for operation at high pressures and temperatures, and it has therefore been desirable to operate the central heating system at the lowest possible temperature. The minimum temperature depends, of course, on the amount of radiator surface in the house, and as in this case the available surface is fairly considerable it is possible to dispose of the heat inside the house without raising the temperature of the radiators to more than about 100° F. The supply of water for domestic purposes requires to be at a temperature somewhat higher than this, and the extra 20 or 30 degrees of temperature required is given by "topping up" the domestic supply by means of an immersion heater. The water in the main during the winter is normally at a temperature of about 40° F. and, since the heat pump raises it to about 100° F. and the immersion heaters a further 30 deg. F., two-thirds of the heating is done by the heat pump and one-third by the immersion heaters.

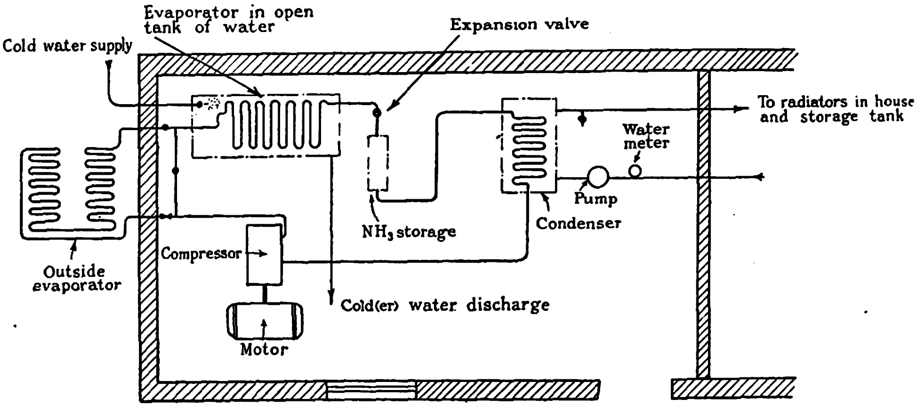

FIG. 6.—Experimental plant installed in author's home.

Repeated measurements of the heating efficiency of the plant have been taken over a prolonged period, and the efficiency curve is shown in Fig. 7. As might be expected with a small machine of this sort, the heating efficiencies obtained are considerably lower than those which have been obtained on large refrigerating plant such as those referred to in Table 1; and, as might also be expected with a small machine which is not intended to work at high pressures, the efficiency falls off considerably as the condensing temperature increases. The greater part of the reduction in heating efficiency is due to the comparatively low mechanical efficiency of the compressor and the comparatively low electrical efficiency of the motor. The maximum load of the motor is about 5 kW, and the input to the motor when the compressor is running light (i.e. not pumping) is slightly over 2 kW, thus giving an overall mechanical efficiency of rather less than 60 per cent. This compares with the overall mechanical efficiency of about 80 per cent which is obtained on larger machines, and consequently, quite apart from other sources of increased loss in so small a machine, such as valve leakage, increased radiation losses and gas friction losses, etc., the heating efficiencies for this small type of machine are about 25 per cent less than those which would be obtained on large machines.

The measurement of these heating efficiencies was carried out in two ways. In the earlier experiments the water coming from the condenser, instead of passing into the central heating system, was run to waste. Simultaneous readings were taken of the electrical input to the motor, the quantity of water run to waste, and the temperatures. Although the heating efficiency can be measured in this way with reasonable accuracy if careful readings are taken over a prolonged period, the method is somewhat laborious, and it has been found much easier to measure the quantity of water passing from the condenser by means of an accurate water meter fitted on the central heating system. The incoming and outgoing temperatures of the water from the condenser are measured by thermometers fitted in thermometer pockets on the inlet and outlet pipes, and the quantity of water flowing is recorded over a prolonged period; this gives, accurately, the average rate at which heat is being supplied to the circulating water.

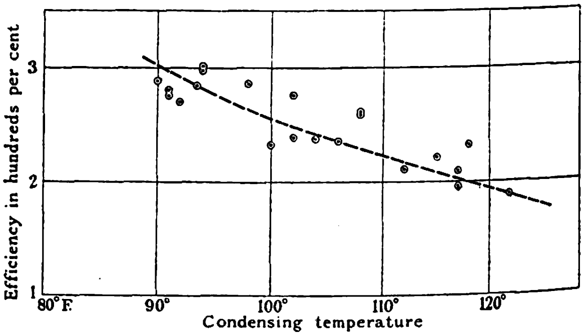

FIG. 7.—Test results on experimental heat-pump installation. Evaporating temperature 20° F.

One of the main objects in installing this experimental plant was to obtain information as to the general convenience of operation of such apparatus, and in many respects the information obtained on these points has been of more interest than the data relating to the operating efficiency. Generally speaking, the author's experience is that the plant is extremely simple to operate and requires very little attention. Compared with any coal-fired central heating apparatus, the heat pump has the very great advantage that it can be started up in a few seconds and can be shut down by the operation of an ordinary electric light switch. The adjustment of the expansion valve was found to be the only operation involving some care. This, however, has been obviated by means of an automatic expansion valve which keeps the pressure in the evaporator constant at any required value. A little difficulty has been experienced with regard to noise, but the running of the machine is audible only in the two rooms immediately adjacent: these rooms are separated by only a single brick partition. The noise has not been sufficient to necessitate any alterations to the partition walls.

CONCLUSION.

In conclusion it is advisable to point out that the author does not suggest that the heat pump is always the most economical method of heating buildings. The object of this paper is to draw attention to its possibilities in order that where conditions are favourable this method of utilizing electrical energy for heating may be used. It is probable that the heating of swimming baths is the most suitable field for the immediate application of the system.

The author's most grateful thanks are due to all those who have assisted him in the experimental work and in the collection of data for this paper. In particular he would like to acknowledge his indebtedness to Mr. L. Chew, of Messrs. L. Sterne and Co., who has taken an active part in the whole of the work, and without whose co-operation the experimental work could not have been carried out.

[The discussion on this paper will be found on page 676.]

DISCUSSION ON THE PAPERS BY MESSRS. MONKHOUSE AND GRANT (SEE PAGE 657) AND MR. HALDANE (SEE PAGE 666).*

DISCUSSION BEFORE THE INSTITUTION, 19TH DECEMBER, 1929.

Dr. S. Z. de Ferranti: All the more obvious uses of electricity have been applied on a very large scale. Lighting was naturally the first thing that brought big-power electricity into prominence. The various applications of power were obvious and have been adopted to a very great extent. Chemical processes provided another direction in which the use of electricity was advantageous; heat at high temperatures again was obviously to be obtained by electrical means. The use of electricity for providing low-grade heat was, however, quite a different matter, and for long was not considered at all, or regarded as quite out of the question. I think that, notwithstanding its present enormous applications, the opportunities for electricity in the production of comparatively low-grade heat are very great. To produce one heat unit, by electricity, at the very best nearly 4 heat units have to be used in the way of combustible at present. As time goes on, no doubt there will be revolutionary improvements in the economical conversion of electricity to heat. Everything that is done in that direction will make what has been described to-day all the more practical and all the more economical. The transmission of electricity, an expensive item, will undoubtedly be more economically effected as the amount of electric power and the length of time for which it is in use, increase. Capital charges in the production of electricity, which form a big item of expense, will undoubtedly decrease as time goes on. Now, all these things tend to show that the arguments which have been used to-day for the electrical production of low-grade heat are sound, and that such production will be more advantageous and more economical in the future. I consider that we are very indebted, as an Institution and as an industry, to the three authors for the papers which they have presented, because they give us a great deal of information and food for thought on this very vital question of the use of electricity for low-grade heating.

Messrs. Monkhouse and Grant's paper, which really deals with the use of electricity at off-peak times for heating purposes, is of the greatest importance. Some time ago, Prof. Parker Smith read a paper on his all-electric house in Glasgow. At the meeting in London I spent some time in endeavouring to stress the importance of storage. I said I felt that the immediate future of the development of electricity depended enormously upon storage, and that I could not say enough to impress the general importance of this on members. One of the electrical journals took me very severely to task for speaking at far too great a length on the subject. They said I spoke too long in proportion to the importance of the subject. Now, if I talked for the rest of my life I should feel I had not talked enough to emphasize the importance to the electrical industry of this question of storing the electricity produced. In electrical work we have not the advantage of the gasholder, which the gas industry has. We cannot store the article itself commercially. In accumulators we store the chemical product of the electrical energy. This is costly and has many limitations. Fortunately, however, in hot water we have perhaps the easiest and most economical means of storing a large amount of electrical energy, and it will be, I feel, by the use of this or some similar method that the very great electrical developments of the near future will be possible. I have had personal experience of this question of the storage of the product of electricity for household purposes, because at the beginning of 1924 I planned an installation for my home in Derbyshire, in which a 6-ton water tank, very well insulated, was installed in the basement; the heating was effected by means of ceiling panels in all the principal rooms, and there was a separate general supply of hot water for baths and washing throughout the house. At the same time a considerable amount of constructional work was done in the house to make the scheme possible. The panel-heating system is much more suitable to a new building than to one which has been already completed; the house, during the process of installing the panel heating, was considerably damaged, but the final result was excellent. The panel system of heating lends itself particularly to the use of low-grade heat. The house was not at that time connected to a public electricity supply, and we therefore had to use an oil engine to generate the electrical energy. A portion of the heating of the water in the storage boilers was done by means of the surplus current, because we had arrangements always to run the plant at full load. Advantage was taken of the presence of the oil engine to do the remainder of the heating from the exhaust of the engine and the jacket water of the cylinder. Since that time we have had the great advantage of being connected to a public supply. The engine and dynamo have disappeared, and the whole of the heating is done direct by the current from the mains. Incidentally, though it does not have a very great bearing on the subject under discussion, I may state that the principal reason for changing over from the oil engine to the public supply from the mains was to save dirtying the house and gardens by the exhaust from the oil engine. It is apparently impossible to burn oil in any form without having some greasy soot as a result. Undoubtedly this is the case where it is burned under boilers, but even with a semi-Diesel engine working under the most advantageous conditions, and where every care is taken, there is still the greasy smoke to contend with, and I have heard of installations in towns which could not be continued because of this trouble. Certainly we found the exhaust from the engine a most serious handicap and were very pleased to change over to the completely electric system. We installed a very simple automatic valve made in a single unit and controlled by a thermostat for regulating the amount of water drawn from the hot store and passed into the circulating system. This, of course, took into the heat store at the bottom of the cylinder a corresponding amount of cooler water out of the storage system. The valve, with the rest of the installation, was put to work in the autumn of 1924, and we have never known since then that we had an apparatus regulating the heat supply; it has been uniformly satisfactory during the whole period, as in fact has been the whole installation.

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* Messrs. MONKHOUSE and GRANT's paper was read before The Institution, the North-Eastern Centre, the North-Western Centre, the Mersey and North Wales (Liverpool) Centre, the North Midland Centre, the Scottish Centre, the Irish Centre (Dublin), and the South Midland Centre, and Mr. HALDANE's paper before The Institution, the Hampshire Sub-Centre, and the South Midland Centre.

Mr. Haldane's paper starts off by stating that so far the heat pump has not received the attention of engineers. I think that the heat pump, or the reversed heat engine, has received a great deal of attention from engineers. It has not been worked out in practice because it has not been found to be sufficiently attractive or, as in my case, because there usually seemed to be a more attractive alternative. More than 20 years ago I was keenly interested in the reversed heat engine and did a great deal of work in connection with it. From time to time at short intervals since then I have reconsidered it to see whether it could be taken up commercially. I think the very greatest credit is due to Mr. Haldane for having been bold enough and persistent enough to take up such a subject as this and to work on it as he has done. If it has been so apparently unattractive to many engineers from the commercial point of view, it means that whoever steps in, at whatever period, and does useful work on the subject has conferred a very great benefit on the community. I knew Lord Kelvin rather intimately a great many years ago owing to my connection with him over early alternator patents, and discussed many problems with him. The reversed heat engine happened to be one of the subjects about which we talked. Later on, but more than 20 years ago, the late Prof. Perry was very keen on the question of the reversed heat engine. I am sure that, had circumstances permitted, he would have liked to have taken it up and would have worked on it with his usual energy. An assistant of his, who later became an assistant of mine, frequently discussed this matter with me and we made various plans for carrying it out, but, as I have said, it did not seem to me quite as attractive as other things in which we were very deeply immersed and over which we were working so hard that there did not seem to be a margin of time for anything else, and this is my excuse for not having worked on the problem more thoroughly in those bygone days. Mr. Haldane, who has not been put off by anything, has gone straight to the point and has made a trial installation, which though small is exceedingly interesting. He has given us and the world the result of his experience on this most important and interesting subject.

Mr. D. Betts : The first point to which I propose to refer in the paper by Messrs. Monkhouse and Grant is in connection with the use of the electrode boiler on high-tension circuits. When I first investigated this proposal on the Continent I was very surprised to find that the Swiss and others had no hesitation in connecting these electrode-type heaters or boilers, whether for steam-raising or merely for water-heating, to 15 000-V, or 10 000-V, or 6 000-V, 3-phase networks, without considering the question of the earthing of the neutral point. When the proposal to use this system for a rather large installation was made in London some four years ago, the first difficulty which confronted us was that the supply authority would not agree to have a boiler connected direct to its high-tension network. They insisted that we must use a 1 : 1 transformer with high voltages, so as to avoid earthing the neutral point of their system. The objection to the use of these boilers in such cases has in certain instances been removed because the supply, though of high voltage (6 000 V), is not direct from the generating station busbars. There are, however, a number of instances in which several of these high-voltage boilers are connected to a network supplied directly from generating station busbars. That is a practice which years ago would not have been countenanced, and I should like the authors to give a little further information as to what is the general opinion amongst station engineers as to the wisdom of the course. The other point to which I shall refer is this. The authors exhibited a lantern slide on which the relative heat values of coke, gas, oil and electricity were shown, and the ratio between coke (taking its efficiency as 50 per cent) and electricity (taking its efficiency as 100 per cent) was, I think, 35 to 13½. That is a ratio which is calculated on the assumption that the same quantity of heat will be required to warm a building, whether the heat is supplied by burning coke or other fuel under a boiler, or whether the heat is supplied by using electricity and thermal storage. The experience of heating engineers, however, shows that the great flexibility of control which is obtainable by the use of electricity enables a very considerable economy to be effected in the actual amount of heat required to maintain comfortable conditions in a building. A stoker, however skilful, who is firing a coke or coal-fired boiler finds it quite impossible to follow, and in fact is probably not aware of, the variations in the demand for heat which take place from time to time during the day. They may be due, for example, to variations in weather conditions, to the individual preferences of the occupants of the various rooms, or to the loss of heat resulting from the opening and shutting of doors and windows. His efforts, if he makes any, to keep his boilers at a steady temperature merely result in averaging out these variations and in the loss of considerable heat up the chimney. But with the thermostatic plant heated electrically, the amount of electricity which has to be supplied during the off-peak period is exactly proportional to the amount of heat withdrawn from storage during the day; and if, as a result of carefully designed control-apparatus, the amount of heat which is taken from that storage is reduced, there will be a corresponding reduction in the electricity consumption. Thermostatic control of the temperature in the storages and of the temperature of the water supplied to the circulating system is quite easy and is applied in practically every installation, but a very great economy can be obtained by applying thermostatic control to the rooms themselves. A recent experiment on a quite extensive panel-heating installation, with thermostatically controlled valves on the panels themselves, shows that this has resulted in extraordinary economy in the amount of heat used in the system. It is not an electrically-heated system; it is fired from a large anthracite boiler, but the economy which has resulted can be ascribed only to the fact that variations in the heat requirements of each of the rooms are promptly reflected in the amount of heat which is actually supplied to those rooms. Now, if a calculation is made of the price at which electricity must be supplied in order to compete, on the basis of heat-supply, with coke, it will be found that the figure works out at about 0·1d. That is to say, in the case of an installation where it is assumed that the same quantity of heat will be required whether coke or electricity is used, electricity would have to be supplied at 0·1d. if the electricity bill were to be equal to the coke bill, with coke at about 40s. 0·1d. is a figure which nobody has even thought of asking for a supply, but 0·25d. is a figure at which a number of authorities are prepared to supply at off-peak times. It is not difficult to show that by the saving in labour costs the figure of 0·1d. can be increased to 0·15d. and still the comparison will hold. But 0·15d. is not good enough. The further increase in the price which may be justified and which results from close thermostatic control appears to be something like 0·05d. Therefore, in the case of an installation of from 1 million B.Th.U. per hour upwards, the figure of 0·2d. is the one at which electricity would have to be purchased if the electricity bill were to be equal to the coke bill, taking into account the saving in labour. That leaves a margin of 0·05d. between the figure at which electricity can be purchased, namely 0·25d., and the figure of 0·2d. I have just quoted, and it remains for prospective users of this system to assess the money value of the amenity which results from its use. No nuisance from smoke or soot is caused, there is no ash to be handled, and, what is quite important, the boiler-house plant can be installed in a portion of the building which would otherwise not be available for this purpose. Whether the value of these amenities is equal to the outstanding 0·05d. is a matter which will depend on individual circumstances, but I think that the great economy in the actual heat requirements resulting from the use of carefully designed control-apparatus is one of the most important aspects to which attention should be devoted in dealing with the question.

Mr. P. Kemp: I shall confine my remarks to Messrs. Monkhouse and Grant's paper. It seems to me that before this method of heating can come into general use, it must be an economical proposition. Mr. Betts has mentioned the fact that electricity must be sold at the rate of 0·2d. per kWh before it can be considered as an economical proposition, viewed from the point of view of the heat basis alone. Bearing in mind the fact that the majority of the large power stations consume coal at about 2 lb. per kWh, and taking coal at about 18s. per ton, the cost is found to be about 0·2d. per kWh. Allowing the allocation of 25 per cent of the fuel costs to the standing charge (which percentage is considered to be quite normal), the price would be reduced to 0·15d. This is the absolute minimum at which electrical energy can be supplied at the present time. Of course, no undertaking would supply at that figure. It does not, however, seem to me to be beyond the bounds of possibility that that 0·15d. might be a practical proposition when increased to 0·2d., and if an undertaking can supply at 0·2d., Mr. Betts's objections will have been met. In my own case we are being supplied at 0·27d. Purely from the point of view of the heat supply, it is not an economic proposition. The amenities, the absence of smoke stacks and, in a busy London quarter, the floor space which is set free by employing thermal storage have an appreciable value. Further, in the case of the installation in which I am interested, that of the Regent Street Polytechnic, when the first tentative plans for the new building were brought forward it was decided to go down to a certain level. When the question of thermal storage was mooted, the original plans were revised, and it was found possible to go down one story deeper into the earth. From that point of view it is seen that the storage vessels and electrode boilers occupy no floor space whatever. That is a point worth considering. I notice at the end of the paper a statement that at the present time certain labour charges are incurred with the electrical equipment. These will shortly be eliminated, it is said, when the complete automatic apparatus is installed. Regarding maintenance and upkeep I cannot speak with any authority, as the plant has been running for only a very few months; but I have found that it is not so far completely automatic. I have found that in certain cases rooms may not be required for, perhaps, three or four hours at a time. By shutting off the supply of heat to those rooms quite appreciable savings have been effected, but we have had to employ labour. However, it is hoped that this labour charge will shortly be eliminated.

Mr. L. Chew: In their first lantern slide, Messrs. Monkhouse and Grant gave a table showing the available heat units from coke as 35 000 for 1d. and from electricity as 13 500 for 1d. That, of course, does not seem very favourable or hopeful from the point of view of the the development of electric heating, and I gather from the remarks of Mr. Betts that the cost per unit will have to be considerably reduced to enable electricity to compete. Mr. Haldane has told us, however, that by first converting electricity into mechanical energy by means of a heat pump, we shall get an efficiency not of the 100 per cent that we get with this direct method, but of from 300 to 400 per cent. Taking the mean of those two figures and working out Mr. Betts's calculation, I find that 46 500 B.Th.U. could be obtained for 1d. by the heat-pump process, as compared with the 35 000 units for 1d. with coke. This appears to have some bearing on Mr. Betts's remarks. The test results which are tabulated in Mr. Haldane's paper have all been taken from plants used as refrigerating machines. Unfortunately, there are no large plants—in fact, no plants at all except that of 4 kW, which Mr. Haldane illustrated—available, and none on a sufficiently large scale to enable them to be tested for commercial efficiencies. Consequently the efficiencies shown in Mr. Haldane's table are very low indeed; they are of the order of 300 per cent. The reason for this is that in a refrigerating machine every available expedient is used to dissipate the heat from the ammonia after compression. The cylinders are water-jacketed; the discharge pipes are left bare, and sometimes there is a liquid ammonia injection into the cylinders during the compression stroke to provide isothermal compression. These factors increase the efficiency of a refrigerating plant;. but all the precautions which are taken when the machine is used as a refrigerating plant are just the reverse of those which must be taken when we use the same plant as a heat pump. The object in the latter case is to conserve the heat which is given to the gas during compression, and therefore everything beyond the discharge line should be thoroughly insulated. That, of course, has a very great bearing on the tabulated efficiencies given in Table 1 of the paper; it would improve them very greatly. The mechanical efficiency of the reversed heat engine, amounting to some 10 or 15 per cent, is a dead loss in the case of refrigerating machinery. When the same machine is used as a heat pump, a good deal of that loss which is included in the mechanical efficiency really becomes a gain. For example, the friction produced by the piston rings is given to the gas as heat which should be credited to the efficiency of the machine when used as a heat pump, and would again improve the figures given. In some of these tests I observe that the machinery is driven by a steam engine, and the power input to the machine is taken as the indicated horsepower of the steam engine, probably because that was the only means of ascertaining power input. But direct-coupled steam engine sets run at a very low speed, about 60 r.p.m., and are necessarily inefficient combinations. Thus the 10 or 15 per cent loss which is debited to these efficiencies would be very greatly improved if direct-coupled motors were used; moreover, modern refrigerating plant, or heat pumps, are essentially machines which can be direct-coupled to electric motors, since the speeds are of the right order. Perhaps the average installation would be of about 100 h.p., running at 350 r.p.m. A 100-h.p. electric motor at that speed can have an efficiency of the order of 89 to 91 per cent. In Table 2 of Mr. Haldane's paper I notice labour charges amounting to £387—one skilled mechanic, one assistant, and so on—and these are debited to the heat-pump system, the comparison being between that and a coke-fired boiler. It is the general practice to-day, however, to make refrigerating machinery fully automatic. In all butchers' shops, for instance, it runs without any attention at all, starting and stopping itself and being thermostatically controlled. The same automatic features could, of course, be applied to the heat pump, and this will no doubt be done when that machine comes into use. The figure of £387 could thus be reduced very considerably, and it would make the comparison even more favourable to the heat pump. Reliability and safety are very important points. The refrigerating machine, at present the only known form of heat pump, is essentially reliable. It has had to be designed on those lines, because the produce for which it is responsible is of such very great value.

Mr. D. J. Bolton : I should like to make one or two remarks on Mr. Haldane's paper. The great ease with which mechanical power can be obtained from electricity as compared with its competitors, and the comparative difficulty and expense of getting heat from electricity, are well known. Therefore any method which uses mechanical power to get heat is to be welcomed, if only because of the high efficiency of the electric motor as compared with that of the gas engine. That is why the subject of Mr. Haldane's paper appears to be so attractive. The author speaks only of the use of condensable gas, such as the ammonia which is used in refrigerating machines. That naturally makes the apparatus small in size; but there is another gas, not easily condensable, which has several advantages, of which cheapness is only one: I refer to the atmosphere. But air presents serious difficulties; very much larger apparatus, larger surfaces, and of course a very much bigger volume, have to be dealt with. One suggestion, however, which has been made is to combine the heating of a building with its ventilation. This removes one of the disadvantages I have mentioned, that of having to deal with a large volume of gas. A large volume is necessary for ventilation and it is no disadvantage for the heat pump. The other disadvantages still remain. The use of air necessitates a large area of pipe exposed to the cooling element, making the apparatus very bulky. The arrangement would have an inlet from the atmosphere, a long pipe, containing air at a pressure less than atmospheric, and then the condenser (or blower as it would be in such a case), which would deliver at atmospheric pressure. Thus we get both ventilation and heating, while the objection of having to deal with a large volume of gas no longer arises, because that volume is necessary for ventilation purposes. The objection arising out of the large area of pipe remains; it is not desirable for the building to be adorned by a large pipe, going round it two or three times; presumably it would have to be put in the roof. I do not know if the author has investigated that, or the difficulty of the moisture in the atmosphere. I do not think the idea has ever been tried in practice. Now for another point which applies to any of these heat pumps, and which may sound somewhat fantastic. Naturally, heat can only be pumped from one place to another. If all the buildings in London were heated in this way, would the temperature become even more Arctic than it is at the moment? If every building in Oxford Street were heated thus, the heat would be pumped from Oxford Street into the buildings, and Oxford Street itself would be slightly cooler. From the point of view of someone who was selling fires or overcoats, it might improve business to make it not only warmer indoors but slightly colder outside, but for London as a whole what would be the effect? Coming up to London from the provinces, one notices that Lond on is several degrees warmer than the surrounding country, due to the fuel and kWh consumed. By this method, however, London might be made several degrees cooler!

Mr. P. M. Baker (*communicated*):—A feature of the paper by Messrs. Monkhouse and Grant is their frank recognition of the fact that electrical heating by resistance methods cannot have a thermal efficiency as high as that obtainable by other, more direct, means. Electrical heating gains nothing but rather loses by claims which cannot be substantiated. It is better to take the line adopted by the authors and to emphasize the collateral advantages of ease of control, economies arising from increased cleanliness of buildings and savings due to the elimination of chimney stacks, etc., which are purchased at the cost of a slight loss of efficiency. The plant described in the paper can give all these advantages at an overall cost, although the charge of 0·25d. per unit seems to be very low even in these days of cheap electrical energy. The figures of 8 000 kWh per hour given on page 664 for the consumption of the heating installation at the offices of the London Underground Railways appears to be high and out of proportion to the magnitude of the other quantities given. Will the authors confirm the figure?

It is quite reasonable to predict that Mr. Haldane's paper may form the starting point for a new type of water heating free from the disabilities of ordinary resistance methods. The statements on page 667 would appear to contravene the law of the conservation of energy, but the real facts of the case are, I suggest, that the elementary theory of heat is incomplete as it takes no cognizance of the temperature at which heat units exist and, therefore, of their "availability." This can easily be seen by drawing temperature/entropy diagrams, one for the original engine which supplies the mechanical energy and another to represent the heat pump; the two should have equal "mechanical energy" areas. Such diagrams confirm the author's figures. I endeavoured, for my own satisfaction and in order to gain a better understanding of the action of the heat pump, to find an analogy which would illustrate its action. I would compare the heat pump with a battery booster. A battery contains a store of energy which it cannot discharge on to the busbars of a generating station until its voltage is raised by a booster; similarly, the water supplied to the circulating system of the author's compressor contains a supply of heat energy whose temperature is raised by the pump, thus enabling it to be transferred to surrounding objects. I consider that an analogy of this kind, which to some extent enables a clear conception of the physical happenings in a piece of apparatus to be obtained, is of value. The author's experimental application of Lord Kelvin's theory seems to have made an excellent case for the use of the heat pump in such work as the heating of water for swimming baths. The combination of a swimming bath with a skating rink appears to be of sound commercial value.

Mr. A. G. Freeborn (*communicated*): As stated in the paper by Messrs. Monkhouse and Grant, heating by thermal storage does not become feasible until electricity can be purchased at something in the neighbourhood of 0·25d. per unit, and, even when purchased at this figure, it depends on the special circumstances in each particular case as to whether it is even then an economical proposition. With regard to one of the largest jobs that has been done electrically, i.e. St. James's Park station, it must be borne in mind that it has, in effect, its own power station, viz. Lots Road. Although I have no doubt that its energy is charged for on a commercial basis, the fact remains that the station and the building have common owners. In Appendix 2 of the paper comparative figures are given for the plant at Carliol House, Newcastle. I note that 1 100 000 kWh are charged for, whilst, for comparison, 500 tons of coke are taken. This does not seem to me to be quite right, because if a coke boiler were to burn 500 tons to heat the same premises it would be working at a very low efficiency. I have actual experience of modern coke-plant working in London, the volume of the building being 2 350 000 cubic ft., or a little larger than Carliol House. Half the building is heated on the "Plenum" system, which requires much more heat than the panel system of the other half, but only 251 tons of coke per annum are used. I do not see why maintenance and renewals at Carliol House should be so much larger in proportion. An annual charge of £50 is ample for the maintenance and renewals of the plant described above, and this figure is confirmed by heating engineers. For attendance, £550 seems to me to be very high. The corresponding figure for the plant which I have mentioned is well within £200. These reductions bring the figure for the coke boiler down to a total of approximately £1 100. I am not well acquainted with the working of electrical thermal storage plant, but I cannot conceive that it would run without any attention at all. To install plant of such capacity and to have it continuously in operation without attention would not be advisable. I think that the minimum cost, including an occasional inspection by a competent engineer, would be £2 000. The comparative figures are now £2 000 for electricity against £1 100 for coke. It appears to me that consideration should be given to the engineering requirements of buildings as a whole, instead of to separate supply units. As an example, I would take a block of buildings in London the heat requirements of which during the winter are between 24 and 35 million B.Th.U. per hour and the peak requirements for light and power of which are in the neighbourhood of 4 000 kW. As solid fuel is somewhat difficult to deal with in the centre of large towns it will be assumed that oil is used as the fuel. In the first place, oil of 18 000 B.Th.U. content does not cost 90s. per ton, as stated in the paper, but it is now being purchased at a little over 60s. per ton. By installing modern high-pressure (200 to 250 lb. per sq. in.) water-tube boilers, complete with auxiliaries such as economizers and superheaters, great flexibility and a thermal efficiency of not less than 70 per cent would be obtained. This means that the boiler would provide, at a cost of 1d., about 37 000 B.Th.U. in the form of high-pressure superheated steam. As this could not easily be used in calorifiers it would be passed through a back-pressure turbine so as to reduce the pressure to approximately 25 lb. per sq. in. and extract the superheat from it. Power of the order of 0·8 kWh would be obtained from a generator coupled to this turbine. The steam would then still contain 30 000 B.Th.U. which could be used in the ordinary calorifier. The net result would thus be the generation of 0·8 kWh of electrical energy and 30 000 B.Th.U. for 1d. The labour and other charges involved would be approximately 0·3d. or 0·4d., and would certainly not approach 0·8d. There are other considerations, such as make-up, on the electrical side; for this it would be necessary either to parallel on to the outside supply or to install heavy-oil engines. Modern heavy-oil engines are working in various parts of the country now, and the all-in cost per unit is considerably less than 1d., especially when, as in this case, there are no transmission losses. This equipment, in conjunction with the back-pressure turbine, will supply all the electrical energy and will satisfy the engineering requirements of the establishment at a cost which is, at present, lower than that of any other available method. The following is a comparison between the energy charges involved by an external supply and by an independent engineering scheme, for the building mentioned above. Dealing first with the outside electrical supply, the lighting and power load will have a peak of approximately 4 000 kW. The actual requirements will be about 7 million kWh per annum for light and power, and an additional 6 million kWh are required for heating. For power and lighting a price of £5 per kW of maximum demand plus ½d. per unit will be assumed, and, for heating, a rate of ½d. per unit for energy consumed during the night. The total cost is then £33 500. For the other scheme, assuming 10 000 B.Th.U. per lb. of oil delivered to the heating plant, approximately 1 000 tons of oil are required. Through a turbine working under the conditions stated above at least 600 000 kWh are obtained, which means that 6 400 000 kWh must be generated by the oil engines. This amount of energy can be generated by oil-engine installations at the rate of 0·73d. per kWh, a figure which includes interest, depreciation, labour, fuel, etc. Taking into account the charges for oil (£3 000), for stoking and maintenance of the boilers, for attendance, interest, depreciation, etc., in connection with the turbine (£2 500), and for 6 400 000 kWh generated by the oil engine (£20 000), a total of £25 500 is obtained. This represents a considerable saving on the first scheme and it has, in addition, the advantage of independence of external sources. A point which becomes very evident after working out the above is that whilst the maximum demand for power and lighting is 4 000 kW the peak load for heating is between 7 000 and 8 000 kW, or very nearly double the day-time peak. If such systems become general, it is reasonable to suppose that the supply authorities will require a certain amount of the electricity for heating to be taken during the day so as to flatten out their load curve. This may have the effect of increasing the maximum demand during the day and, therefore, the costs of thermal storage. The buildings mentioned above consume large quantities of energy for power and lighting and relatively less for heating. No mention has been made of the very obvious economies which can be obtained by installing waste-heat boilers in connection with the exhausts of the Diesel engines. In this particular case, the whole of the summer heating-requirements could be met in this way. It will be noted that whilst 100 per cent efficiency has been allowed on the electrical scheme, only 60 per cent has been ascribed to the other system. The third method mentioned above—that of obtaining the heat from oil-fired boilers, passing the steam through a back-pressure turbine and then paralleling this turbine on to an outside source of supply—is quite worthy of consideration. It has not been very extensively adopted in London, but in other parts of the world it is by no means uncommon. It would cost £3 000 for oil, £2 500 for maintenance, etc., and the electricity supply from outside would cost approximately £24 000, assuming that the turbine output is sufficient to keep down the peak by 600 kW. This gives a total of £29 500. It seems from the above that independent generation of power as make-up on the turbo-generator is the most economical proposition. The actual space required for generating-machinery is not so great as might be imagined, and the very considerable saving shown over either of the other schemes makes it a proposition to which serious consideration must be given. I have dealt only with one particular case and must therefore point out that, although electrical thermal storage is not the most economical proposition under the conditions selected, there may be many cases in which it would present decided advantages.

Prof. E. W. Marchant (*communicated*): The use of electrically operated boilers in the present-day type of hot-water system is essentially wasteful. It must be recognized that while a coke boiler provides 35 000 B.Th.U. for 1d. the electric boiler can only produce 13 000 B.Th.U. for the same cost, assuming 100 per cent efficiency for the electrical system of heat distribution. The amount of heat, therefore, which is produced by an electrically heated boiler is not much more than one-third of that obtained for the same price from a coke-fired system. Any system of thermal storage applied to the electric boiler may equally well be associated with the coke-fired boiler; it is therefore misleading to regard the introduction of heat storage as a solution of the electrical heating problem. It is clear that the coke-fired boiler must be the more economical of the two types unless the energy for the electric boiler is supplied during off-peak periods at a figure which will not cover the cost of the coal required for its production.

Mr. Haldane's paper describes an arrangement whereby low-grade heat is obtained from an inverted refrigerator, and the experiments which the author has conducted at his house in Scotland are evidence that the scheme is practicable. It is remarkable that Lord Kelvin's suggestion of using a reversed compressor has never been adopted before: it is scientifically sound and enables the present disability of having only 24 per cent of the thermal content of the coal available for heating purposes to be avoided. A great deal of time and energy has been wasted in the past upon experiments which could never have been successful. I hope that this device will be the subject of research in the future, as it should lead to extensive economies in electrical heating.

Mr. J. C. Stobie (*communicated*): It is only during quite recent years that a satisfactory shaft seal packing has been in use, and as a consequence the small domestic refrigerator is now very common. These machines will run for years with practically no attention, and without trouble due to loss of refrigerant. Investigation of the temperature-entropy diagram of ammonia when used for heating from 32° F. to 120° F. (see Fig. A) shows that the compression line AB generally results in considerable superheating at fairly high pressures. The expansion line through the expansion valve results in the line CD, and the energy lost is represented by the area CDF. Mr. Haldane does not consider that this area is sufficiently large in comparison with the total area FABEC to warrant the installation of an expansion

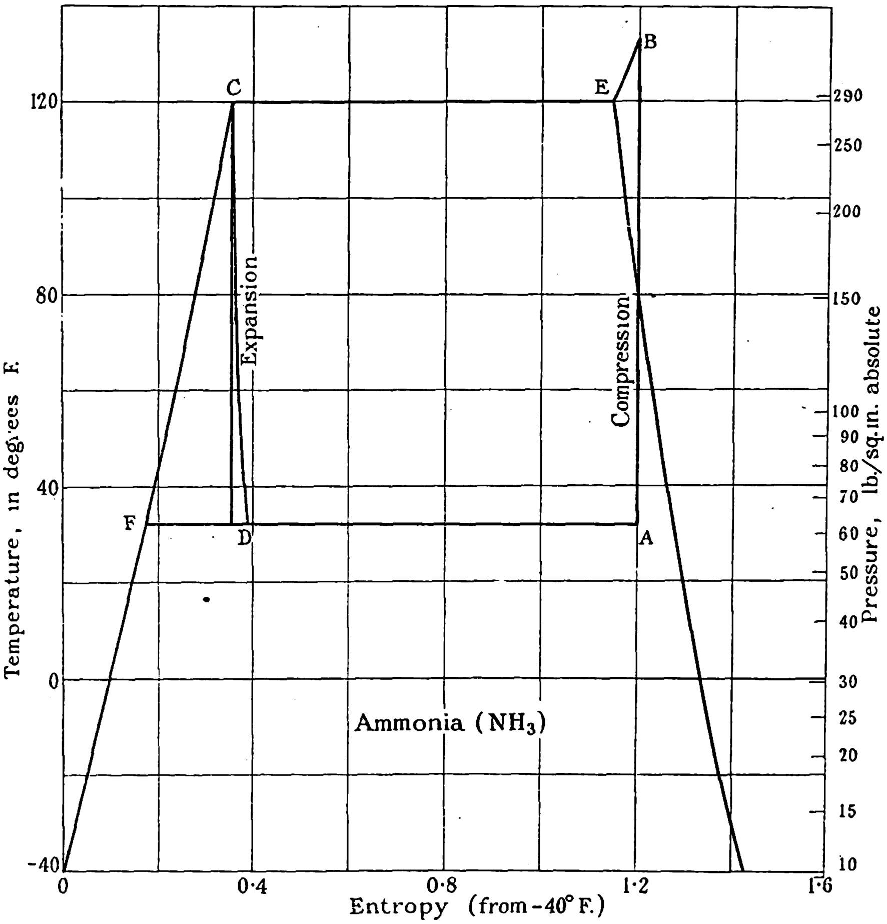

Fig. A.—Temperature/entropy diagram for ammonia.

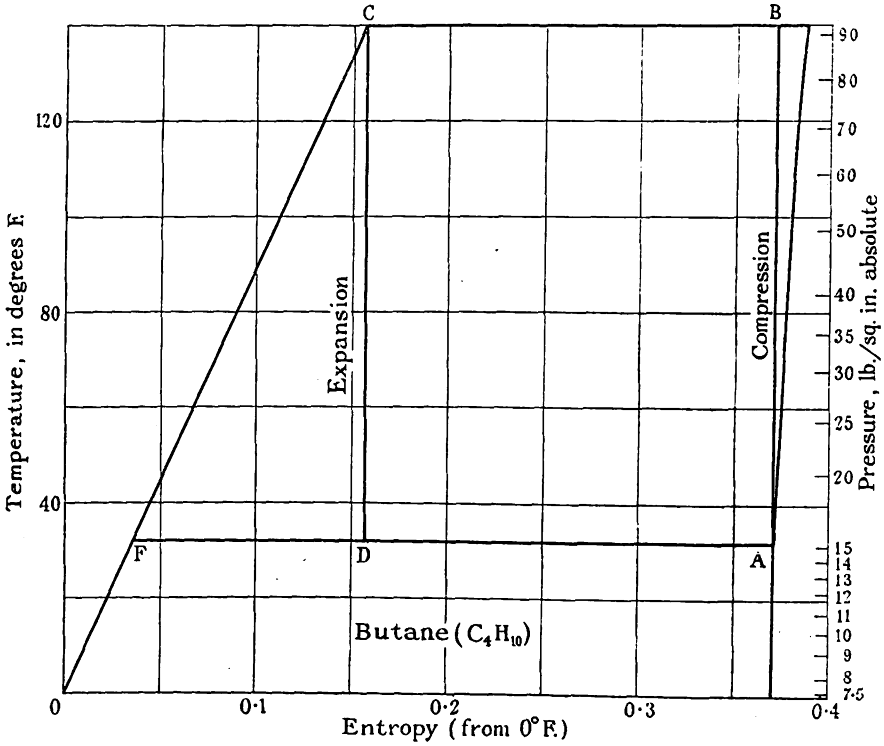

Fig. B.—Temperature/entropy diagram for butane.

cylinder. With low temperature-rises this loss is not great, but it can be seen that it increases rapidly with the temperature range. Other refrigerants in general use gave similar characteristics. They all require extremely high pressures when temperatures up to, say, 160° F. are required, so that I decided to search for other substances with the idea of boiling water. Fig. B shows the temperature-entropy diagram for butane. Here the shape of the saturation line does not cause any superheating at all on compression, from a temperature range of 32° F. to 140° F. In addition the pressure only increases to 90 lb. per sq. in. in comparison with approximately 4 times this value for ammonia, and it allows considerable energy to be returned by an expansion cylinder instead of the wasteful expansion valve. In Fig. B this saving would be about 20 per cent, but this increases with greater temperature ranges and the ideal performance is in agreement with Carnot's cycle. If the heat discharged from the pump system described above is passed through a heat exchanger to evaporate methyl-alcohol or water,

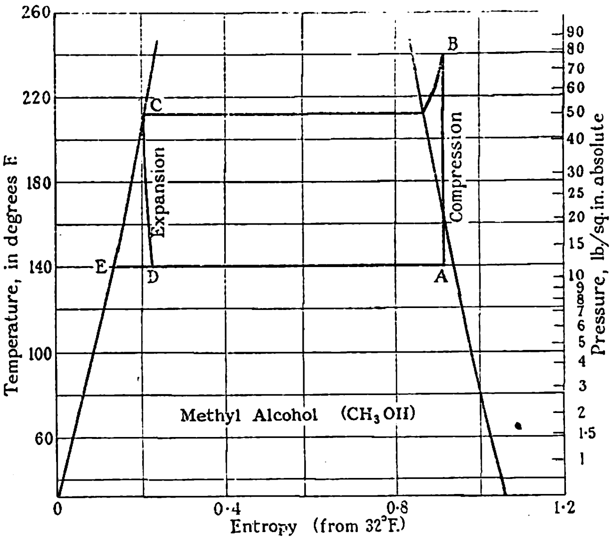

FIG. C.—Temperature/entropy diagram for methyl-alcohol

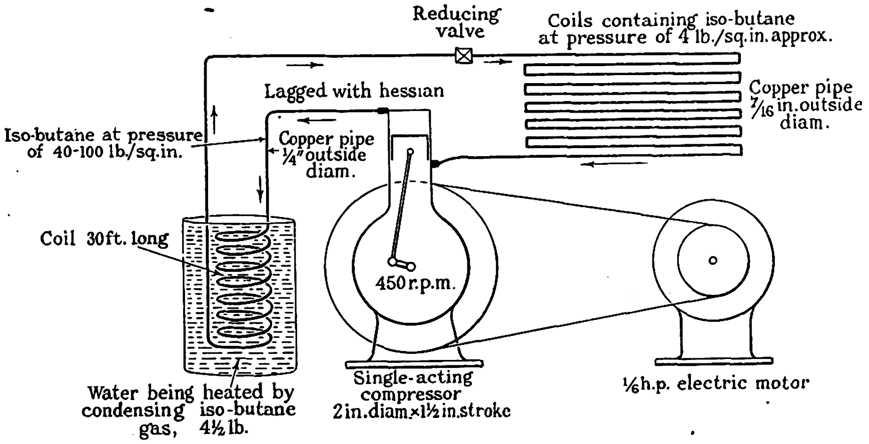
Reducing valve
Coils containing iso-butane at pressure of 4 lb./sq.in. approx.
Lagged with hessian
Copper pipe 7/16 in. outside diam.
Iso-butane at pressure of 40-100 lb./sq.in.
Copper pipe 1/4" outside diam.
Coil 30ft. long
450 r.p.m.
Water being heated by condensing iso-butane gas, 4½ lb.
Single-acting compressor 2in.diam×1½in.stroke
1/6 h.p. electric motor

FIG. D.—Diagram to illustrate the use of butane as the heating medium in a small heat pump.

TESTS ON SMALL COPELAND REFRIGERATOR ARRANGED TO HEAT WATER.

Test No.	Time	Kelvins used	Temperature of water (° F.)	Compression pressure	Suction pressure	Coefficient of performance (or Heating efficiency)
	mins.			lb./sq. in.	lb./sq. in.	per cent
1	0	0	63	30	—	—
	2½	0·02	76	—	—	86
	5	0·03	84	40	—	92
	6	0·04	90	—	—	89
	10	0·05	100	50	—	97
	12	0·06	108	60	5	99
	14	0·07	114	—	—	96
2	0	0	63	—	—	—
	2	0·01	80	40	5	224
	—	0·02	90	46	5	178
	7	0·03	102	55	5	171
	9	0·04	110	62	—	155
	12	0·05	116	—	—	140
	13	0·06	120	70	—	125
	15	0·07	124	75	—	115
	17	0·08	125	—	—	102

still higher temperatures are economically obtainable. The temperature-entropy diagram for methyl-alcohol is shown in Fig. C for an increase of temperature from 140° F. to 212° F. For this range an expansion valve would be quite suitable for the expansion line CD of the diagram. With this system in use in warm climates such as we have in Australia, thermal efficiencies up to 250 per cent may be possible in order to raise water to boiling temperature. In order to demonstrate the possibility of butane as a heating medium in a heat pump I was able last year to place some in the smaller sizes of Copeland refrigerator. With the assistance of the Australian Implement Co. of Adelaide we arranged a $\frac{1}{8}$-h.p. belt-driven unit to heat water as shown in Fig. D. The evaporating coils were exposed to the atmosphere, and fan arms on the motor flywheel assisted in making a draught for heating purposes. No expansion cylinder was used. With larger machines and an expansion cylinder the performance efficiency would be many times greater, but the experiment served to demonstrate the increased efficiency of the heat pump system even with this improvised equipment. The

TESTS ON SMALL COPELAND REFRIGERATOR ARRANGED TO HEAT WATER.

Test No.	Quantity of water	Temperature of water (° F.)	B.Th.U. to water	Kelvins used	Kelvins expressed in B.Th.U.	Time	Head pressure	Suction pressure	Coefficient of performance (or Heating efficiency)
	lb.						lb./sq. in.	lb./sq. in.	per cent
3	4·375	65	0	0	0	1·40	30	—	—
		76	48·2	0·023	78·6	—	30	—	61·3
		78	56·8	0·031	106·0	—	30	—	53·6
		Stopped	to put in	more iso-b	utane.				
		83	0	0	0	2·00	60	5	—
		93	43·8	0·017	58	2·03	50	—	75·5
		99	70·0	0·025	85·4	2·06	55	—	82
		107	105	0·039	133	—	60	—	79
		115	140	0·054	184·3	2·10	65	—	76
		123	175	0·071	242	2·13	75	—	72·3
		127	192	0·083	283	2·15	80	6	67·8
4	4·5	67·5	0	0	0	2·20	—	—	—
		83·0	69·8	0·017	58	2·23	—	—	120·4
		94·0	119	0·030	102·5	2·26	40	4	116·
		101	151	0·041	140	2·27	48	—	108
		110	191	0·051	174	2·30	—	—	109·8
		117	223	0·065	222	2·33	—	—	100·5
		121	241	0·077	263	2·34	75	—	91·6
		125	258·5	0·086	294	2·36	80	6	88
		128·5	274·5	0·093	318	—	—	—	86·4
5	4·4375	64	0	0	0	2·43	—	—	—
		80	71	0·013	44·4	—	40	—	160
		89·5	113	0·023	78·6	—	50	—	144
		99	155	0·034	116	2·50	—	—	134
		105	182	0·043	147	2·52	63	—	124
		116	231	0·061	208	2·55	—	—	111
		127	279	0·083	283	2·58	—	—	98·6
		132	302	0·095	325	3·01	83	—	93
		135·5	317	0·096	328	—	85	—	96·7
		139	333	0·104	355	3·03	90	—	91
		141	342	0·120	410	3·05	94	—	83·4
6. Aluminium water container lagged with brown paper	4·25	64	0	0	0	3·12	35	—	—
		80	68	0·010	34·1	3·13	40	—	199·3
		90·5	108	0·020	68·3	3·15	50	—	158
		99·0	149	0·031	106	3·17	53	—	140·6
		108·5	189	0·044	150	3·20	60	—	126
		116·5	223	0·055	188	3·22	72	—	118·7
		121	242	0·064	218	3·24	74	—	111
		126	263	0·070	239	3·25	—	—	110
		131	285	0·080	273	3·27	80	5	104·3
		137	310	0·097	331	3·29	90	—	93·7
		141	327	0·107	365	3·31	93	—	89·6
		144·5	342	0·118	403	3·33	94	—	84·8

cooled air passing the evaporating coils suggested to us that the pump would cool down our buildings as well as heat them. A further advantage brought out by these experiments was the effect of the large amount of heat which can be put into the water with a low temperature difference. As the temperature increases the performance is decreased, and only a portion of the heat is obtained at the extreme temperature difference. When we commence heating the water we have a performance efficiency of, say, 2 000 per cent which decreases to, say, 200 per cent as the water is brought up to boiling temperature. I was not aware at the time that similar experiments were being carried out elsewhere.

[The replies of Messrs. Monkhouse and Grant and Mr. Haldane to this discussion will be found on pages 699 and 702 respectively.]

North-Eastern Centre, at Newcastle, 11th November, 1929.

Mr. H. W. Clothier : Messrs. Monkhouse and Grant in their paper have demonstrated on a large scale that there is practical economy in the heating of buildings by the use of electricity compared with coke boilers; and, in addition, one has to put convenience, cleanliness and automatic regulation to the credit of electricity. As an example of the convenience of regulation it may be of interest to mention the method of control of the Reyrolle h.t. electrode boiler referred to by the authors. The electrodes are fixed inside the boiler in order that there shall be no glands for moving parts, and so the power consumption is regulated by the level of the water, which in turn is controlled by the rate of feed. Automatic control spreads the load evenly over the " off-peak " period. The required consumption for the temperature conditions of the time of the year is ascertained by experience; the control, set by a rheostat according to the required consumption, is effected by a differential wattmeter-type relay. The absence of dust and smoke is in itself a great labour-saving factor which is not always taken into proper account when comparing costs. Electricity combined with automatic control eliminates the troubles associated with laying fires and the labour occasioned by the dust and flue products, which cannot be entirely excluded from the house. The costs of electricity are so easily and accurately measured, whereas such other factors as cleanliness and health are so difficult to reduce to a monetary value, that there is a danger of paying too much attention to comparative thermal efficiency of the requisite sources of heat energy. The authors' Appendices 1 and 2 are of great importance in helping us fully to realize the problems before us. It would be useful if they would also state the efficiency allowed in compiling their balance sheet, and the effective calorific value of various forms of fuel available. The paper, though dealing only with large buildings, raises questions which apply also to small buildings. Table A comprises a comparison between electric and coke-boiler heating for a dwelling-house. The possibilities of night load in this form must, of course, depend upon the supply companies giving exceedingly low rates. A really attractive night-load tariff for dwellings would carry some profit, however limited, to the supply undertakings who wish to fill the valleys in their load curves; it would also bring a larger demand in day load for topping-up for local heat, and other uses. I have endeavoured to ascertain from the figures in the paper a basic figure for daily watt-hour consumption per unit dimensions and temperature. Presumably the figure varies with different types of buildings, the amount of ventilation, etc. What is required is the total power, in watts, used in several types of buildings, divided by the product of the total cubic capacity of the buildings, in cub. ft., the period considered, in days, and the temperature-rise, in deg. F. This figure should furnish

Table A.

Estimates from Experimental Data Obtained in a Dwelling-House, September, 1928, to September, 1929.

Off-peak night load: 8 p.m. to 7.30 a.m.

	Coke			Electric		
Capital charges.						
	£	s.	d.	£	s.	d.
Cost of whole scheme, including domestic hot-water apparatus ..	150	0	0	250	0	0
Estimated annual charges.						
Energy—58 000 kWh at 0·3d.	—			72	10	0*
Energy for lighting ..	20	0	0	20	0	0
Energy for cooking and domestic hot water (7 200 kWh)	—			30	0	0
Fuel—2½ tons per month at 27s. per ton ..	40	10	0			
Interest on plant at 6 per cent	9	0	0	15	0	0
Depreciation fund on boiler-house plant:						
Coke—10 years at 7·95 per cent per annum ..	12	0	0	—		
Electric—20 years at 3·02 per cent per annum	—			8	0	0
Maintenance	6	0	0	5	0	0
Balance, representing difference on account of attendance, convenience and cleanliness	63	0	0			
	150	10	0	150	10	0

Approximate average temperature of house, allowing for topping-up in places to 60° F. and excluding summer-time temperatures when artificial heating is not in use .. .. 58° F.

Assumed average outdoor temperature, on same basis .. .. 45° F.

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* Central-heating night load.

a useful working standard for the electrical energy required per cub. ft. per deg. F. temperature-rise per day. On page 661 the authors give a figure of 0·08 watt-hour, but this is not confirmed by the data given for Carliol House. The differences are shown in Table B.

TABLE B.

Installation	Consumption	Page
Banca Commerciale Italiana di Roma	Wh/cub. ft./deg. F. = 0·08	649
Carliol House	$\frac{5\,300 \times 1\,000}{1\,750\,000 \times 1 \times 18{\cdot}7} = 0{\cdot}162$	652
Carliol House room ..	$\frac{46 \times 1\,000}{7 \times 2\,000 \times 18{\cdot}7} = 0{\cdot}1757$	652

Having compared these figures with the results obtained from the above-mentioned dwelling-house, I would suggest that the larger figures are more correct.

Mr. S. S. Jewsbury: The authors mentioned that they believe the Carliol House plant to be the largest of its kind in use in the world. Taking the installation as a whole, that is the electrode steam-boilers, thermal storage apparatus, and the panel, or invisible radiant heating, system, as we now call it, I believe it is the first installation of its kind in the world. The adoption of a system which is a definite departure from the accepted methods of heating is a matter for congratulation. This paper will do much to stop the unfounded rumours which have been circulated regarding the heating of buildings by electrical methods. It has been suggested that if this method of heating is adopted to any considerable extent the demand will very soon exceed present peak loads. If the demand exceeds the supply the supply undertakings would, of course, only be expected to sell at the low rate that quantity of current which is represented by the valleys in their load curves, but, as the average load factor of the large power stations in this country is, I believe, at present between 20 and 25 per cent, there is at present no likelihood of using up all the available supply of current for this purpose. To have so many different rates is, no doubt, a difficult matter for the supply undertakings; and consumers will probably want to know why energy for one purpose can be supplied at a lower rate than energy for another. It is for the electrical industry to educate the public to realize that the methods adopted to maintain constant loads at the power stations will increase the efficiency of the stations as a whole, and so ultimately benefit all consumers owing to the lower rate at which it should be possible for the current to be supplied. The authors mentioned that a panel-heating installation works, normally, at a lower temperature than a radiator system, and this means that the panel system is particularly suitable for use in conjunction with thermal storage schemes. A panel system works, normally, at 120° F. and a radiator system at 160° F.; therefore, when the maximum temperature to which the water in the storage cylinder is heated is 230° F., the panel system has an operating range in its storage cylinder of 110 deg. F. as against 70 deg. F. for the radiator system. Thus the storage cylinders required for the panel system will be only a little more than one-half the size of those required for the radiator system. Incidentally, it is found that the total quantity of heat required to maintain conditions of comfort in buildings heated by the panel system is rather less than is found necessary in the case of buildings heated by radiators.

Mr. A. G. Shearer: In any scheme for using electrical energy for a thermal storage system it is essential that all losses should be reduced to an absolute minimum. When one considers that the capital cost of the lagging is spread over 20, or maybe 30 years, during which time the heat loss will be continual during an operating period of about two-thirds of each year, it can readily be proved that the first cost of applying sufficient lagging to reduce the losses to the minimum figure recommended by the authors is justifiable and essential. This subject of heat loss during storage is becoming increasingly important to electrical undertakings, particularly in view of the demand for domestic hot-water installations.* Metallic cellular heat-insulation which practically eliminates loss by radiation is now available; it consists of specially prepared bright aluminium foil. The dimensions of storage cylinders should be very carefully considered by designers, so that for a given volume the surface area is as near the minimum limit as is practicable, and where there is adequate space the volume of the storage cylinders should not be fixed at a minimum figure, as it is more economical to operate at a lower than a higher temperature. Throughout the country there must be many electrically equipped works where the consumers' transformers are not fully loaded during the off-peak supply period; this available transformer capacity can be utilized for supplying thermal-storage load to heat offices and other works buildings. If the annual payments to the depreciation fund referred to in the Appendix are invested at 6 per cent (the same rate as the interest on borrowed capital) then, in order to accumulate to a total of £5 600 in 20 years, the annual payment will only be £143 12s. 6d. instead of £169 as shown in the paper. The difference of £25 will enable the total costs against the electric scheme to balance those against the coke-fired scheme. The cost of handling and removing ashes in coke-fired installations is one which must be carefully considered, and this item is rarely fully recognized.

Mr. F. N. Linstow: Referring to large immersion-heater installations such as the one illustrated in Fig. 2B, it seems to me that it would be preferable to place the immersion heaters in a small tank by themselves, and circulate the water between the heater tank and the storage cylinder either by thermo-siphon or by force pump. With the small separate heater tank, it would be much easier to carry out cleaning operations on the heater tubes, or even replacement of a tube, if necessary, as this could be done without draining off a great deal of water; also we cannot overlook the possibility of a fault on an immersion heater being sufficiently severe in nature to burn through the tube and allow an escape of water. With the heaters in a separate chamber, stopcocks could be closed which would definitely limit the escape of water, even under the worst conditions, to that which was contained in the heater tank. In view of the possibility of electrical faults in immersion heaters causing damage to the tube, some system of sensitive earth-leakage protection is very desirable for such installations. Where the supply is taken direct from the mains, relays operating on a 2½ or 5 per cent fault current could probably be provided, but where a separate transformer is installed a much more sensitive trip-setting could be obtained and is desirable. I suggest that, under these conditions, the neutral of the transformer should be connected to earth via a relay-coil winding, and the most sensitive setting obtainable should be employed.

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* Dr. M. FISHENDEN: "Heat Loss from Thermal Storage Tanks," *Electrical Review*, 1928, vol. 103, p. 644.

Mr. V. A. H. Clements: The authors have not stated the cost at which it is economical to supply off-peak units for thermal storage. The Appendices show that, on running costs alone (assuming 0·3d. per unit and 26s. to 27s. per ton of coke), there is little to choose between the two methods of heating, and it seems that to persuade those who are responsible for erecting new buildings or altering those in existence may be very difficult unless more favourable balance sheets can be shown. The price of 0·3d. per unit seems high where generation is carried out efficiently, and it would be of great interest to know exactly how this particular figure is arrived at, so that supply engineers in general may have guidance in furthering this excellent method of improving both their load factor and their revenue. One wonders also if the proportion of coal cost is the same as that ordinarily taken for general supplies, remembering that the coal cost itself is reduced owing to the improved load factor. In the figures shown for the first cost of the equipment, how much is allowed for the cost of the substation equipment and high- or low-voltage mains? One assumes that, in a large building such as Carliol House, a substation is almost essential, merely to cater for lighting and power, and therefore a proportion only of this should be charged against the heating plant. As the development and use of electrical thermal storage proceeds, the home market for coke, which is very considerable, will be spoilt, and the price of by-products will increase considerably, owing to decreased production. The effect of this is, of course, further losses to the colliery owners and, in coal-producing districts such as this, a decrease in revenue to the supply authorities from colliery load. We have also to consider the national point of view, whereby better use is made of our resources by burning coke than by burning raw coal, as is the present practice, in generating stations. It seems, therefore, that the development of the system of heating advocated by the authors should proceed hand in hand with that of burning coke, more especially low-temperature coke, for steam-raising in our generating stations.

Mr. W. Richardson: On page 658 the authors refer to the storage media, and a comparison between water and oil is given, in which water is shown to be the better medium. They have not made it clear that this comparison depends very largely on the effective temperature range through which water can be heated and that the circumstances may be such that oil is the better medium. There are one or two small installations working in the Midlands in which oil is used. The authors have taken for water the temperature range of 160 deg. F., i.e. from 280° to 120° F. The latter temperature is too low a circulating temperature for a central heating installation, using standard hot-water radiators, and 140° F. is a better figure; also 280° F. is rather high and I would prefer a figure of 260° F., which is the temperature which can be obtained with a suitable margin for a building providing about 70 ft. head. With these figures the storage per cub. ft. of water is 7 500 B.Th.U. Turning to the oil installation, it is not usual to circulate oil through the building, and water is used. This water is heated through a calorifier. Assuming a minimum water circulating temperature of 140° F. and 20 deg. F. drop in the calorifier, this gives a minimum oil temperature of 160° F., so that the available temperature range is 340 deg., instead of 380 deg. as given in the paper. This gives a storage capacity of 7 250 lb. per cub. ft. It will be seen from this that for any building with less than 70 ft. head, oil storage may be the better proposition; although it must be remembered that an additional calorifier is necessary to transfer the heat from the oil to the water. Can the authors give us particulars of any installations working on this system? The description of the Carliol House heating plant is full of interest, but I think that if progress is to be made with this system of heating it will be on the lines of the Newcastle-upon-Tyne block of offices and showrooms, described on page 664. This installation is very simple and can be operated with a minimum of attention. Doubts may be expressed as to the reliability of large immersion heaters, but it should be remembered that these are rather different in design from the ordinary small domestic immersion heater, as the rating and internal temperatures are very much lower. The heating installation used at the Vaudeville Theatre, London, which was the original thermal-storage heating system working in this country, and which utilizes large immersion heaters, has operated for more than 5 years without any heater breakdowns. The usual method of controlling a thermal storage installation is to circulate the water round the heating system at a predetermined temperature, and frequently this temperature is controlled automatically, but in spite of this the method of heating is not fully automatic; one has to predict the probable weather conditions outside, so as to arrange for a suitable circulating temperature. The problem in the heating of a building is to maintain a definite air temperature in the rooms, say 63° F., independent of the outside conditions, and I should like to know whether it is possible to control the installation from a thermostat registering the air temperature in a portion of the building. If this can be done, then the plant will become fully automatic, and this should be a big factor in popularizing this method of heating. I would also suggest that with thermal-storage installations it is important that the pipe arrangement should be such that the storage cylinder can be completely isolated from the circulating system, so that this can be emptied, in the event of a leak or burst radiator, without having to lose all the stored heat in the cylinder.

Mr. F. H. Williams : Thermal storage as an off-peak load should be very attractive to the supply authorities. It should be equally attractive to the owners of large buildings, but from this point of view the Appendices are not as helpful as they might be. A casual examination of Appendix 2 suggests that as regards operation the electrical installation costs about the same as the coke installation but that its capital cost is nearly 50 per cent greater. This does not sound attractive to the ordinary landlord who does not care how his building is heated; he is only interested in obtaining the maximum net return for the money invested. If the adoption of electrical thermal storage enables him to put more office accommodation on a given site and obtain a greater net revenue, he will install it. This is what electrical thermal storage enables him to do, but it is by no means self-evident from the Appendices. I think Appendix 2 should be modified, so that (i) the capital cost of the coke installation is debited with the cost of chimney and flues; (ii) the running cost of the coke installation is debited with the cost of cleaning and maintaining the chimney and flues; and (iii) the capital cost of the electrical installation is credited with the capitalized value of the extra accommodation rendered available by the omission of chimney and flues. These alterations would give a truer comparison of the costs of the two systems, and one which would attract consumers. I should like to know whether the price given for the coke installation in Appendix 2 covers duplicate plant to the same extent as the electrical installation is duplicated. Modern electric boilers should be quite as reliable as coke boilers and, if used on an " off-peak " system, there are available for maintenance 12 hours during each day which would not be available with a coke boiler. I should also like to know whether, in considering alternative schemes for Carliol House, the authors obtained prices for the ordinary hot-water radiator system and, if so, how these prices compared, both as regards capital and running costs, with the panel system. I believe that the panel system is easily the more economical in running cost, and the panel heater has no ill effects on the decorating, whereas in certain offices I occupied the ordinary radiators ruined the decorations in a single winter. I have had experience of five systems of heating for large buildings:—(i) hot air circulated through the building from a central heating chamber; (ii) coal fires; (iii) electric radiators; (iv) hot-water and low-pressure steam radiators (convectors); and (v) the panel heating of Carliol House. Although I have still to meet the ideal system of heating, I consider the panel system to be easily the best of these from the point of view of general comfort.

[Messrs. Monkhouse and Grant's reply to this discussion will be found on page 699.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 26TH NOVEMBER, 1929.

Mr. C. Howard: The recent advances in the utilization of electricity by means of thermal storage for the heating of large buildings in London has intensified the interest which was originally created by the earlier installations at Newcastle. The authors' statement that with the Sulzer boiler " movable electrodes are employed which are hydraulically raised or lowered to the required degree of immersion " is somewhat surprising, as it is to be presumed that the authors have had access to the Sulzer electrode boiler-plant installed at the Newcastle Motor Depot, of which a full description appears in the paper. The fact that the position of the electrodes is fixed has always been one of the principal claims for the Sulzer electrode system, and this seems to have been overlooked by the authors. The actual method adopted for load regulation in the Sulzer boiler depends upon the voltage of supply. With boilers arranged for low voltage, movable counter-electrodes are employed; and with high-voltage supply, movable evaporating tubes of insulating material surround the electrodes, i.e. one tube surrounds each electrode. Both these methods obviate the necessity for any form of "electric cum steam" glands to which the authors object. In the low-voltage boiler the counter-electrodes form the neutral point of the system and can therefore be electrically connected with the boiler shell. The reference to the Reyrolle electrode boiler is very interesting, as I believe that this boiler has not yet been employed commercially and few, if any, particulars have hitherto been published. It is at present, presumably, in its experimental stage. The statement that the load is regulated by " varying the rate of feed " is somewhat ambiguous, as it is not at all clear which " feed " is to be regulated. Is it the electrical feed? If so, the only means of regulation would appear to be a variation of the voltage at the electrode terminals. If, however, it is the feed water to which reference is made, then it would appear that the boiler in question is a steam boiler and that " varying the rate of feed " would be but another way of describing " alteration of the water level " as in the Oerlikon boiler. It is well known that the serious objections to this method of regulation are the arcing which occurs at the electrodes, the violent fluctuations in the electric load, and the corrosion of the electrodes themselves. These objections can only be overcome by complete submersion of the electrodes, and hence load regulation must be provided by means other than an alteration of the water-level. It will be realized that with electrode water-heaters, as opposed to steam boilers, the electrodes must of necessity be entirely submerged. The authors state that " because of the somewhat greater difficulty of applying low-voltage electrode boilers to a low-voltage earthed-neutral system the resistance heater method is frequently preferred when only a low-voltage supply is available," the reason given being that "the resistance heaters are completely insulated from earth and consequently avoid the formation of a short-circuit through earth to the network neutral." I claim that there is no difficulty whatever in applying a low-voltage electrode boiler to a low-voltage earthed-neutral system; this has actually been done in the case of one London installation in which a 750-kVA boiler operates upon a 3-phase 400-volt supply. The electrode area is provided by means of concentric cylinders into which a similar set of movable concentric cylindrical counter-electrodes move. The counter-electrodes are connected to the neutral part of the supply and thus need not be insulated from the boiler shell. Load regulation is provided by movement of the counter-electrodes. The electrodes and counter-electrodes are always completely submerged. This system of electrodes cannot be described as costly, and is certainly less so than a set of resistance heaters of similar size. The switch arrangement is also more simple, consisting of a 1 000-ampere 3-pole circuit breaker with no-volt and overload releases. A further advantage of the electrode water heater is such that arrangements can very easily be made for the time switch which terminates the supply at the end of the off-peak period first to reduce the load to the minimum before finally cutting out. The advantage of this to the supply authority is obvious, as it avoids any possibility of a large single load being suddenly thrown off the mains. A statement is made by the authors to the effect that a steam-raising boiler is more flexible than a water heater. It is surely not a question of water or steam, but rather whether the heaters—resistance or electrode—are placed in the storage vessel or are separate units. It is obvious that the separate unit is more flexible, but it is not correct to state that a separate steam-raising boiler is more flexible than a separate water-heating boiler. The water-heating boiler has the very great advantage of requiring no calorifiers for a heating installation, as the heated water can be passed directly either to the heating system or to a storage vessel. This is a special advantage where night heating of buildings is required, where the storage vessels and the heating system can be supplied with their definite quota of heat direct from the boiler. It is interesting to learn from a statement in this paper that although one new set of electrodes has been provided for the water electrode boiler at the Newcastle Motor Depot the replacement was unnecessary. As no similar reference is made in the case of the Carliol House plant, which is a more recent installation, it is to be assumed that the replacement of electrodes was a necessity. As there exists here an example of systems working under the same voltage and general conditions, but in the one case consisting of a water electrode boiler with fully immersed electrodes, and, in the other, steam boilers with partially immersed electrodes, a comparison of the state of the electrodes after 1 year's use would be interesting. The authors' comparison between oil and water for heat-storage purposes is decidedly interesting, and when the additional risks in the event of fire, and the impossibility of using other than immersion heaters, are taken into consideration it will be found that the oil storage system is only suitable for relatively small installations. The chief advantage which has been claimed for the employment of oil in thermal storage plants is the smaller volume of storage required. This paper is very interesting in exploding that theory. Although the temperature to which water may be raised in a normal heating installation for storage under the static head of the building is, I believe about 250° F., even at this temperature the comparison with oil is as 815 to 817, which small advantage is unjustified when considering cost and the difficulties of using oil for this purpose. I regret that the authors have not stressed to a greater degree the desirability of this class of load to the electrical supply authorities. From the results in the paper it would seem that the consumption of such a plant is in the neighbourhood of 1 000 units per annum for each rated kVA, and although the actual load factor is only 11·5 per cent its effect on the general load factor of the supply system is considerable. Taking the published load curves of the Manchester Corporation Electricity Department during 1928, a load of 50 000 kW could be superimposed on the existing loads between 7 p.m. and 7 a.m. without exceeding the corresponding maximum load during the day, and, assuming this load to be composed of heating plants of the nature described in the paper, the load factor would be improved from 34·64 to 38·4 per cent. Assuming the constant losses at the generating station to be as low as only 18 cwt. of coal per day per 1 000 kW of the maximum demand, such an improvement in the load factor would decrease the coal consumption per unit by 0·02 lb., equivalent to a saving of 4 200 tons per annum, or, say, £2 500 with coal at 12s. per ton. Thus each installation of 1 000 kW rating in Manchester might be regarded as additional unseen profit of £50 per annum, exclusive of the profit made on the actual consumption of current by the heating apparatus.

Mr. S. M. I. Saunders : The problem which station engineers in particular will have to face is the cost of the fuel. There are bound to be comparisons between "electrical fuel," coke fuel and oil fuel. With "electrical fuel" it appears possible to approximate to the costs obtained with oil firing, for electrical heating is much more amenable to automatic control. Automatic control can be applied to coke and oil firing, but not with the same degree of accuracy as can be obtained with electrical heating. In making the comparison between the cubic capacity required with water storage and oil storage, the authors give an absolute figure for the specific heat of the oil, viz. 0·4. Elsewhere it is given as 0·5 or 0·56. Taking the higher figure, if the lower limit of the temperature-range for the circulating water is not quite so low as quoted in the paper, the cubic capacity for the storage of equal amounts of heat in water and oil will be in favour of the latter, unless the water is at a very high temperature. A decided change is taking place in the method of heating buildings. At the beginning of the War the usual method was by ordinary pipes and radiators, but now panel heating of various types is being adopted. It appears to be a very good opportunity to combine thermal storage with panel heating, as against the pipe and radiator with oil or coke firing, because with panel heating equal comfort can be obtained with considerably less heat input than is the case with pipes and radiators, with relatively cheaper fuel cost.

Mr. W. E. Swale : The authors describe plant which has long passed the drawing-board stage, which is essentially simple in operation, cheap to install and comparatively cheap to operate, and which offers the heating engineer the advantages of electricity in an eminently practical form. Criticism of electric thermal storage plant will come mainly from three sources; from the architect and his collaborator, the heating engineer; from the electrical mains and installation engineer; and finally from the unfortunate individual who has to offer—to quote the authors—" an appreciable reduction in the prices charged." The architect and the heating engineer can, I venture to say, have nothing but whole-hearted approval for the new systems. In effect, the authors simply propose to substitute a different central heating unit. In this country hot-water heating installations are still in the overwhelming majority. Thus, no part of the building heating plant in itself need be changed. The absence of a chimney stack and facilities for fuel storage, and the correlated fact that the heating unit can now be placed anywhere in the building, are obvious advantages which need only to be fairly assessed in money values. The design and control of the plant are so simple that operation difficulties should be non-existent. The electrical installation engineer likewise has no serious difficulties to face; the connection of a 1 000- or 1 500-kW heating load to the system presents conditions in many respects less onerous than those of connecting a motor of equivalent capacity. Referring to page 659, can the authors state definitely that no troubles have been experienced by earthing the neutral point of the 6 600-volt boilers on the premises? The mains engineer's problems need more careful consideration, because on large distribution systems the load curve of the individual e.h.t. feeders does not necessarily coincide with the load curve of the generating station. To make a low price economically justifiable extra capital expenditure must be avoided, and existing mains must be utilized during suitable hours. Again, the longer the charging period the smaller can be the rating of the thermal storage unit. It seems that a charging period of at least 12 hours is desirable. It will thus be the duty of the mains engineer to choose a period or periods in the load curve when the heating load can be taken without creating fresh peaks on the distribution system. The method of regulating the load, judging from the authors' remarks, is to switch on the full capacity by time switch and to switch off successive sections by thermostat. The whole load being switched on at once, at, say 7 p.m., may cause difficulties through coincidence with existing night loads. I suggest that a device could be included in the switching arrangements akin either to a current limiter or a clock-operated cam gear, by which, during the early hours of the evening, sections could be switched on proportional to the feeder capacity available, and the complete heat rating left on until the later limit of the charging period. The last of the three possible sources of criticism will be from those who have to sell electrical power at a suitable price. The authors, very wisely, " have refrained from making any definite statement on the subject." It is primarily the function of public supply undertakings to safeguard the interests of all consumers equally. One class of load ought not to be encouraged at the expense of other consumers. The rates which have been mentioned as economical from a heating point of view are well within the range of large supply authorities, and there need be no fear that they will not take full advantage of the facilities offered. But the economics of the question must always be kept in mind, and very cheap rates cannot be quoted where extra capital expenditure is involved. Comparatively small installations of, say, 250, 500, or even 750 kW can no doubt be connected by large undertakings at a price which will make the installations competitive. With larger-sized units the question of additional expenditure on mains may have to be faced, and such installations will need very careful and individual investigation. The load factors of thermal storage plants will probably not be much higher than 16 per cent, owing to the fact that they will generally be shut down completely for 6 months in the year. The descriptive phrases now in use seem to be unnecessarily cumbersome, and I suggest the adoption of the following terms: (i) electrode T.S. plant, (ii) resistance-water T.S. plant, and (iii) resistance-oil T.S. plant. The authors' figures regarding total connected capacity in this country alone show the very considerable progress which has already been made in this new application. It seems, as the authors point out, that electricity supply engineers can now offer an ideal means of heating large buildings, with the additional benefits of substantial improvement in the station load-factor.

Mr. J. Anderson: The paper appeals to me mainly from a thermal-storage point of view. This aspect of the subject is a most important one, as it is quite apparent from the authors' remarks that the full economic benefits from the heating of buildings electrically are only possible when some form of thermal storage is adopted. I have in mind a specific case of a building which is now in course of construction, where the combined scheme of electrical boilers and thermal storage is used on a much larger scale than in ordinary buildings. The particular scheme is for a large poultry farm where constant temperature is the most vital factor. The arrangement comprises three electric boilers and a Ruths steam accumulator. The boilers will generate steam at a constant pressure and steady output during off-peak periods prevailing in the local power station. The current so consumed will be bought at specially low rates. All surplus steam will be automatically by-passed into the steam accumulator, which has a thermal storage capacity of 12 000 lb. over a pressure range from 120 to 2 lb. per sq. in. At times the whole output from the boilers will be passed into the accumulator at a pressure of 120 lb. per sq. in. When the peak periods occur at the power station the current will be shut off, thereby closing down the electric boilers completely. All steam for heating purposes is then automatically taken from the accumulator at a pressure of 2 lb. per sq. in. The storage capacity of this accumulator is sufficient to run the plant with the boilers switched off over a period of 6 hours, at an average of 2 000 lb. per hour, or 8 hours at 1 500 lb. per hour, 12 hours at 1 000 lb. per hour, and so on. Much has been written lately on the importance of filling in the valleys in a supply undertaking's daily load curve. The paper is all the more welcome on account of showing how the various professions can assist in achieving the object of more economical production of electrical energy and at the same time receive all the advantages of a more efficient system.

Mr. O. Howarth: The authors describe an electrode boiler connected direct to a 6 600-volt 3-phase supply.

The system is, therefore, used as a 3-phase 4-wire system. Are any of these boilers installed on a high-voltage system with the neutral earthed through a limiting resistance? If so, when an earth occurs on one phase of the system the electrodes in the boilers which are connected to the other two phases of the system may have full line voltage to earth impressed on them until the fault is cleared. Have the authors had any experience of such occurrences? It would be interesting to know what the Post Office engineers have to say about the adoption of an earth-return path to the station neutral for the out-of-balance current. Can the authors tell us what type of metering is used to measure the energy consumed by the electrode boilers which have been installed? A 3-phase 3-wire meter can hardly be considered to be satisfactory for measuring the energy, as current may pass via earth to the station neutral point. A 3-phase 4-wire meter is undoubtedly called for, and there are two methods of connecting the potential system of the meters. Either a 3-phase or 3 single-phase potential transformers may be used with the primary star point earthed, or a 3-phase core-type potential transformer may be employed with the primary star point left free (there are alternatives to this arrangement giving the same result). The former arrangement will measure accurately the energy consumed by the boiler. The latter arrangement practically picks out the station neutral point and will measure not only the energy consumed by the boiler but the energy consumed by the earth connections back to the station neutral. When the system is earthed through a limiting resistance the out-of-balance current returning via the earth must traverse the resistance to get back to the machine neutral, and the energy consumed by this resistance will be registered by the meter if the primary star point of the potential transformer is not earthed. The consumer will therefore pay for the energy consumed by his electrode boiler and by the station earthing-resistance.

Mr. J. Sunlight: Can the authors state what will be the inducement to the owners of a building to venture upon an installation of this kind instead of the type to which people are now accustomed? I can understand the architects, in the case of the new London Underground Railways building, having designed a very modern type of building, being anxious to attain the height of their ambition by adopting the most modern scheme, but what is going to persuade an owner to adopt it, apart from the pioneer instinct? When this method of heating is adopted, will the atmosphere in a building be in any way different from that of a building heated by hot water, coke or oil? Consider the case of a coal fire in a room at home as compared with an electric heater in the fireplace. Is there not a distinct difference in the feeling of the air? Is there going to be any difference in an office heated by this system as compared with coal or coke heating? Can it be relied upon that the temperature will be maintained at the end of the day? Another point is the question of replacement and maintenance. At the end of 20 or 30 years, owing to the wear and tear, will the bulk of the heating chamber and the machinery require replacing? If so, the question of the cost of renewing this elaborate machinery will be a very serious problem. But above all, are we likely to get supplies at economical rates? One can buy coke anywhere, but by adopting a system like this one is placed entirely in the hands of one authority.

Mr. S. S. Jewsbury: On the Continent electrically-heated thermal-storage plants have been in use for about 20 years. I have examined several of the Continental installations, and have found the conditions existing there to be somewhat different from those existing in this country, due chiefly to the extensive use on the Continent of hydro-electric power stations. The authors have mentioned several thermal storage installations where current is supplied at about 0·3d. per unit. My experience has been that very few consumers in the provinces are willing to pay this price for restricted-hour high-voltage supplies. I believe that at present the Manchester Corporation Electricity Department supplies current to dwelling-houses at the rate of £5 per annum plus ½d. per hour per unit consumed, this being a continuous low-voltage supply. In London conditions are slightly different; but in centres like Manchester 0·2d. is apparently the highest figure at which development can be expected to take place in the case of installations such as those mentioned by the authors. There are, of course, buildings where serious financial loss would be caused by dust and dirt damaging the stock, but in the majority of cases consumers are only willing to pay slightly more for the privilege of using electricity than they would have to pay if they used solid fuel, in spite of the fact that by using electricity they will avoid the dust and dirt inseparable from the use of solid fuel. My firm have found that these conditions are also applicable to oil-fired installations. The paper shows that suitable apparatus is now available, and the question of the future development of the large installations depends upon whether the power companies can bring down their charges sufficiently to justify their clients installing apparatus of the type described to us. Some years ago, at a joint meeting between the Institution and the Institution of Heating and Ventilating Engineers, a paper was read by Mr. Haden and Mr. Whysall, advocating the use of waste heat from electric generating stations. Many engineers are of the opinion that, if such stations could be erected in positions where industries using heat are located, the cost of generating electricity could be reduced considerably, and it might even become a by-product at certain times of the day. If this happened it would then be possible to supply current to districts some distance away from the generating stations at a price which would make the adoption of thermal storage schemes a paying proposition. On page 660 the authors refer to the fact that a panel-heating installation requires a lower circulating-water temperature than a radiator system. The panel system is therefore particularly suitable for use in conjunction with thermal storage schemes. Take, for example, the Carliol House installation. The water in the storage cylinders is heated to a temperature of 230° F. The normal temperature of the water in the panel system is 120° F., giving a margin of 110 deg. F. for heat storage. If a radiator system had been installed, with a normal working temperature of 160° F., the operating range in the storage cylinders would have been only 70 deg. F., and consequently cylinders of considerably greater capacity would have been required. Incidentally, we find that the total quantity of heat required to maintain conditions of comfort in buildings heated by the panel system is less than is found necessary in buildings heated by radiators. The authors did not mention one distinct advantage possessed by thermal storage installations: that is, that the maximum heat is available in the early morning, when it is most required. In some buildings sufficient heat can be stored up in the fabric and air to maintain a satisfactory temperature during the greater part of the day, when the heating apparatus is in use during part of the night and the morning. I know of one large building where the heating apparatus is only worked from 4 a.m. to 1 p.m., even in cold weather, and this enables the proper temperature to be maintained during the ordinary working hours, which are from 8 a.m. to 5 p.m.

Mr. J. Frith: We have heard a good deal about heat insulation of the apparatus immediately concerned to enable thermal storage to be carried out, but have any efforts been made to regard the building as a whole instead of merely the heating apparatus? All the pipes, cylinders and everything else are carefully insulated until we come to the actual building, and then we get rid of the heat at a tremendous rate. When faced with a heating bill of £2 000 a year, would it not pay to attempt to insulate the building? Those who have studied bricks know how very much they differ in thermal conductivity, and one might very easily use a brick which would halve the loss of heat from the building itself. I must protest against some of the terms used; for instance, a boiler is a thing that produces steam, and we should not refer to a water heater as a "boiler."

Mr. A. B. Mallinson: Whilst the cost per unit quoted in the paper is undoubtedly very low, I have no doubt that many of our supply engineers would be very glad to undertake "off-peak" loads of this character at between 0·25 and 0·27d., which is about 4 times as much as is paid in Canada for supplies for electric steam-raising. The authors indicate that this is quite a simple system, but it is extremely difficult to follow from the diagrams. For instance, in Fig. 4 there are 20 pipes leading away from the main plant, but the use of only three of these is indicated. In the figures given for Carliol House, "attendance" is *nil*. Surely somebody has to look after the apparatus. What happens if it goes wrong? For the coke-fired system, the authors give £550 for attendance. That seems to be an exaggeration. The authors mention that the system is easy to adjust, and if the day was warm less current would be switched on. The thermostats would of course maintain, say, 63° F. in the rooms, but are there not many days in our English winter when a lower temperature, say, 60° F., would be more comfortable? Has any trouble been experienced with corrosion, not particularly in regards to the electrode but in the boiler itself, and in the pipes? Can the authors give us any idea what it will cost to produce 1 000 lb. of steam or hot water at, say, 160° F.? It is a proposition which power station engineers would welcome in districts such as Lancashire where there are many works which are bound to have a certain amount of steam for their processes. If such manufacturers could buy steam at 1s. 6d. to 2s. per 1 000 lb. generated electrically on the off-peak system, it would induce them to do away with their own coal-fired steam boilers. Much has been said about the panel system which is practically universally adopted in all the modern skyscrapers in New York, but my experience in that city is that it is not altogether satisfactory. An even temperature is ensured, but this temperature may be excessive. The question of covering is mentioned in the paper and various statistics are given, but the authors are vague in their references to the class and thickness of cover adopted in the installations described. In considering this system we must always remember that coke-fired boilers are improving. There are on the market installations for coke-firing which are greatly in advance of anything produced 3 or 4 years ago, and recently I saw a coke-fired sectional water heater, of 1 000 000 B.Th.U. capacity and fitted with the Wollaston producer boiler, operating at over 80 per cent thermal efficiency. The overall efficiency could be slightly improved by raising the steam in the electrical boiler to a pressure of, say, 160 to 200 lb. per sq. in., passing it through a prime mover and exhausting into a low-pressure calorifier in the heating circuit, the supply from the prime mover being utilized in the heating circuit by a water heater. This would reduce the demand on the supply by 7½ to 10 per cent.

[Messrs. Monkhouse and Grant's reply to this discussion will be found on page 699.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 9TH DECEMBER, 1929.

Prof. E. W. Marchant: The case for electric heating is nowadays much stronger than may appear at first sight. With a modern power station having a thermal efficiency in the neighbourhood of 20 per cent the heat available in radiators or tubular heaters is practically 20 per cent of that in the coal. The ordinary open fire has an efficiency of about 30 per cent and the coal which is burnt in it costs at least twice as much as that used in power stations; it is evident therefore that electrical heating should be cheaper than the ordinary coal fire. As regards the heating of buildings by the means suggested by the authors, the case is not so strong, since the efficiency of the hot-water system with coke-fired boilers is much higher than that of the open fire. The figures given in the paper, of 35 000 B.Th.U. for 1d. with coke-fired boilers, as against 13 500 with electricity at 0·4d. per unit, emphasize this fact. I am inclined to think that the type of electrical heating which will be most popular in the future is that in which heating-tubes working at a fairly low temperature, or radiators, are employed. The great advantage of electricity is that the heat produced by the radiator can be generated precisely at the place where it is required. For example, the radiator can be put in front of a window if there is a draught due to the cooling effect of the latter, and one of the advantages of the electrical method is that the energy can be conveyed so easily to the place where it is to be transformed into heat. The only point in favour of the thermal-storage system is that it consumes electricity at times when it is not being utilized for other purposes. As time goes on and load factors improve, this will become of diminishing importance. There may be cases in which electrical heating by thermal storage will provide a practical solution, but I do not think it likely that they will be very numerous.

Mr. R. G. Devey: The authors have not mentioned the manufacture and life of the materials which have been used for the electrodes. I believe that common materials such as iron have been employed, but more information on these points would be of interest. It is well known that on the Continent electric boilers and storage schemes are used more than they are in this country. I do not know why this should be; it may be due to the fact that on the Continent a good deal of surplus power is available, probably because electricity can be purchased from hydro-electric companies on a kilowatt-year basis. The efficiency of thermal storage in the case of the electric boiler seems to be taken as 100 per cent. I do not think that this can be quite correct, because the night-load input of heat has to be retained and used over a period of 24 hours. It would be interesting to know the total efficiency over 24 hours, rather than over one hour only. In connection with the tubular type of heaters, I wish to ask the authors whether it is possible to use either alternating or direct current, also what is the most suitable material for the construction of the heater. On page 664 there is a paragraph in which the consumption for 2 000 cub. ft. is given as only 46 kWh per week, or something less than 1 unit per hour on a 12-hour day. This seems to be an extremely low figure. I find great difficulty in keeping a room warm with only 1 unit per hour. If electrical heating on the thermal-storage system were to be adopted on a large scale, there is no reason why this should not take place on the basis of the figures put forward by the authors. A large building like Carliol House requires 1 000 kW to provide heat for 24 hours, so that 50 similar buildings would consume a total night load of 50 000 kW. But in a city there may be several hundred buildings each large enough to require 1 000 kW at night time, so that the limits of a large power station would soon be reached, and cheap night power would come to an end. With reference to Appendix 2, page 665, showing a consumption of 100 000 kWh or about 3 740 million B.Th.U., to be compared with 500 tons of coke costing £650, I should be interested to know the calorific value of the coke. If this is taken as 11 000 B.Th.U per lb., the total heat from 550 tons is 12 320 million B.Th.U., which indicates that the coke scheme is worked at an efficiency of 30 per cent; it seems to me that the electricity supply could be shown to greater advantage.

Mr. M. P. Concannon: I am connected with the company which installed the plant at Carliol House, and I am convinced that if that system were adopted more generally by supply authorities and architects, considerable improvements in heating methods would result. It has been found at Carliol House that the panel method for supplying the heat to the rooms is very well suited to the thermal-storage system, because the panel system works at a lower normal temperature than the ordinary radiator system, the average temperature in the panel system being 120° F. The authors have pointed out that 230° F. is the upper limit of temperature to which the storage water is heated at Carliol House. This gives a much greater temperature-range than would be obtained with an ordinary radiator system working at 160° F. average temperature, and giving a temperature range of from 230° F. to 160° F., i.e. 70 deg. F. As the amount of storage water required depends on this temperature-range, considerably less storage space is required by the panel system. It is also found that the panel system requires somewhat less heat than a radiator system, to give equal comfort conditions in a given building. This point probably explains the apparently small electrical consumption per office of 2 000 cub. ft. capacity mentioned by the author, and referred to by a previous speaker as very low at 46 kWh per week. Owing to the radiant effect and to the fact that ceilings and walls are warmed, thus reducing body radiation in those directions, comfort conditions not directly measurable by the ordinary thermometer can be obtained with the panel system. In the past years, I believe, heating engineers have been somewhat unpopular with electrical supply authorities because of the many schemes for the private generation of electricity which have been put forward and carried out by heating engineers for some large public institutions. By utilizing the exhaust steam for heating purposes the overall thermal efficiency of the plant has been increased. If the thermal-storage system were to be adopted in such institutions, or elsewhere, it would provide an opportunity for heating engineers and electrical supply engineers to work together to their mutual advantage. From the architect's point of view, the thermal storage system presents a great advantage because of the saving in cost and valuable space which results from the elimination of flues. There is also greater cleanliness and absence of smoke with electrical heating. I think that if the expenditure involved in operating coke-fired boilers were to be included in the comparison, the total running-costs would work out more favourably for the thermal-storage system than the authors have shown. If the staff were reduced by one man only, the saving should, of course, be credited to the thermal-storage system.

Mr. A. H. Langley: The authors have shown that for large buildings thermal storage electrical heating is economically a sound proposition even though the initial cost exceeds that of a coke-fired system. A decided advantage of the electrical method is that the installation can be made entirely automatic. There are a few points in connection with panel heaters which have not been stressed by the authors and which I think worthy of mention; they are:—(1) draughts are avoided; (2) quite a considerable proportion of the heating-effect is by low-temperature radiation, which is preferable to air-warming; (3) no damage is caused to the decorations by convection currents such as are set up by the ordinary hot-water radiator. I should like to know whether a system of thermal-storage heating could be successfully applied to domestic buildings. It should be feasible to install such systems in the blocks of flats which are so common in London, and to add a fixed charge to the rent. It is also possible that, in future, city councils will have all-electric housing schemes on the following lines. Groups of houses will be arranged in rectangular formation, not scattered about as in the present schemes. They will be heated by a thermal-storage electric plant installed underground in the central space. Their domestic hot-water supply will also come from the installation. Electric cookers and electric light will complete the scheme, the running costs of which will, I think, be far lower than those of the present all-electric municipal corporation houses.

Mr. J. H. Collie: I have been connected with the installation of a number of tubular electric heaters, which are proving very satisfactory. Generally speaking, however, where the tariff is in the neighbourhood of 1d. per unit this system is only suitable for moderate-sized buildings which require occasional heating, such as schools, churches, halls and domestic buildings. For large buildings requiring relatively continuous heating, the running-cost at this figure is considerably in excess of that of other direct methods of heating. Recently, however, several large buildings have been fitted with tubular heaters on a special tariff of 0·5d. per unit, subject to continuous working on thermostatic control and to being cut off during peak-load periods. It is found that this method, which is really a simple type of heat storage, works very satisfactorily, and that the running-costs compare very favourably with those of other methods of direct heating. There has recently been introduced a new type of tubular heater fitted with spiral fins, which can be loaded up to 250 watts per foot, and which has the same outside temperature as the ordinary tubular heater working at 60 watts per foot. This reduces the initial cost considerably, as it is not necessary to double-bank the tubes in order to obtain the necessary heating surface. I should like to ask the authors whether any progress has been made with small storage heaters of the domestic type. The question has been raised of the possibility of heavy peak loads in cold weather in the event of considerable extension of electric heating. In this connection it was stated recently that some of the Canadian supply companies were not encouraging the electrical heating load on account of very heavy peak loads in the winter. A cold spell might embarrass some of the supply authorities in this country if electrical heating came into common practice.

Mr. S. Lowey: The building belonging to the railway company may not offer much difficulty, but, in the case of other installations, how is the load confined to the restricted hours? Is the switching accomplished automatically, or is it left to the consumer's representative to operate the switches according to time-table? The main storage of heat is really in the mass of the building structure itself, and in my view a water thermal-storage system in combination with electric panel or tubular heaters would reduce the installation cost. All these devices would of course be used only during the off-peak hours.

Mr. A. J. Pratt: One advantage in the adoption of the system of electrical heating is its application to the elimination of the smoke nuisance. I believe that in Liverpool, according to record, we are in the position of heading the list of statistics of various towns with regard to the smoke-content of the atmosphere. It seems to me, therefore, that any scheme whereby the smoke nuisance can be mitigated is to be welcomed. An article in the *Electrical Review* of the 29th November last mentioned the amenities of Tunbridge Wells and their close connection with the system of electrical heating and the installation of thermal-storage equipment. On the other hand there is a disadvantage in the electrode system of electrical heating of buildings by means of thermal storage. The paper mentions large installations of the industrial type, and it may be that the percentage cost of water-softening apparatus in such cases is inappreciable as compared with the overall cost of the equipment. However, if the ideal of a smokeless city is to be realized, the use of electrical heating apparatus will have to become fairly general and will need to be applied to groups of offices and residences, as well as to large industrial works. In some cities and towns the water is relatively soft, but in other cases the hardness of the water supply varies from 10 to 18 degrees. The cost of a water-softening installation as applied to fairly small residences is anything between £50 and £100, and to groups of offices the costs are considerable. It seems, therefore, that before the system can become of fairly general application, the small consumer will look for some adequate compensatory advantage. This may come in the reduced cost of building construction, in the avoidance of chimney stacks, etc. If one examines the cross-section of a water pipe in a district where the water is hard the bore of the pipe will be found to have been reduced to about 25 per cent of its original diameter. This is a serious factor which needs to be considered and disposed of before the electrical heating of small buildings can become universal. Local authorities should deal with this matter themselves, but unfortunately such bodies do not usually feel disposed to incur expense on these lines, even when there is a public demand for softer water for reasons of health. Plumbing work also needs to be very carefully completed, and unless air cocks are provided the whole of the system may need reorganization. I wish to ask the authors whether the capital charges quoted on page 665 include the cost of water-softening apparatus.

Mr. A. E. Malpas: The reasons given on page 657 for allocating a smaller proportion of capital charges to supplies for heating may be expedient for the purpose of further development of the heating of buildings by means of thermal storage. They seem, however, to suggest the fostering of one class of consumer at the expense of another. Great stress is laid on the saving of capital expenditure by not providing chimneys and flues in the buildings and houses. However, Prof. Parker Smith laid equal stress, I think, on the necessity for providing efficient means for ventilating all rooms. The need for efficient ventilation is exemplified in the case of the room in which we now are. I should like to ask the authors what type of water-softener has been used, whether the lime-soda or the zoolite process. In the case of the electrode heaters it would seem necessary to adopt some means for maintaining the constancy of the conductivity of the water in the system. This method of heating is inapplicable on direct-current supplies, owing to the evolution of explosive mixtures of detonating gas. Some of us have had experience of the difficulties created in the case of long and complicated pipe-systems due to the deposition of solid matter carried, either in suspension or in solution, in the water which circulates through them. I was interested in the use of the term "lag" as applied to a building, as, having adopted coke heating in my own house, I have been impressed by the slowness of the response of the inside temperature to a change in the outside temperature. I welcome the figures put forward by the speaker as to the number of B.Th.U. available per penny under the various systems quoted, and note that coke is the most economical of these systems, to the extent of about 500 per cent. In view of the ever-rising price of coal, it may perhaps be assumed that the use of coke will continue to be justified.

Mr. L. Breach: I should like to ask the authors whether they do not think it probable that the electrode type of heater will produce undesirable earth currents. With a slight deviation of the electrode from a central position in the boiler there will be a current to the casing of the boiler; this will become a leakage current and will have to find its own way back to the power station neutral connection. If there are several heating systems in proximity, and there are different deviations from the central positions in each, there will be an interchange of leakage currents through earth between the systems. Interference with telephone systems, etc., may result. In Liverpool there are some fine office blocks, equipped on the central-heating system, with coal-fired boilers, but it is found that although the offices are carefully heated, many tenants still have electric radiators. Possibly this is only for the sake of appearance and a cheery effect. Is any provision made, in the buildings mentioned in the paper, for tenants of this description?

Mr. F. E. Spencer: Supply authorities have to be very careful when offering supplies "off peak," as the peak may be moved in consequence. In my own experience the peak has been moved from 4·45 p.m. to 6·45 p.m. owing to the offer of a low tariff for domestic uses. The only safe hours during which an "off peak" tariff may be offered are, in my opinion, between midnight and 6 a.m. The rate of 0·3d. per unit mentioned in the paper is satisfactory for an authority which does its own generating, but when purchases are made in bulk more care is necessary in fixing the figure. It is proposed to erect new public swimming-baths in Birkenhead, and on account of the possible nuisance from smoke and fumes the question has been raised as to whether the water can be heated electrically. I should like to know whether the authors have any experience of the electrical heating of swimming-baths.

[Messrs. Monkhouse and Grant's reply to this discussion will be found on page 699.]

SCOTTISH CENTRE, AT EDINBURGH, 14TH JANUARY, 1930.

Mr. E. Seddon: The value of heat storage is consequent upon a cheap rate being offered for the supply of the necessary electrical energy. The system described in the paper provides just the kind of load that supply engineers desire at a time when the general demand is low, and a cheap rate can therefore be offered with mutual advantage to both parties. Some months ago I was able to inspect the Carliol House heat-storage system; the businesslike appearance and efficient lay-out of the plant impressed me greatly, whilst the figures produced by the authors show that it has been successful. As they point out, it is most important that storage cylinders for this purpose should be efficiently lagged, although I have not yet heard of the use of any commercial lagging which will provide an efficiency equal to 5 B.Th.U. per sq. ft. per hour. I am interested in the relative values of heat-insulating materials given on page 660. I find that Prof. Adams's handbook gives the following table of relative insulation conductances:—

Poultry feathers ..	6·2	Plaster of Paris ..	36·2
Hair felt	11·4	Asbestos powder	47·9
Cork powder ..	13·6	Fossil meal ..	52·1
Sawdust	14·2	Fine sand ..	56·3

A careful investigation of the many heat-storage plants now in operation, taking current during light-load periods, must appeal to station engineers who are interested in the levelling-up of their load curves. I believe it to be only a matter of time before all supply authorities will find it to their advantage to offer a low rate for this purpose. With regard to the method of applying the heat, it seems to me that the resistance type will prove to be the most popular form of heater for average-sized buildings owing to its simplicity of operation, especially where the supply is taken from low-tension distributors. I should like to call attention to the figure of 8 000 kWh per hour given on page 664 for the consumption of the London Underground Railway plant. Does not this represent the daily consumption? The tariff rate for restricted water-heating is given on page 665 as 0·3d. per kWh, whilst the authors in their lantern slides make comparisons at 0·25d. per kWh with other forms of energy. In my opinion, a rate of 0·3d. can be justified for high-tension supply under the conditions referred to in the paper, but I consider that 0·25d. is lower than most engineers will be prepared to go, even with an economical station.

Mr. A. F. Stevenson: It is interesting to hear of large buildings being heated in this way, but the costs have apparently been rather strained in order to make the electrical method come into line with coke heating. I think that smaller domestic installations would do more to fill up the valleys in the load curve. I am disappointed that the authors have not mentioned the electric heating system recently described by Mr. Haldane in which the heating effect is obtained by "reversing" a refrigerator. A comparison of the estimated costs would have been of interest.

Mr. W. Duncan: In order that the thermal-storage system may compete successfully with other heating devices, the electrical energy has to be supplied at a very low cost, and in fixing the latter it will have to be remembered that other night supplies are already being given at ordinary power rates. These rates are low enough to compete with those of other methods and to satisfy the consumers. The night supply is taken by bakeries, colliery pumping-systems, ice factories and for the machinery which prints the early morning editions of newspapers. It is difficult to see how a very low rate can justifiably be restricted to storage heating of buildings. It might be argued that in the latter the electrical supply is restricted, while no limitations are imposed in other cases. The nature of the work of certain consumers, however, is in itself a sufficient restriction in some districts. I cannot agree that a low rate can be given in the one case and not in the other, as there is no distinction between the claims of a consumer who is restricted by the supply authority and those of one to whom the exigencies of his business apply a similar limitation. If the suggested low rates are to be associated with all conditions of night load, the supply authority will require to lower the price to consumers who are already satisfied with the present tariff. All the systems described in the paper make use of water-heating. Have the authors any experience of the electrical oil-heated storage system? In this type of plant the oil, in which the heat is absorbed, is contained in a lagged tank and is passed through a calorifier. The water to be heated also passes through the latter, where it is heated, and then passed on to the radiators or hot-water draw-off points. It is claimed that the oil lasts indefinitely and that, owing to the high temperature at which the heat can be stored, the system can dispose of a quantity of useful heat which is many times as great as that with which a water storage plant can deal, under the same conditions. In addition, it has none of the disadvantages of a pressure system. I believe that several English municipalities are at present having this type of plant installed to provide heat for their showrooms and offices. It has been stated that domestic heat-storage plant is of greater interest to the supply engineer than the large installations which have been described, and I am of the opinion that if thermostatic control were to be introduced in conjunction with plant of that type, levelling of the load curve and improvement of the load factor would be more readily obtained. It would provide an all-the-year-round load which would be almost at its maximum in the summer time when coal fires are out of commission. As hot-water supplies are most commonly in use in the forenoon and late evening it is unlikely that the usual afternoon peak would be materially affected. I should like to ask whether, in the case of the building at Newcastle, the assessment was increased because of the installation of the thermal-storage plant. I think that such would have been the case if the plant had been installed in this district. Although nothing of the kind has as yet been used in Edinburgh, it is hoped that two 3-phase 450-kW electrode boilers for heating purposes will soon be on load. They are to be used for raising steam for the heating of incubators in which the chickens will also be reared after they have been hatched. This is of interest, from the power station standpoint, as an example of the variety of supply which is demanded. The cost of the energy will not, as yet, be at the rate of 0·25d. per unit, but the consumer is quite satisfied with the present rate, in view of the advantages of electrical heating.

Mr. G. Gunn: I should like to ask the authors what means are adopted by supply engineers to ensure that these comparatively heavy demands are restricted to off-peak hours.

Mr. R. Shaw: The authors mention that water has several advantages over oil, and I should like to ask what are, in fact, those advantages.

Mr. D. M. Macleod: The passing of Dr. Ferranti must have awakened feelings of regret in all. In his Faraday Lecture, two years ago, he gave a masterly review of the place of electricity in the service of man, tracing its development from the discovery of the lodestone to the present day. In forecasting the lines of future development, he dealt at some length with the question of electrical heating by means of thermal storage. He saw in that development a probable outlet for the electrical energy of large power stations, and the introduction of a night supply which would serve to level the valleys of the load curve. The authors have described the progress made during the past six years in this direction. Comparisons made between electrical development in America and that in Great Britain have hitherto been greatly in favour of the former. The progress indicated by the figure of 15 million units per annum for the consumption of these heaters during the comparatively short period since they were first introduced is, therefore, both surprising and gratifying. I was interested in the suggestion that the use of electrical heaters made chimneys unnecessary; if it is intended to apply to the usual domestic and office chimney with which we are familiar, the suggestion seems to be rather a bold one. It is a matter of common observation that were it not for the fact that they have chimneys in their rooms, many people would tend to stifle themselves. Chimneys do, in fact, serve a useful purpose in that they allow the vitiated air to escape. It would be a mistake to do without them. The question of the cost per unit of the energy with which the heaters are supplied is important and I am interested to find that the Newcastle installation is charged at the rate of 0·3d. per unit. It is very difficult to decide at what precise point a power station ceases to supply energy at a profit. I agree with Mr. Seddon, however, that 0·3d. or even 0·25d. is not too low a figure for a night load, in view of the fact that the additional output helps to keep down the standing charges per unit.

[Messrs. Monkhouse and Grant's reply to this discussion will be found on page 699.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 3RD MARCH, 1930.

Mr. R. H. Rawll: The paper by Messrs. Monkhouse and Grant is encouraging in view of repeated statements that although electricity can compete successfully with other forms of energy for power and lighting, yet for heating on a large scale it is not worthy of consideration. To counteract this pessimistic view it has been shown that at present there are electric thermal-storage plants, totalling over 12 000 kW, operating successfully in this country, and that the capital outlay on the plants installed is about £3 per kW. The authors are also to be congratulated on a paper describing not only actual installations in use, but also capital and running costs. Supply engineers should be interested in this form of night load, because it provides an ideal method of filling up one of the valleys in the load curve. It appears to me that at the moment the biggest opening for the systems described is in connection with new buildings; here the greatest economies and efficiencies would be obtained. There is, however, a wide field of opportunity for the adaptation of existing buildings to this mode of central heating, but I am of the opinion that concealed panel heaters would be ruled out on the score of cost and inconvenience of structural alterations, and in such cases tubular radiators or surface panels would have to be installed. The authors' views on this question would be valuable to many engineers. The cleanliness, convenience and efficiency of electrical heating as compared with other fuels have rightly been stressed, and they represent a definite cash value per annum which should be put to the credit of the electrical method when comparisons with other methods are under consideration. The monetary value of cleanliness and convenience is often used in propaganda work for domestic electrification, but it is difficult to impress upon the average householder the actual saving in terms of money. This difficulty should not arise in connection with large buildings, because here the savings are more apparent. Wages for stoking, space saved, collection of ashes, etc., are all items whose value a business man will readily appreciate. It is stated in the paper that in some cases it has been found necessary when using resistance heaters to insert these at different levels, or to employ a pump to accelerate the circulation during the water-heating period. The authors are no doubt aware that an immersion heater enclosed in an outer jacket, with inlet and outlet holes in the latter, has been designed for domestic use. An actual circulation of water thus takes place at the heater itself, the cooler water flowing in at one end and the hot water out at the other. On small tanks this has met with considerable success and it would be interesting to know if this method could also be applied to the larger installations to which the authors refer. The question of lagging is important and, as the authors point out, it is in all cases a matter of balancing the cost of the lagging material against the value of the B.Th.U.'s saved. There is, however, in my opinion, considerable need for research into this matter of lagging, for the success of electric thermal storage necessitates a supply of efficient, cheap and compact lagging materials. It must be confessed that the choice of such materials is at present very limited. With reference to the installation at the Banca Commerciale Italiana di Roma, it is not stated whether this is of the electrode- or resistance-heater type. I should also like to know whether a separate calorifier is utilized and the amount of the loading. With regard to the Carliol House installation, I had the privilege of inspecting this some time ago. I was impressed by the simplicity of the electrical equipment, the only visible part of which is a small switchboard. My visit coincided with the cold snap which this country experienced in the early part of last year, and, even under those conditions, all the offices and rooms in the building were comfortably warm. A figure of 46 kWh per week is given as the consumption per office. An ordinary electric radiator, which would be switched on for about 48 hours per week in the average office, could not be of a greater capacity than 1 kW for the same consumption; such a radiator would be unable to maintain a comfortable temperature. This comparison demonstrates very forcibly the efficiency of electric heating by thermal storage. It is not definitely stated in the paper, but I understand that the whole system of panels throughout the building is continuously in operation. It appears from Fig. 5 that the electrodes arc to a common neutral point. The metal casing of the boiler is earthed, and hence there appears to be a path from this neutral point to earth through the comparatively high resistance of the water. This seems to introduce multiple earthing of the neutral points on an e.h.t. system and I should like to know whether the Post Office authorities have given a general consent to this, or whether each installation has to pass their tests before permission is given. The hot-water service at Carliol House is taken from a secondary calorifier, but since there are 6 or 7 floors in this building I should like to know whether a number of storage tanks are used at different levels. This might be necessary on account of the possibility of the hot-water supply on the top floors cooling down, in which case comparatively cool water would be run off for a considerable time before the hot appeared at the tap. The automatic on and off switching of the London Underground Railway's installation is carried out, I think, on the main e.h.t. oil switch of the transformer supplying the low-voltage resistance heaters. The tariffs quoted for night loads by supply undertakings are important as regards developing and encouraging electric thermal storage. As an indication of the importance of this factor, if, in Appendix 1, the price of current had been 0·4d. per kWh instead of 0·3d. per kWh the running costs would have been increased by £90, and, in the case of Appendix 2, by approximately £450—which would possibly have turned the balance against the electric method. The authors also have been very generous in Appendix 2. There is a note that about £2 000 had been saved in buildings by using the electric method. In fairness, therefore, interest at 6 per cent on this amount should have been added to the running costs of the coke installation when a comparison was being made.

Mr. L. G. A. Sims: We in this country are now becoming acquainted with the storage principle as applied to the heating of water for domestic purposes, and the paper shows that the same principle can be successfully carried much farther by applying it to the heating of large buildings. I think that this is one of the branches of electrical engineering which we shall see develop considerably during the next few years when its importance to supply authorities has been more fully appreciated and its adoption has been encouraged. The authors are therefore to be congratulated on having put forward practical methods and figures. It would be unfortunate if, from the general title of the paper, the inference were to be drawn that thermal storage could only be successfully accomplished with water. Yet, apart from two short paragraphs on page 659, the paper is wholly concerned with water systems. I think that the authors should either have worded the title rather differently or, preferably, they should have made it clear that storage in water is only one of several commercially successful systems which have been in use in Europe for a number of years. I wish to confine my remarks, therefore, to two alternative systems for the heating of buildings by thermal storage of which I have had experience. The first employs local heating-units, usually in the form of "accumulation stoves." The complete cycle of storage of heat and subsequent release to the atmosphere takes place at the point where the heat is to be used. This system is used fairly widely in Switzerland, France and Germany for domestic and office heating; as it is scarcely more difficult to install than an ordinary electric radiator it clearly has important advantages in many instances over the elaborate central storage systems described by the authors. The disadvantage of this type of heater has hitherto been its poor temperature-characteristic during discharge. The accumulator has generally been made of stone or special gravel and, in order to obtain the necessary storage capacity, the temperature-range during charge (and consequently during discharge) has had to be considerable. The result is, in particular, a poor heat output towards the end of the discharge period. Furthermore, the heat losses during charge have been inconveniently great. For the past three years I have been concerned with work at the University of Birmingham upon the development of an accumulation heater of this general type: a design which avoids the defects of the Continental models and which shows marked improvements upon them in respect of the discharge characteristic, reduced losses and cheap manufacture, has been evolved. A solid accumulating mass, or core, of material easily obtained in this country is used instead of the special core materials of local origin such as are used in certain of the Continental stoves. The core volume per kW of rated capacity is very small—about 0·7 cubic ft. per kW for an 8-hour charging period. Mr. Sturley, who has been associated with me in this work during the last two years and who has carried out a great deal of the practical development, will give some further figures. I will merely emphasize the fact that, in this form of accumulation or storage heater, there exists not only an alternative method to that dealt with by the authors in their paper, but one which has great advantages in the many cases of existing buildings to which the application of a large central system would not be possible. Both the central system and this local unit system have a very low maintenance cost, and both provide a balanced 3-phase load at almost unity power factor. The local-unit system obviously has its most useful application in the heating of rooms of moderate size, for which a power of, say, 5 kW is sufficient. The second system of storage heating, which has been used in large schemes abroad with success, but which is not mentioned by the authors, depends upon storage in the floor mass. Heating elements are drawn into earthenware pipes embedded in the floor material. The system has a great deal to recommend it because the necessary heat is stored at a very low temperature—a consequence of the large storage mass available. I have seen this system in use in Switzerland: the temperature of the floor is so low that the impression gained when one presses a hand upon it is only one of lukewarmness. The heat, however, is continuously rising and, passing over the whole length of the body, it gives a pleasant sensation of gentle warmth. Temperature curves taken over a period of days show extraordinary smoothness. The following operating figures are remarkable. It is claimed that the heating elements work at a temperature of about 85° C. (185° F.), that is, well below the boiling-point of water. With all the elements working, the floor temperature is about 23° C. (75° F.) and the room temperature 6 ft. above the floor is about 18° C. (64° F.), under winter conditions. As there are no hot currents of air anywhere in the building the losses to the external atmosphere must be a minimum. In general, the vertical temperature-gradient is claimed to be such as to give a decrease of about 12 per cent of the floor temperature at a height of 6 ft. from the floor, and distribution of temperature horizontally is said to be absolutely uniform. The system seems to be very successful in Switzerland but it can only be adopted in conjunction with some form of ornamental tiled flooring. Wooden parquet would not be suitable nor, presumably, would linoleum, but small carpets placed about the floor have no serious effect upon the heating system. In a scheme which I worked out for a suite of offices in this country the only disadvantage was found to lie in the high price quoted for the elements, but this objection should not be permanent. For an installation in the Swiss Popular Bank at Zürich the data are as follows: 1 000 m^2 of floor area are heated by a 500-V 3-phase supply, the total loading being 270 kVA at almost unity power factor. Each element has three alternative loadings and the maximum is about 90 watts per ft. The accumulation mass is a river gravel plentiful in Switzerland. Thermal insulation is inserted on the lower side of the mass in those cases where no diffusion from the under side of the floor is desired.

Mr. K. R. Sturley: The authors will have accomplished much if electric supply undertakings are led, as the result of the paper, to give more serious consideration to the development of an off-peak load. The different conditions under which Continental authorities work—many of the systems utilize water power with its high capital charges and comparatively small running costs—have certainly encouraged the consideration of an off-peak tariff. Unfortunately, the issue in Great Britain is complicated by the fact that coal is comparatively expensive as a source of power. This difficulty, however, is not insurmountable and I hope that competitive facilities at competitive prices will soon be given for off-peak thermal loads. Of the two methods described in the paper, the separate wire-wound resistance is the better, for any electrical breakdown can be repaired without opening the boiler. In connection with resistance heaters, it is stated in the paper that the load during the heating period is automatically controlled. Why is there any necessity for this? Temperatures in the early autumn are, for example, usually higher than those of mid-winter so that some sort of seasonal control is necessary, but load variation during the 12-hour heating period should not be necessary. Wear of the electrodes and the need for constancy of the resistance of the water are the disadvantages of the electrode boiler, and I should be interested to know how long the electrodes will last under ordinary conditions. Under the heading "Consumption," in the description of the Carliol House installation, the electrical consumption per office of 2 000 cubic ft. capacity is given as 46 kWh per week. Can the authors give any information as to the number of hours weekly for which the boilers were in circuit? When research upon heat-accumulation stoves was being carried out at the University of Birmingham, the need for further development in connection with laggings was strongly felt. Difficulties were experienced in finding any connected report upon heat-insulating materials and I agree with the authors in their remarks on this point. These stoves, which have been briefly described by Mr. Sims, are designed to work by storing heat during 8 hours and discharging during the remaining 16 hours. The maximum temperature in the Continental design was about 340° C. (646° F.) and the storage factor was 46 per cent. The storage efficiency will actually be higher than this, but the experimental difficulties involved in making an accurate determination are considerable and, in order to obtain a basis of comparison with later improvements, the expression called "the storage factor" was adopted. This storage factor is the product of the heat capacity (specific heat × weight) of the core multiplied by its mean temperature-rise. It does not take into account the heat stored in the heating elements, the case and lagging, and the bed-plate. As was to be expected, this stove gave a bad discharge-characteristic, the room temperature being far too high at the beginning of the 16-hour discharge (about 75° F.) and too low (about 55° F.) at the end of this period. In the design which has been developed, all these defects have been almost completely remedied. A different solid storage-medium and laggings of ordinary commercial thickness and material have been employed. The maximum temperature is still 340° C. (646° F.) and the storage factor is as high as 72 per cent, under suitable conditions. Marked improvements are registered in the outer-casing temperatures; a reduction of nearly 70 deg. C. (158 deg. F.) from 105° C. to 35° C. (95° F.), has been effected. The storage factor may not appear quite so high as would be expected from a water storage-system, but it must be remembered that all the heat "lost" during the charging period is given out at the point at which it is required. In this respect it is more efficient than the thermal storage water-heaters which give out heat to the boiler room, where little use can be made of it, during the whole 24 hours. No figures for the storage efficiency of the installations described in the paper are given, and, even if these figures were available, I doubt whether they would show any advantage over the solid-core type of storage heater. The authors comment on the variation of heat-flow from solid storage-media at different temperatures, and in the new design this feature has been so successfully eliminated that an even room-temperature is preserved over 13 out of the 16 hours of discharge. There is a slight fall during the remaining 3 hours, with a sharp drop at the end of the discharge period, when the supply of heat to the room is cut off. Provision is made for control of the input of heat to the stove so that at the beginning of autumn, when a comparatively small amount of heat is required, the room is not overheated. Another good feature of this method of thermal storage is the almost complete absence of maintenance costs. All the materials used in the stove are of robust construction and are almost everlasting. For office use, where a steady room-temperature is required for about 10 hours, this stove may develop into a formidable competitor of the water thermal-storage system of the central heating type.

THE AUTHORS' REPLIES TO THE DISCUSSIONS.

Lieut.-Col. S. E. Monkhouse and **Mr. L. C. Grant** (*in reply*): We must all have felt the warmth and enthusiasm of Dr. Ferranti's characteristic and far-seeing contribution to this discussion. We mourn the passing of this great engineer and kindly personality. Dr. Ferranti was a prophet in a great many things and his latest remarks on this branch of electrical engineering for which he has done so much are surely words of true prophecy which will encourage us to persist in a work which can mean so much to the electrical industry.

Several speakers seem rather surprised that electrode boilers can be operated from a single electrical power source, a practice which has been common on the Continent for many years. Before the decision was made to install electrode boilers in this country, a comparison of Continental with British conditions was made and a number of Continental installations were inspected and discussed with power suppliers and users. There seems no doubt that boilers may be so used without causing trouble to communication circuits or protective gear from diffusion of the earth currents, and the experience of the last few years in this country has shown that reasonable precautions only are required to ensure trouble-free working.

We share Mr. Betts's opinion of the effect on economy of unskilful stoking; there seems no doubt that at least 10 per cent and probably 20 per cent reduction in consumption can be obtained by the use of thermal storage with automatic regulation.

Mr. Betts and other speakers have analysed the elements of the cost of a unit of electricity and it is interesting to note Mr. Betts's experience that electricity must be supplied at 0·2d. to compete with coke. Many heating plants have, however, been installed which use handier and possibly cleaner fuels than coke and usually an increase in overall operating costs of, say, 25 per cent is regarded as a fair figure for the improved facilities and amenities, which brings us again to the zone of $\frac{1}{4}$d. a unit. When, therefore, it is considered that the flexibility, cleanliness and other attributes of the electrical method are ahead of what can be obtained with any other method of heating, the small increase in operating costs should not be an important factor. In countries where central heating is largely employed, the tendency is more toward an appreciation of factors other than the fuel cost and we have been impressed with the attitude of American engineers who are accustomed to large central heating plants and who have on several occasions voluntarily expressed the opinion that the peculiar advantages of electrical thermal storage are worth not 25 per cent but 100 per cent increase in cost.

Mr. Kemp discusses the same question, and he also shows a tendency to differ about the 0·05d. This does not seem to be the logical attitude; the actual existence of that relatively small fraction of a penny is debatable, but even should it be a reality it is a very small sum to pay for the elimination of dirt and soot.

Mr. Chew should note that in the cost data on the lantern slide, labour and other charges must be added to the coke-plant figures.

Mr. Clothier's remarks and the figures he has obtained from the electrical thermal storage plant at his residence are of great value. He shows that the figures relating to the Banca Commerciale di Roma are not in agreement with the Carliol House figures when compared on the basis of a cubic foot and degree F. rise per day: we agree that the higher figures are more suitable for British conditions. Dr. Semenza's figures for the Italian Bank were obtained at an early stage of the experience with the installation, but what is more to the point is that the Italian method of calculating building cubical content seems to be different from the British method and in the Italian bank figures there is apparently an unheated section included in the cubical contents.

Mr. Linstow refers to the possibility of earth leakage and emphasizes that sensitive protection is required. Some of the storage installations with which we have been associated have been protected by means of fuses controlling banks of immersion heaters. Fuses can be obtained to blow reliably on the occurrence of 10 per cent overcurrent. Even in quite small installations there are at least four groups of heaters, so that this method is equivalent to a fault setting of $2\frac{1}{2}$ per cent, which is obtained at a relatively low cost. A circuit breaker is better but is economically justifiable only in the larger installations.

Mr. Clements asks what proportion of the substation charges would be debited to the thermal storage in an installation such as that at Carliol House. No substation is required as the installation is operated at the transmission voltage, but the switchgear (two ironclad oil switches, one for each boiler) and cablework are charged entirely to the thermal-storage installation.

Mr. Richardson refers to oil-storage installations, but it is believed that so far there are no oil-storage central heating installations in operation. Oil storage is, of course, in use for certain types of industrial work. The figures in the paper refer to oil storage with oil circulation; if water circulation is used with oil storage the storage range will be smaller. There is more to be taken into account than the mere storage range. The capital cost of the oil is considerable; it may easily be 25 per cent to 50 per cent of the total capital cost and an annual oil leakage of over 5 per cent has to be provided for. Mr. Richardson also suggests that the immersion-heater type of installation is more likely to be the general method of the future because of its simplicity. In our opinion this type of installation is usually cheaper and, of course, simpler for installations up to about 400 kW, where usually the available transformer or mains capacity is sufficient, but in larger sizes where the cost of special transformers would influence a decision an electrode boiler system is often cheaper.

With regard to Mr. Williams's remarks, the appendices were intended to show only actual results. A note is added to Appendix (2) to show the influence which the cost of flues would have, and in another part of the paper the effect of a thermal-storage installation in releasing more space for human accommodation is disclosed. These two factors alone in a modern building are sometimes sufficient to swing the balance to the electrical method. The prices for coke plant in Appendix (2) do not cover duplicate plant.

We are obliged to Mr. Howard for pointing out the error in the description of the Sulzer boiler; this has been corrected for the *Journal*. He appears, however, to have forgotten that with a steam boiler and calorifiers a greater storage capacity can be obtained for a given amount of equipment, because a higher average temperature can be obtained in the cylinder. Electrodes have been replaced both in the motor depot and the Carliol House plants.

In reply to Mr. Swale, no troubles have been experienced with high-tension boilers connected to an earthed neutral system.

Mr. Howarth's first question has already been answered. Some of the boilers in use have been connected to systems which on several occasions have had earth faults and on which consequently the electrodes of the other two phases have risen above their normal potential difference to earth. This appears to be much a matter of design, as in the case of switchgear and transformers. The actual balancing of the boilers is very nearly complete and there is never sustained out-of-balance in any particular phase. There may be a temporary out-of-balance on one phase but it quickly disappears, and variations are fortuitous and probably due to outside influence. It should be remembered that an electrode boiler does not introduce a direct path to earth. There is the considerable resistance of the water to take into account, and the resistance to earth is much greater than the resistance between phases, so that the tendency for earth current to pass is very small.

With regard to Mr. Sunlight's remarks, the elimination of a tall chimney stack and the release of space for rent production must be of great value to an architect. With a low-temperature panel system the atmosphere should be nearly perfect as there is no burning of dust particles to cause irritation of the pulmonary system or any production of fumes or noxious gases. It is debatable whether the " complication " of the electrical system is as great as the complication of, say, an oil-burning system, and the wear and tear and replacements required in connection with an electrical system are unquestionably smaller than with any known heating system.

Mr. Jewsbury emphasizes one of the advantages peculiar to an electrical thermal-storage system, namely, that normal room temperature is available at any time, even early on Monday morning.

With regard to Mr. Frith's remarks, the term " boiler " is used in the paper with all reserve and the term " water heater " is applied to installations which do not involve the production of steam (see page 659, par. 1). Incidentally it is debatable whether a " boiler is a thing which produces steam."

It is doubtful whether current is available anywhere, as Mr. Mallinson suggests, at " a quarter of the price paid here." Even on the few unique Swiss installations where energy is supplied from the pre-State-electrification hydro-electric power stations (all capital charges being written off) we have found no example of current being supplied at such low prices as 0·06d. and 0·075d. per unit. Although the thermostats are set for 63° F. they can be altered to any temperature between that of the ambient air and 70° F. The cost of obtaining a given quantity of steam at a given temperature can be calculated from the data given in the paper.

In reply to Mr. Devey, the radiation loss from the boiler is absorbed in the building, but the efficiency referred to was actually inherent efficiency. There does not appear to be any reason why direct current and alternating current should not be almost equally suitable for immersion heaters.

Mr. Collie is no doubt aware that large numbers of small storage cylinders have been installed for hot-water service. There are also one or two domestic central-heating installations working on the thermal-storage system. Simple apparatus has been developed to equip such installations, and small boilers of suitable form have been shown on the lantern slides. Mr. Collie's remarks with regard to the Canadian companies are interesting, but is there not something more to be added to this, namely, that the rate at which the domestic load has grown recently in Canada has outgrown that provided for in the Hydro-Electric Commission's concession?

In reply to Mr. Lowey, time switches are used for switching on and thermostats for switching off.

Mr. Pratt seems to have discovered that his town heads the list of towns with regard to atmospheric pollution. At one time we understood that Newcastle-upon-Tyne held that record, but a little while later it was noted that Sheffield had the honour. It is very evident, however, that the soot and smoke content of the atmosphere in large cities is a grave danger both to health and to building structures. In reply to a further question, a water-softening plant is unnecessary in small installations; simple methods are available by which this can be avoided. The figures on page 665 include the cost of water-softening apparatus. Mr. Malpas also discusses water-softening. It should be emphasized that a water-softener is purely an economical factor and not a necessity. The temperature-lag between the structure and the inside air and the outside atmosphere are important factors in the design of a heating installation; one of the lantern slides shows not only the time required to raise the temperature but also the time required for it to fall after heat is cut off. In his remarks on the relative cost of various fuels, Mr. Malpas has forgotten the all-important question of efficiency.

Mr. Breach again raises the question of earth currents, which have already been dealt with. His remarks give the impression that the adjustment of the electrodes is a delicate matter, but this is not so. He states that in Liverpool in centrally-heated offices the tenants still have electric radiators. Perhaps the central-heating installations are designed to be used with radiators for topping up.

Data in connection with the heating of swimming baths have been sent to Mr. Spencer.

In reply to Mr. Seddon, the economic point for lagging with thermal-storage installations with current at about 0·25d. per unit appears to be about 15 B.Th.U. per hour (average storage temperature). It is encouraging to find Mr. Seddon stating that it is only a matter of time before all supply authorities will find it to their advantage to offer a low rate for thermal storage. His own far-sighted and successful tariffs are well known. The heating rate of the Underground plant should be 8 000 units per *day*, not per *hour*.

Mr. Duncan questions whether a low rate is justifiable for restricted supplies. In Switzerland, Germany, Italy and other countries this is an accepted method. His remarks with regard to oil storage are interesting; we have considered oil storage for several installations but so far have not found oil storage economically justifiable. Some of the factors which must be considered in connection with this problem have been mentioned in a reply to an earlier speaker. What *are* the disadvantages of a pressure system? The installation of thermal-storage plants in Newcastle has affected neither the rates nor assurance assessments.

In reply to Mr. Gunn, usually the method of confining supplies to off-peak hours is to use clock-switch control which defines the hours of and makes available the supply, while thermostats are used to switch the plant on and off when necessary.

In reply to Mr. Shaw, the chief advantages of water over oil are that oil costs about 15 000 times as much as water, that the fire risk is greater with oil and that leakage is more troublesome with the latter.

Replying to Mr. Macleod, when flues are not embodied in a structure a simple form of wall ventilator or the judicious use of the window usually provides inexpensive and effective ventilation. A chimney is surely an expensive form of ventilator.

In reply to Mr. Rawll, the Banca Commerciale di Roma installation utilizes electrode boilers. The rating of the boilers is about 1 000 kW. Referring to the Carliol House installation, it should be noted that there is no arcing inside these or any electrode boilers. Only one storage tank is used for the hot-water service at Carliol House, and the pressure is maintained from the high-pressure town main.

We have investigated the "accumulation" stoves mentioned by Mr. Simms. Changes in design would appear to be necessary before such equipment could be generally adopted. The accumulation stove reverts to the unit heating idea and is not truly central heating. One of the obstacles to the more extended use of the accumulation stove is their high cost and their excessive bulk. We have inspected the floor-heating method adopted at the Popular Bank at Zurich and similar installations; as Mr. Simms states, the chief objection to the extended use of this method is the cost.

Mr. Sturley asks why automatic regulation is required for resistance heater installations. Because the two 12-hour cycles differ in requirements day by day and because the water temperature throughout the cylinder varies, the control gear must be prepared to take up different amounts of energy on successive days and also to cut out heaters when one part of the cylinder becomes sufficiently warm (another part may not be up to maximum temperature). Electrodes in electrode boilers give very satisfactory service and at a conservative estimate should last, under full-load conditions, more than 1 000 hours. The Carliol House boilers normally run for the whole of the week. The remarks regarding lagging are interesting and bear out our experiences. Attention was paid to the insulation and economic value of laggings before any specification was prepared. Lately an effort has been made to use methods of heat conservation which are not truly laggings. Highly polished surfaces such as prepared aluminium foil and chromium plating have the great advantage of lightness but are somewhat handicapped by the cost of installation.

The coke-boiler efficiency referred to by Mr. Freeborn is not in any way unusual; perhaps he has not counted stand-by losses: the attendance figures have already been dealt with. Mr. Freeborn is evidently able to obtain fuel oil from a source and at a price which we have so far not discovered. There is an obvious error in his B.Th.U. figures. The proposed installation which he outlines would be expensive and elaborate when due regard is paid to modern methods of giving electrical supply and other public services. The remainder of his remarks do not come within the scope of the paper.

Mr. T. G. N. Haldane (*in reply*): I should like to record how much I appreciated the late Dr. Ferranti's comments on my paper and with what deep regret I received, a few weeks later, the news of his death. Dr. Ferranti's remarks were of the greatest interest as they described his personal discussions on the subject of reversed-cycle heat engines with Lord Kelvin, to whom the world owes the fundamental principles of the operation of all heat engines. As is noted in the paper, Lord Kelvin describes the reversed-cycle heat engine in his "Collected Papers" (vol. 1, p. 515). This description was written in 1852 before refrigerating plant had been developed technically to any appreciable extent. Consequently he deals with the air-compressor type of plant, which has of course been long since superseded by the ammonia plant and other systems using condensable gases. Refrigerating plant is now developed technically to a stage which makes the heat-pump plant a much more practical proposition than it was when Lord Kelvin first suggested the idea. Unfortunately, the fact that the proposal when first put forward was turned down as impracticable, diverted attention from the method so that at a later date when technical progress had made the idea practicable it received little or no further consideration.

I am interested to note that Mr. Betts considers that electricity at the price of 0·2d. per unit will compete on a heat basis with coke. Although this is a low figure a heat pump operating with an average efficiency of 3·5 would, on this basis, compete with coke if supplied with current at the not unreasonable cost of 0·7d. per unit. This point is also illustrated by the figures given by Mr. Chew.

I am glad to note that Mr. Chew considers the figures given in Table 1 to be conservative. His long connection with the refrigerating industry and his great experience in the testing of refrigerating plant make his opinion on this matter particularly valuable. I am also fully in agreement with him with regard to the practicability of making the heat-pump plant fully automatic, and so reducing labour charges to a minimum. As regards reliability and safety, I think it would be difficult to find any plant much safer and more reliable than refrigerating plant. The reason for this is that the two moving parts of the system, i.e. the electric motor and the compressor, have all the essentials of inherent reliability. An electric motor is of course an extraordinarily reliable machine and the compressor, which runs at a comparatively low speed and is not subject to any violent shocks, explosions or high temperatures such as occur in an internal-combustion engine, is therefore also extremely reliable. The number of antiquated refrigerating installations which are to be found in operation in various parts of the country is a tribute to this inherent reliability.

Mr. Bolton describes an air-type plant which he suggests as an alternative to the ordinary condensing-gas type of plant. The scheme he puts forward is similar to Lord Kelvin's original proposal, except for the suggestion that the expansion and compression cylinders in Lord Kelvin's scheme should be replaced by a fan and that the receiver should be replaced by a long length of pipe on the suction side of the fan. The idea is attractive in its simplicity, but unfortunately there are several difficulties which make the proposal somewhat impracticable. In the first place, as Mr. Bolton himself points out, a very considerable length of suction pipe would be necessary; this might be difficult to arrange and might involve serious air friction losses. Mr. Bolton assumes that the air drawn into the pipe on the suction side of the fan will be cooled and will therefore take in heat from the surrounding air. In point of fact, however, the air drawn into the pipe is not doing work and, as in the case of gas passing through a reducing valve, will not appreciably change in temperature.

The conditions are, in fact, quite different from those obtaining in Lord Kelvin's scheme, in which expansion is carried out in a cylinder and the air is cooled by the equivalent of the work done against the moving piston. Apart from this, the efficiency of the fan would be low compared with that of an ammonia compressor. An overall mechanical efficiency of about 80 per cent can easily be obtained on an ammonia plant, but the greatest efficiency which could be hoped for with an air fan would necessarily be very much lower than this figure. For these reasons I do not consider that Mr. Bolton's scheme, exceedingly interesting though it is, can be put into practice. If the heat-pump system were to be widely used in London I do not think there would be any risk of a serious reduction in the atmospheric temperature, such as Mr. Bolton fears. All the heat passed into the buildings must sooner or later find its way back into the atmosphere, and in addition there is a small gain due to the heat equivalent of the electrical energy used.

Mr. Baker compares the operation of the heat pump with that of a battery booster, which, by raising the voltage of the battery, makes available its energy by allowing it to discharge on to the busbars. This analogy may be of some assistance, but it can only be applied to a very limited extent. The energy of a battery can, by means of a booster, be transferred from the battery to the busbars without the need of any source of external energy, but heat cannot be transferred from a cold to a hot source without employing some external source of mechanical energy. Mr. Baker's suggestion of the combination of the swimming bath and the skating rink is quite practicable and had, in point of fact, been seriously considered. A more obvious combination is that of the heating of a building with the production of ice for commercial purposes.

I am much gratified to have Prof. Marchant's support and I share his hope that the heat-pump system will be the subject of research in the future, this being one of the principal objects of the paper.

Mr. Stobie points out that the absence of an expansion cylinder leads to increasing loss with increasing condensing temperatures. This is correct, but for any moderate range of temperature such as that considered in the paper the loss is comparatively slight, whereas the additional complication would be considerable. The suggestion that butane should be used for small machines working at high temperatures is interesting and the low-pressure characteristics of this substance might be of value for high-temperature work. As regards the effect of superheating, it is theoretically desirable to operate the plant "wet" so as to avoid superheat, but the gain in efficiency is not great as compared with "dry" operation, provided the amount of superheating is not excessive. In practice ammonia plant is found, on the whole, to operate more satisfactorily with a "dry" cycle, mainly because the "dry" cycle avoids condensation and evaporation losses to the cylinder walls. The figures given by Mr. Stobie from his tests on a $\frac{1}{6}$-h.p. belt-driven refrigerator are of the greatest interest and it is to be hoped that he will continue his experiments on larger machines. Taking into account the very considerable losses due to the small size of machine and the belt drive—which together probably amount to more than half the input to the machine—the results are remarkable. It is unfortunate that the tests were not taken with larger quantities of water over longer periods and with well-lagged tanks. Test 6 shows an average efficiency of over unity for heating water to over 130° F., which for such a very small machine is a good performance. With a reasonable-sized plant this efficiency would obviously be very much higher.

INSTRUMENT TRANSFORMERS.

By J. G. Wellings, Associate Member, and C. G. Mayo, M.A., B.Sc., Graduate.

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Summary.

The paper deals in a general way with the whole field of instrument transformer work, and in a more extensive manner with certain developments and views for which the authors are more particularly responsible. Among these are the following:—

Current Transformers.—(i) Short-circuit limitations are described, the conclusion reached being that reduction of ampere-turns is the only real means of increasing the short-circuit capacity.

(ii) *Accurate transformers for metering.*—The conclusions reached are that high accuracy can and should be obtained without recourse to a large number of ampere-turns, and that single-turn or bar-primary transformers with compensating windings should be used on all heavy-duty circuits.

(iii) *The design and application of current transformers for protective-gear systems.*—The conclusions reached are that current transformers are not necessarily the limiting features in the performance of protective gear; but that transformers for protective systems can and should be designed to be "ideal transformers" as far as the requirements of the protective systems are concerned.

Voltage Transformers.—(i) General features are described, the conclusions being that voltage transformers on low-voltage circuits are a satisfactory proposition subject to suitable provision of protective fuses and resistors.

(ii) On high-voltage circuits means of eliminating voltage transformers are described, by utilizing an existing power transformer, and connecting the voltage transformer to the low-voltage side and compensating for regulation of the power transformer.

Special-purpose Instrument Transformers.—Design and application of current and voltage transformers with varying ratio characteristics are described, especially in regard to voltage- or current-change amplifiers for the more sensitive operation of relays, voltage regulators, etc.

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Special-purpose instrument transformers.

Varying ratio features for special purposes.

Voltage- and current-change amplifiers.

Introduction.

General Considerations of Instrument Transformer Design and Application.—The subject of instrument transformers, in the authors' opinion, deserves more specialized attention and general publicity than it has hitherto received. It is admitted that instrument transformers are only ancilliary apparatus; nevertheless, they are of such importance in modern switchgear that, unless specially considered, they may constitute the weakest point in the gear.

The general requirement is that they shall be capable of giving the desired accuracy under normal load conditions, particularly bearing in mind the high degree of accuracy now necessary, and that they should also be able to withstand, as an ordinary occurrence, the extreme overload or short-circuit conditions to which, as part of the main circuit connections, they will repeatedly be subjected.

Hitherto, there appears to have been some tendency to consider the instrument transformer either purely from the meter or from the switchgear point of view.

Naturally, from the meter standpoint, the first consideration is that the transformers should be highly accurate; viewed from the switchgear standpoint, primary importance is attached to rendering the transformers suitable for the switchgear and for the short-circuit conditions which require to be met. The result, in the authors' opinion, is that one or other of these two somewhat conflicting requirements is generally to some extent overlooked; and hence little advance has been made in producing a transformer which meets equally the requirements of both the switchgear and metering interests. Instrument transformers for protective gear should embody certain features which are no less important than either metering accuracy or ability to withstand short-circuit conditions. The authors have, therefore, made a special study of instrument transformer design with a view to reconciling the needs of all three interests. It is with these matters that this paper deals, in addition to reviewing the subject in general and describing recent advances in design and application for which the authors have been responsible.

Before passing to the separate consideration of current and voltage transformers, it may be appropriate to touch on the fundamental difference in the performance of a current transformer as compared with that of a voltage transformer.

A voltage transformer functions in the same way as a power transformer, but special attention must be given to minimizing the losses in order that the secondary voltage may be an accurate representation of the primary voltage both in magnitude and in phase.

A current transformer, however, functions on an entirely different principle. Whereas in a voltage transformer the effect of secondary burden is to produce current through the windings without appreciably affecting the flux in the core, in a current transformer the effect of burden is to produce flux in the core without appreciably affecting the current in the windings. A further contrast is that zero burden on a current transformer corresponds to a short-circuited secondary, while on a voltage transformer this condition corresponds to an open-circuited secondary.

In a current transformer, it is the production of flux in the core that has hitherto been the source of all error; thus, in order that the secondary current might be an accurate representation of the primary current, it has been necessary to keep to a minimum the losses incurred in producing the flux. The authors have, however, developed means by which the errors of a current transformer are no longer merely a function of these losses, but may be compensated for, and the accuracy of the transformer maintained, even though the losses may be relatively high. This has naturally changed the whole outlook on current transformer design and application, and is having a far-reaching effect on switchgear in general.

CURRENT TRANSFORMERS.

Current transformers may be broadly divided into two types:—

(1) Metering transformers for the operation of meters and plain overload relays. Such current transformers are only required to give a predeterminable performance from light loads up to approximately 50 per cent overload.

(2) Protective transformers for the operation of protective gear. Such current transformers are required to give a predeterminable performance from comparatively light loads up to extreme overload corresponding to the maximum "through" short-circuit current to which the protected zone may be subjected.

Both types, however, must of necessity be capable of withstanding the maximum short-circuit current to which the circuit may be subjected in the event of a fault occurring in that part of the circuit where the transformers concerned are installed. Unless this requirement is fulfilled, the transformers are always liable to be a source of trouble; and in protective gear applications the trouble is of a more serious nature in that the protective gear itself may become inoperative, resulting in considerable damage. The subject of the short-circuit rating or capacity will, therefore, be reviewed in some detail.

(A) SHORT-CIRCUIT CAPACITY LIMITATIONS.

Current transformers, being series-connected apparatus, should at all times be able to withstand any condition of through short-circuit current or transient voltage to which the circuit may be subjected. An approximate value of the maximum through short-circuit current to be allowed for can generally be deduced from the rupturing capacity of the switchgear on that part of the circuit concerned. It is practically impossible, however, to predetermine what value of transient voltage may occur.

A current transformer subjected to either one or other or a combination of both of these conditions may fail in three ways if it is of the multi-turn primary construction. The bar-primary type of construction is to all intents and purposes proof against failure under any condition of short-circuit, and such transformers may be regarded as being as reliable as the actual circuit connections.

Reverting to the multi-turn primary transformer, the causes which may lead to failure under sufficiently extreme conditions of short-circuit are as follows:—

(1) Thermal Effects, i.e. extreme overheating of the windings due to the magnitude of the short-circuit current and the time for which it is maintained. Predetermination of thermal effects presents no great difficulty, the principal uncertain factors being the cooling effect of the surrounding material, and the degree of asymmetry in wave-form during the initial period of the short-circuit.

(2) Mechanical Effects, i.e. bursting forces in the windings due to the maximum peak value of short-circuit current. Predetermination of mechanical effects is difficult, particularly as the forces may act in such a way as to damage the insulation between turns and cause local short-circuiting and consequent breakdown.

(3) Electrical Effects, due either to transient voltages "piling up" on the end turns of the primary winding and causing short-circuits between turns, or to actual puncture of the primary insulation from the same cause. It is not feasible to predetermine the electrical stresses, but, on an average primary winding

a surge of comparatively moderate frequency can cause sufficient voltage per turn in the primary winding to puncture the average insulation between turns, especially in view of resonance between inter-turn capacity and inductance, which may have the effect of piling up the voltage on the end turn.

A transformer may fail electrically owing to voltage transients only, depending on the steepness of the wave front, without the occurrence of heavy-current conditions; i.e. a transformer suitable for withstanding the short-circuit current conditions is not necessarily able to withstand the transient voltage conditions to which it may also be subjected. The authors have attempted to deduce for multi-turn primary transformers what may be termed a "short-circuit factor" which will express as a multiple of the rated current that current which an average multi-turn current transformer will withstand under average conditions of short-circuit.

It can be shown that the primary is the limiting feature as, owing to core saturation, the secondary winding cannot be subjected to much more than about 40 times full load. Accordingly, from considerations of an average primary winding, based on thermal effects, this factor appears to be about 150; but if based on mechanical effects the factor appears to vary between 50 for long rectangular coils, and about 400 for a circular coil, and is probably in the neighbourhood of 200 for an average rectangular coil.

According to the authors' experience and investigation, however, electrical effects as defined in (3) above comprise the limiting feature in the majority of cases, and the limit which is imposed by such electrical effects, caused by extreme overload conditions, appears to be about 100 times rated current. A current exceeding this value is liable to cause sufficient piling up of voltage to puncture the insulation between turns and cause a breakdown. Currents of smaller magnitude may produce similar effects if of surge frequencies, and this limitation is, in the authors' opinion, the most serious one.

For short-circuits of long duration but of limited value and free from transient conditions the thermal effects may be the limiting feature, and increasing the copper section may enable the short-circuit factor to be raised. In practice, however, it is impossible to dissociate transients from short-circuit conditions and accordingly the electrical effects remain as the limiting feature; that is to say, merely increasing the copper section in the primary winding of a multi-turn transformer cannot be said to increase its short-circuit factor. If, however, the number of primary turns is reduced the reactance is also reduced, there is less tendency for voltage to pile up between turns, and the short-circuit factor can be raised. The authors consider this to be the only practical means by which multi-turn transformers of high short-circuit capacity can be built. Conversely, a transformer with a large number of ampere-turns is more liable to fail than one with a moderate number of ampere-turns.

Hitherto, for accurate metering, a large number of ampere-turns has been necessary, and in the authors' opinion any freedom from breakdown has been mainly due to the fact that short-circuits have been of limited value. With the increase in generating plant and the linking up of stations now taking place, this condition may no longer obtain, and it is thought that multi-turn current transformers are liable to become a source of appreciable danger, especially if a short-circuit ratio of 100/1 is exceeded.

The development of highly accurate current transformers with reduced ampere-turns and, whenever possible, bar-primary construction, is accordingly of very great importance, and means by which this has been achieved in practice are described in the following section.

(B) METERING CURRENT TRANSFORMERS.

(i) *Accuracy and Causes of Error.*—The essential characteristic of the metering current transformer is its accuracy, combined, of course, with the ability to withstand with safety the worst short-circuit condition to which it may be subjected.

Bearing in mind the fundamental principle of operation of a current transformer, i.e. that the application of secondary burden is to cause flux to flow in the core without appreciably affecting the current in the windings, the limit of useful operation occurs when the production of flux does appreciably affect the current in the windings. The production of flux depends upon the magnitude of the secondary burden, and is not a direct function of the primary current. Secondary burden should strictly be expressed as an impedance, but as the secondary current is usually of some known standard value, the term "volt-ampere burden" is more frequently employed; but it must not be overlooked that this corresponds to rated load conditions only.

A current transformer on a truly zero burden, i.e. with no external or internal resistance or reactance, would require no secondary voltage to drive the secondary current through the secondary circuit, and accordingly would require no flux; and, therefore, there would be no error in transformation between primary and secondary currents. With a definite value of secondary burden a definite secondary voltage is required, necessitating a flux, which in turn requires exciting current drawn from the primary input. This exciting current is composed of core-loss and magnetizing-current components, both of which are conveniently expressed in ampere-turns. The core-loss component will be in phase with the voltage, and the magnetizing current in quadrature. For secondary burdens consisting mainly of resistance the core-loss ampere-turns will subtract practically arithmetically from the primary ampere-turns and cause an error of magnitude in the value of the secondary current termed "ratio error," while the magnetizing ampere-turns will subtract in quadrature, causing little ratio error but introducing in the resulting secondary current a phase displacement termed "phase-angle error."

On burdens consisting mainly of reactance the opposite is the case, and for intermediate power factors of secondary burden both core-loss and magnetizing-current components respectively contribute to ratio and phase-angle error. Owing to the inherent characteristics of transformer steels the core loss and magnetizing currents are not proportional to the flux density, and accordingly the ratio and phase-angle errors do not remain constant, and in general increase appreciably on lower values of primary current.

To minimize these errors, core loss and magnetizing components have required, hitherto, to be kept as small as possible, either in an "absolute" or "relative" sense. A reduction in the former may be achieved by using large iron section, a short magnetic circuit, high-permeability material for the core, etc.; and in the latter by using a larger number of ampere-turns, which hitherto has precluded the use of the bar-primary transformer below about 1 000 ampere-turns if any pretensions to accuracy are required. Accuracy is most readily obtained by using a reasonably high value of ampere-turns, but, as already shown, the provision of a multi-turn winding is by no means satisfactory from the point of view of short-circuit safety; increasing the iron section has only limited effects, and low-loss alloys, apart from being extremely expensive, are subject to the disadvantage that saturation occurs at comparatively low flux densities, and there appears to be some difficulty in ensuring that the characteristics of such low-loss irons shall be stable under service conditions.

The authors have accordingly concentrated on a means of obtaining the highest degree of accuracy with a primary of the bar type and a core of ordinary silicon steel, full advantage of which can be taken as regards known characteristics and permanency in performance. The same means, however, can be employed with any type of high-permeability alloy cores, and a saving effected in the amount of such material required.

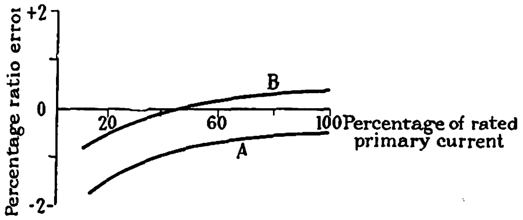

FIG. 1.

(ii) *Theory of Ratio and Phase-Angle Correction.*—In describing the development of the compensated current transformer it will be convenient first to review the elementary features in the design of the ordinary current transformer.

It has been almost a universal practice for ratio error to be corrected to some extent by adjustment in the number of secondary turns. This involves the provision in the secondary winding of slightly fewer turns than the nominal number, so that, the ampere-turns being constant, the current is slightly increased and corrects for the discrepancy due to core loss.

Fig. 1 indicates the natural ratio performance of an average current transformer, curve A representing the performance if the number of secondary turns are equal to the nominal number, and curve B showing the effect of providing "turn correction."

Hitherto, however, there has been no practical means of correction for phase-angle error, with the result that this error has always been the limiting feature in design, and has required to be kept to a minimum by the use of liberal core section and ampere-turns. Moreover, it is of greater importance to minimize phase-angle error than ratio error since, while the latter is independent of the power factor of the main circuit in its effect on metering errors, phase-angle error changes in effect with the power factor of the main circuit, being greater the lower the power factor. The reduction of phase-angle error to a minimum is, therefore, of very great importance if the highest possible metering accuracy is to be obtained.

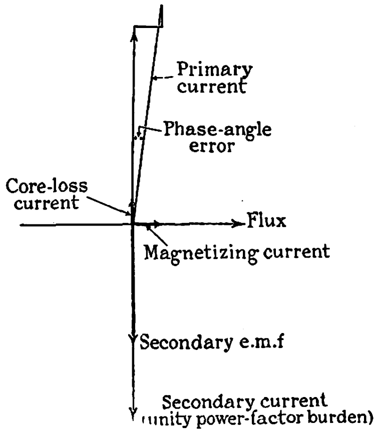

FIG. 2.

The authors are, of course, aware that it is possible to correct for some of the error of a current transformer by special adjustment of the meter when calibrating with the transformer. They have concentrated, however, on reducing the inherent errors of the transformer and rendering them as far as possible negligible, so that in the ideal case the use of the transformer introduces no errors in itself and reduces the overall errors of the combination practically to that of the meter only.

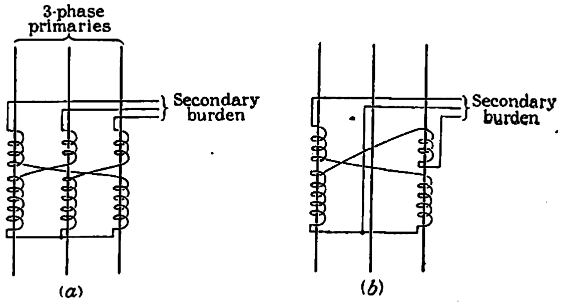

FIG. 3.

In explaining the course of development pursued by the authors it is convenient to regard the theory of ratio-error correction by conceiving that the turn adjustment is applied to the primary winding, in which case there would be a slightly greater number of primary turns than the nominal, the excess number simply providing the additional excitation necessary to allow for the discrepancy which occurs due to core loss. Once having visualized this theoretical possibility, a further step is to regard the extra primary turns as being physically separated from the main primary turns, but carrying current which in phase relationship and in ampere-turns provides exactly the same effect as when the extra turns are actually part of the primary winding.

It will now be possible to appreciate the effect produced if the extra primary turns were energized with current which had an angular displacement relative to the main primary current. In Fig. 2, which shows the elementary vector diagram for a current transformer, under unity power factor conditions of secondary burden it will be noted that the core-loss component is practically in phase with the primary current, and, therefore, can be corrected for by supplying additional excitation in phase with the primary current. If such additional excitation could be supplied with an angular displacement with respect to the primary current as mentioned above, then there would be a component available for correcting the core-loss and magnetizing-current errors.

If it were possible to excite the current transformer separately, and in such a way that the separate excitation was exactly equal to the total excitation both in magnitude and in phase, then the current transformer would operate without error between the main primary and secondary. Broadly speaking, it is along these lines that the authors have developed their type of compensated current transformer.

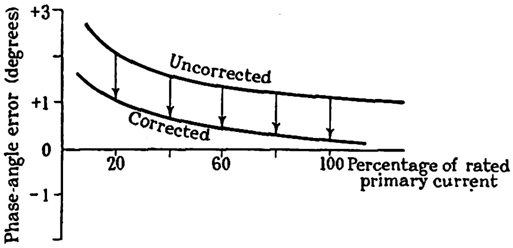

Fig. 4.

(iii) *Development of Compensated Current Transformer.*—In its simplest form the auxiliary excitation may be obtained by the provision of a small auxiliary winding associated physically with the secondary winding, and energized from the secondary winding of a current transformer in one of the other phases of a polyphase circuit. On a 3-phase circuit this automatically provides a 60-degree phase displacement, which forms a convenient value for providing components to take care of the core-loss and magnetizing-current errors. Fig. 3 (*a*) shows transformers connected in this way. If two transformers only are used, the connections are as shown in Fig. 3 (*b*).

By this arrangement phase-angle correction is made possible in the same way as ratio-error correction, and the error for a given value of ampere-turns is reduced, or, what is more important, the same accuracy is obtained with a reduction in ampere-turns; this means that the bar-primary transformer is given an extended range of application on the lower ratios. Fig. 4 shows the performance of a current transformer with its phase angle corrected in this way.

Having established this method of phase-angle correction, the next step was to develop a method by which the same effect could be obtained by using auxiliary means provided as part of the same transformer, and the method developed to accomplish this was to embody a small auxiliary core within the structure of the transformer to energize the phase-angle correction winding. In order to obtain the necessary phase relationship the auxiliary core requires to be operated at a relatively high flux density, and this, as well as accurate control of the auxiliary exciting current, is secured by inserting suitable resistance in the auxiliary exciting circuit.

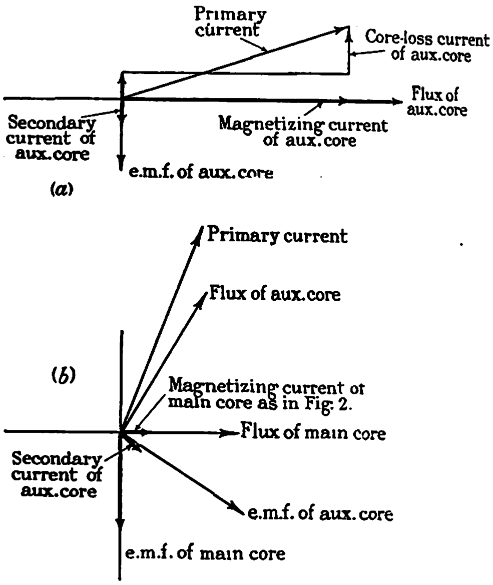
Primary current
Core-loss current of aux.core
Flux of aux.core
Secondary current of aux.core
Magnetizing current of aux.core
e.m.f. of aux.core
(a)
Primary current
Flux of aux.core
(b)
Magnetizing current of main core as in Fig. 2.
Flux of main core
Secondary current of aux.core
e.m.f. of aux.core
e.m.f. of main core

Fig. 5.

Fig. 5 (*a*) shows the vector diagram for these conditions, and if this diagram is swung round so that the primary currents are coincident with the vector diagram of the main transformer, as shown in Fig. 5 (*b*), it will be seen that, although the auxiliary excitation is not quite in phase with the actual magnetizing current, as in Fig. 2, it is sufficiently nearly in phase to give the necessary components to satisfy the requirements.

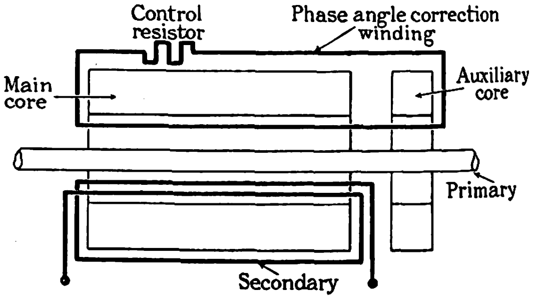

Fig. 6.

This scheme will be seen to be capable of producing phase-angle correction similar to the earlier developments, but with the advantage that the correction is obtained from the same phase, rendering feasible a self-contained transformer. The general arrangement of this auxiliary-core method of obtaining phase-angle correction is shown in Fig. 6.

Immediately the development of the auxiliary-core method of auxiliary excitation had reached this stage, further possibilities were seen by which, in addition to displacing the phase-angle curve nearer to, or even to cross, the zero line, the curve itself could be "flattened." This is achieved by arranging the design of the auxiliary core so that there is a greater relative auxiliary excitation at light loads than at full load, with the result that where the error is greatest the correction also is greatest, and a phase-angle curve of the type shown in Fig. 7 is obtained.

This constitutes a very important advantage, in that previously it had never been possible, however liberal the provision of ampere-turns or iron cross-section, to obtain a flat characteristic. Even the use of high-permeability alloys for the core material does not provide this feature, which has a very important effect on the accuracy of a meter at light loads.

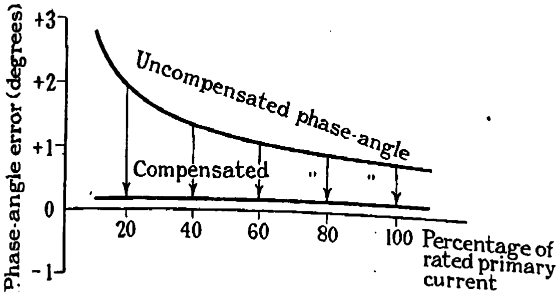

FIG. 7.

Having now developed means by which the phase-angle error was completely under control, or what may be termed "compensated" as well as "corrected," attention was turned to ratio error, with a view to eliminating this error in a similar way.

After considerable research it was found that the same auxiliary core could also be made to give correction and compensation for ratio error, and could thus be used to obtain a flat characteristic for this feature in addition to that of phase angle. Fig. 8 shows the rearrangement of windings to give this effect, where it will be noted that a few turns of the secondary winding are taken round the auxiliary core. The theory of this effect may be understood by reference to the vector diagram in Fig. 5 (*b*) in which it will be seen that the flux of the auxiliary core leads that of the main core—in practice by nearly 90 degrees—and this leading flux induces a leading e.m.f. in the secondary turns embracing the auxiliary core. By one of the first principles of current-transformer theory the voltage in the secondary circuit of a current transformer is purely a function of the secondary burden, and not of the transformer. Therefore, for a fixed burden, if a leading voltage is introduced, in order that the total secondary voltage, as determined by the secondary burden, may remain unchanged, the main secondary voltage as produced by the main core must be caused to lag sufficiently to neutralize the effect of the leading voltage. This angle of lag in the main secondary voltage causes the main flux also to lag behind its normal position, and in turn the magnetizing current for the main core lags behind its normal position.

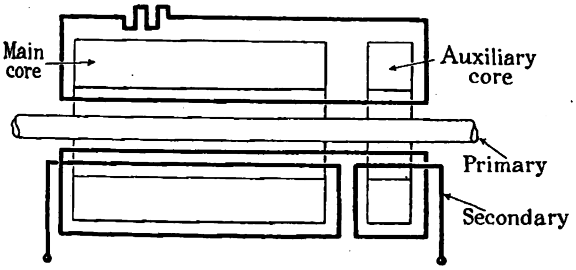

FIG. 8.

Fig. 9 shows the leading e.m.f. and its consequent effects introduced into the ordinary diagram of the current transformer, from which it will be seen the magnetizing current now takes up a position so as to call for an increase in the main secondary current, instead of the slight decrease which results from the usual vectorial position of the magnetizing current. It will be appreciated, of course, that an increase in the secondary current is equivalent to a positive ratio error, and the positive ratio error determined in this manner can be arranged to off-set the natural negative ratio error as shown in Fig. 1, curve A.

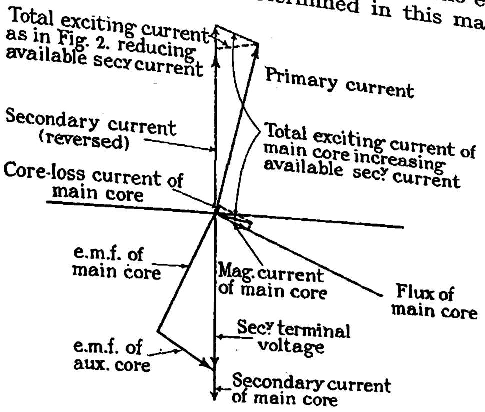
Total exciting current as in Fig. 2. reducing available secy current
Primary current
Secondary current (reversed)
Total exciting current of main core increasing available secy current
Core-loss current of main core
e.m.f. of main core
Mag. current of main core
Flux of main core
Secy terminal voltage
e.m.f. of aux. core
Secondary current of main core

FIG. 9.

Control of the ratio correction so obtained can be effected in the same way as in the case of phase-angle compensation; i.e. a greater relative correction may be obtained at light loads than at full loads, so that the resultant ratio-error characteristic is flat.

Thus it is seen that both ratio and phase-angle errors are now capable of adjustment as required, and that for any given amount of error resulting from a given condition of secondary burden a transformer can be designed which will have both its ratio and phase-angle curves coincident with the zero line.

While this meets the requirements of any specific case in a way which has never before been possible, it is possible that a transformer compensated in this way, if sold on a commercial basis and not operated exactly at its rated burden, may have errors which are not sufficiently low at some other value of secondary burden; i.e. the transformer may be either over-compensated if the burden is less than the rated figure, or under-compensated if the burden is more. Means by which the amount of error could be reduced before compensation, therefore appeared desirable.

It is well known that the permeability of ordinary silicon steel reaches its maximum at a flux density which is considerably greater than the density at which it is possible to operate the core of the current transformer. Accordingly, by maintaining a silicon-steel core at the optimum point of the permeability curve by means of some form of auxiliary excitation, the change in flux density due to the secondary burden alternating about this optimum point can be obtained for an expenditure of magnetizing ampere-turns several times less than usual.

This scheme lends itself very readily to the compensated current transformer described above. The main core merely requires splitting into two portions, each portion being magnetized in the opposite sense by a winding energized from the auxiliary core which provides ratio and phase-angle compensation. Fig. 10 shows the core and windings arranged for this duty.

It will be understood that, the two portions of the core being magnetized in the opposite sense, there is no resultant effect on the secondary winding if the two portions are equal, as the induced e.m.f.'s in any winding which embraces both portions will cancel out. Actually, however, it is sometimes convenient to arrange for the two portions to be slightly unequal, as this then has the same effect as keeping proportions equal and retaining the ratio compensation by some of the secondary turns embracing the auxiliary core. This, however, is more a feature of mechanical arrangement than of electrical design, as the results are the same in both cases.

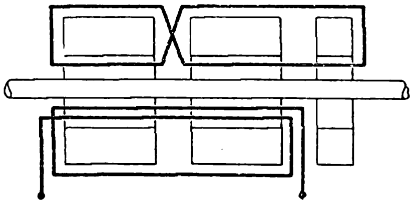

FIG. 10.

By this scheme of " cross magnetization " the ratio and phase-angle errors are reduced to roughly one-third of the figures normally obtained by the use of silicon-steel cores. Furthermore, the natural phase relationship which exists between the " cross flux " and the main flux is such that an improvement can be obtained when the secondary burden becomes reactive. This automatically compensates for the greater ratio error which otherwise exists when the burden becomes reactive.

Accordingly, in a good many instances the use of this cross magnetization is sufficient in itself to give the required accuracy for commercial application, but, as in the case of the use of special alloy cores, the errors can never be reduced to zero, and where the highest degree of accuracy is necessary a combination of cross magnetization and compensated windings is necessary. A further possibility of the compensated windings is that, if necessary, they actually permit of the ratio and phase-angle errors being reversed at light loads; i.e. the ratio error, instead of dropping to negative values as it does with an ordinary transformer (see Fig. 1) can actually be made to rise, and the phase angle to fall. This characteristic may be of advantage in compensating for any inherent error in the meter which, unless otherwise corrected, droops on light loads; thus in such instances the introduction of the compensated current transformer improves the accuracy of the meter. Summarizing the characteristics of the compensated current transformer, it will be seen that the chief points of advantage are as follows:—

(1) A degree of precision accuracy is obtainable which is not possible with any other type of transformer built hitherto, particularly with regard to the " flat " or " inverted " characteristic, and the possibility of adjusting for zero error at any specified burden.

(2) This high degree of accuracy may be combined with the use of the bar-primary construction.

(iv) *Advantages and Applications.*—In view of the absolute security of the bar-primary transformer against breakdown due to heavy overloads or surges, this constitutes a great advance in design and application; and the authors feel that in all important power-station work the use of the multi-turn primary transformer should in future be abolished, now that the compensated transformer has been developed. For small circuits of current values of about 100 amperes and less, a compensated multi-turn construction may be used, having comparatively few ampere-turns, which permits of a high short-circuit factor being obtained; such transformers may be used with much greater safety on circuits where heavy-current and short-circuit conditions are likely to be experienced.

A further advantage of bar-primary transformers is that the latter in general occupy much less space than multi-turn transformers, and this lends itself to economical layout of switchgear; for example, in high-voltage switchgear such transformers may be accommodated in oil circuit-breaker bushings or slipped over lead-covered cables, a position which is practically ideal from the point of view of reliability and safety.

In metal-clad gear their application again presents very great advantages owing to their compactness and the ease with which they can be fitted into various parts of the gear. The possibility of obtaining a high volt-ampere output from a comparatively small size of transformer is a further advantage with this type of gear. Typical accuracy characteristics of precision-type compensated current transformers are given in an Appendix. These are commercial transformers designed to satisfy the conditions of accuracy necessary in metering supplies from the " grid."

(C) RATED SECONDARY BURDEN.

From consideration of the principles of operation of the compensated current transformer, it will be appreciated that the highest accuracy can be made to occur under conditions corresponding to rated burden or load in the same way as a motor is designed to give its highest efficiency at or near to its rated load. On an ordinary current transformer this feature of design is not possible, as the highest accuracy occurs on zero burden and there is always some error under service conditions. Fig. 11 illustrates this advantage of the compensated current transformer.

It has been a common practice in the past to specify a current transformer rated at a considerably higher secondary burden than it will carry in service, with the idea of obtaining a higher accuracy when operating on the lower burden. While this practice serves its purpose with ordinary current transformers, it will be seen from the foregoing remarks that it is very advantageous that the compensated transformer should be rated according to the burden it will carry under service conditions, or some burden approximating to that value, and not an increased burden as has been customary hitherto.

It should be recognized, of course, that the rated burden may be departed from without serious detriment to accuracy, but the estimated volt-ampere burden should form the basis of the specification for the transformer required, so that the latter may operate under optimum conditions as regards accuracy.

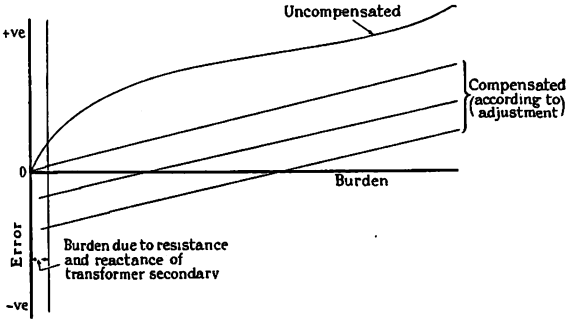

Fig. 11.

(D) Rated Secondary Current.

Hitherto this has been standardized at 5 amperes. While this value of current gives a conveniently low value of volt-ampere loss in the leads between transformer and meters, provided these leads do not exceed about 30 yards in length, above this length the loss may become excessive. This particularly applies in modern switchgear layout, where the distance between current transformers and meters may be several hundred yards. For such cases the use of a lower rated secondary current, such as 1 ampere, may be adopted with very considerable advantage. This reduces the load loss to 0·04 of the 5-ampere value, and as such is generally negligible. The only serious disadvantage in using a reduced value of rated secondary current is the resultant higher open-circuit voltage and the increased accommodation required for the larger number of secondary turns. Fortunately, however, on compensated metering current transformers with 300 amperes or more, the need to economize in lead losses is not of great importance, and it is also at primary currents in excess of this value that the open-circuit secondary volts and the number of secondary turns tend to become excessive. Accordingly the authors feel that, while on circuits of 300 amperes and above the use of 5-ampere secondaries may be retained, on circuits of lower current value, or where warranted by other considerations, a 1-ampere secondary should be standardized.

It is recognized that this involves the windings of the meters and relays, but it is thought that any difficulty in this respect is outweighed by the advantages obtained in improvement of accuracy, and the economy in cost of leads.

(E) Fractional-Turn Windings.

With the advent of the single-turn low-ratio current transformer for metering purposes, difficulties may sometimes arise in connection with the exact number of turns required in secondary windings. It will be appreciated that, for example, with a 100/5 ampere ratio one number of secondary turns may be too large and the next smaller number of turns too small.

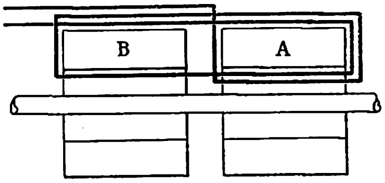

Fig. 12.

If 1-ampere secondaries are used, the difficulty is generally avoided owing to the large number of turns and the fine adjustment which one turn affords. For 5-ampere secondaries, however, the authors have developed a means of obtaining the effect of fractional turns. This is secured by making one or more secondary turns interlink only a portion of the core by passing these turns through an aperture as shown in Fig. 12. The portion of the core area embraced by the fractional turn expressed as a fraction of the total core area is an approximate measure of the degree of fractional-turn effect afforded.

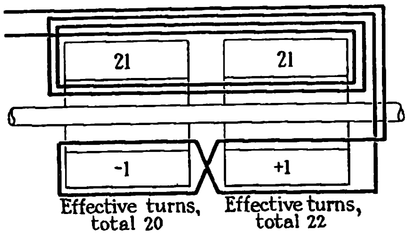

Fig. 13.

At first sight it would appear that this construction would give a high secondary reactance, but on analysis it is seen that this reactance is not large enough to be harmful and is, in fact, positively advantageous.

Referring to Fig. 13, suppose that there are 20 secondary turns over the whole core, i.e. over both sections A and B, and say 2 turns over section A only. This is equivalent to (20 + 1) turns over both A and B with, in addition, a turn over A and a turn in the inverse sense over B.

This figure-of-eight winding will, of course, constitute an inductive load on the current transformer, but the magnitude, which is readily calculated, is moderate and, owing to the fact that there is a flux due to this superposed on the normal working flux, the effective permeability of the core is increased, so that in certain cases better performance is obtained with the use of fractional turns than without. If mumetal or permalloy are used, however, the reactance due to the fractional turn may be too high, and this can be neutralized by adding a winding as shown at C in Fig. 14.

In the case of a transformer with, for example, $19\frac{1}{2}$ turns, this winding would carry $2\frac{1}{2}$ amperes at full rated primary current and this current would completely neutralize the reactance which would otherwise result from the fractional-turn construction. A further development would be to insert resistance in this winding so as to enable the transformer to operate at a more favourable part of the magnetizing curve than would otherwise be the case, since even with such alloys as mumetal the initial permeability is less than that for higher values of flux density.

An alternative means of producing a fractional-turn effect is to divide the core into two sections and wind each section for half the rated secondary current, requiring double the normal number of turns, and connecting the two windings in parallel. A 1-turn adjustment on each section then corresponds to one-quarter of that which would result from a 1-turn adjustment on a winding wound so as to embrace both sections. For a series of fractional-turn taps this scheme has advantages.

(F) PROTECTIVE TRANSFORMERS.

(i) *General Requirements.*—In the preceding sections dealing with metering current transformers, it has been pointed out how the necessary accuracy may be obtained by the provision of compensating windings, in a manner claimed to be more advantageous than has hitherto been the case.

The metering current transformer, however, has a working range limited in general from about 0·05 load to 50 per cent overload. Actually, up to about 5 times full load, the accuracy of a metering transformer tends to improve with increased load, but on higher overloads, according to the magnitude of the secondary burden, the accuracy becomes impaired. While this is of no consequence on a metering transformer, the point requires the closest attention on protective current transformers.

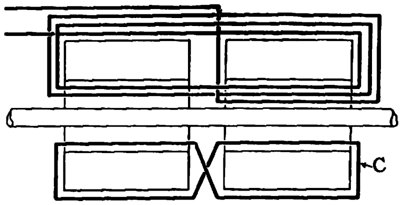

FIG. 14.

The essential requirement of a protective current transformer is that it shall enable the particular protective-gear system concerned to respond to a fault developing within the protected zone, but shall remain unaffected by any fault occurring outside the protected zone.

(ii) *Sensitivity and Stability.*—The specified value of primary current to ensure the operation of the relays when the fault is within the protected zone is termed the "sensitivity," and the specified value of primary current which the protective system must transmit, when the fault is outside the protected zone, i.e. (a "through fault") is termed the "stability." Failure to comply with the required stability may be termed "false tripping"; and the ratio of stability to sensitivity is the "figure of merit" of the protective system as a whole since, although increase of stability can always be obtained by sacrifice of sensitivity, an increase of stability without sacrificing sensitivity, or vice versa, can only be achieved by an improvement in the protective gear.

The attainment of a high value of stability ratio is the main problem in the consideration of any protective-gear system. The possibility of minimizing the sensitivity, i.e. arranging for the protective current transformer to trip the relay at the lowest possible fault current, is solely dependent upon the output available from the current transformer and the input required by the relay system. The output of the transformer is dependent upon its ampere-turns and iron cross-section; the ratio or number of turns is of secondary importance, since with any ratio the optimum condition of tripping can always be maintained by suitably adjusting the winding of the relay. The expression "optimum condition" is used advisedly, since sensitivity can be adversely affected not only by employment of too high a value of relay operating current, but to an equal extent by employment of too low an operating current. This feature is indicated in Fig. 15, which shows the primary

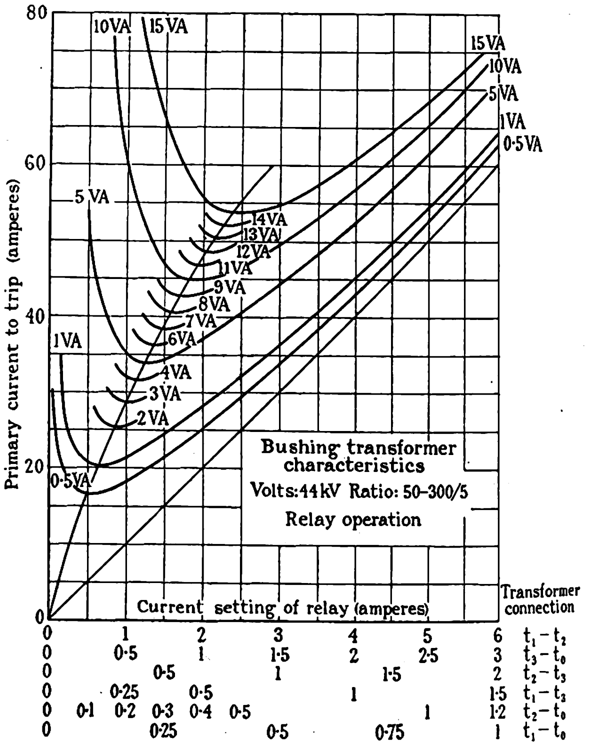

FIG. 15.

current required to operate relays of various volt-ampere consumption for variation in relay operating current. It will be seen that for every value of volt-ampere consumption there is a definite minimum primary current to operate the relay.

(iii) *Effect of Magnetizing Current.*—The losses occurring in the leads between the transformers and the relays must not be overlooked, and also those absorbed in magnetizing any other current transformers which may be in shunt. If the lead loss is comparable with the relay volt-amperes, the adoption of a lower value of secondary current, the relays being wound to suit, has a marked advantage in improving the sensitivity. As regards losses in magnetizing other current transformers in shunt, these cannot be altered for a given arrangement of transformers and must be allowed for in computing the sensitivity, especially if the transformers are of the single-turn type and of low ratio.

These considerations of sensitivity apply to any application of protective current transformers, whether of a direct-connected arrangement, such as for overload or earth leakage, or for circulating current.

The attainment of a high value of stability depends fundamentally on the performance of the protective current transformer under the extreme overload conditions to be experienced, and, indeed, if ideal current transformers were possible, there would be little difficulty in securing any desired stability and sensitivity.

In the authors' opinion, there has been a tendency to accept too readily the supposed unavoidable imperfection of protective current transformers, and much ingenuity has been expended in devising means of securing high values of stability ratio, usually by endeavouring to nullify this premised lack of perfection in the performance of the current transformers.

(iv) *Elimination of Spill Current.*—Assuming that the current transformers have been wound with the nominally correct number of turns, then any false relay or spill current will be the difference between the magnetizing currents of the transformers concerned, and, if large enough, this spill current will falsely operate the relay, causing a false trip.

It is possible that this can be prevented in three ways without rendering the apparatus less sensitive to true internal faults, viz.:—

(1) by rendering the relay less sensitive when there is heavy through current;

(2) by reducing the spill current by making the magnetizing currents of the two transformers concerned as nearly equal as possible (balancing the transformers);

(3) by reducing the magnetizing current of both transformers to an amount insufficient to trip the relay, i.e. making the transformer ideal from the standpoint of the relay tripping current.

With regard to (1), consideration of this line of attack is outside the scope of the present paper but the authors are of opinion that too much attention has been given to restraining the relay against the effects of spill current under heavy through fault conditions, instead of concentrating on eliminating the spill current at its source, or at least reducing it to a negligible value.

As a principle of general design, the authors submit that in any arrangement of apparatus each individual part should be made as perfect as possible in itself before attempting to make up for the deficiencies of the one part by an adjustment of, or special provision in, another part.

With regard to (2), balancing of the transformer means in effect that the relay will be connected across the equipotential points of the circulating pilots, extra loading resistances being employed if necessary, and the transformers adjusted to have similar performance. The disadvantages are that between transformers of different ratio there may exist no points which are equipotential at all loads, and that if the magnetizing currents are high a relatively small percentage change of magnetizing current produces a relatively large increase of spill current. This latter objection is especially cogent when account is taken of increase of magnetizing current due to transients and sudden changes of load (the so-called " doubling effect ").

With regard to (3), this would at first appear to be impossible. However, by suitable design the authors maintain that it is possible in all cases to keep the magnetizing currents as low as may be desired.

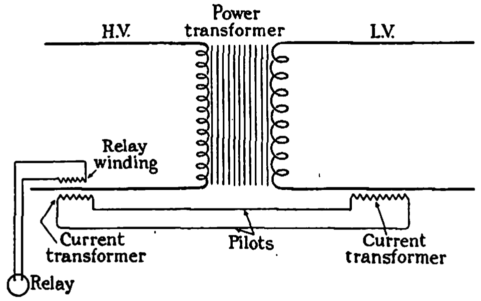

FIG. 16.

If the primary current is greater than 600 amperes at both ends, then the matter is merely one of allowing fairly generous iron and copper section in the transformers, if necessary using liberal cross-section in the pilot leads, or using a secondary rated at 1 ampere.

(v) *Position of Relay Tapping Points.*—If one of the transformers has a much lower ratio than the other and a tendency to a higher magnetizing current for equal burden, it can be relieved of part of its burden of driving current through the pilot leads by moving the relay tapping-off points nearer to it, or even attaching the relay to its terminals. In this case the only burden on the transformer is its own secondary resistance, and this can in most cases be made small enough. In this respect it is important, in the authors' opinion, to use only ring-core transformers for protective-gear purposes so that secondary reactance is avoided.

(vi) *Separate Winding for Relay Operation.*—In the extreme case, when even the resistance of the transformer secondary would lead to too high a value of magnetizing current, the relay is connected to a separate winding on the transformer, as shown in Fig. 16. In this case there is no burden whatever on this transformer, the higher-ratio transformer at the other end undertaking the entire burden of its own resistance, the pilot resistance and the resistance of the secondary winding of the low-ratio transformer. The spill current then consists merely of the magnetizing current of the higher-ratio transformer, which may be kept low by the use of ample iron section.

(vii) *Advantage of Reduced Secondary Current.*—The most difficult case, however, is that in which the primary currents at both ends are low, and in this case satisfactory performance is obtained by making the normal circulating current 1 ampere or ½ ampere. instead of the usual 5 amperes. When it is remembered that the pilot burden with a normal current of ½ ampere is 0·01 of the pilot burden with 5 amperes normal current with the same pilot section, it will be realized that this process will enable the pilot burden and secondary resistance burden, and consequently the magnetizing currents, to be reduced to any desired amount. Clearly, relays of small operating current are required with this arrangement, or alternatively relay transformers must be employed in order to reduce the current required by the relay so as to give the necessary sensitivity. In this respect the authors do not favour the use of transformers in the circulating circuit, owing to the additional burden imposed by them, and complications caused thereby.

(viii) *Avoidance of "Doubling" Effect.*—On lower-ratio current transformers the above limitation of magnetizing current automatically ensures that the maximum flux density is sufficiently low to prevent serious trouble arising from doubling of flux density due to switching, etc. With higher ratios, however, the flux density forms the limiting feature, and this should be deliberately kept within safe limits.

It should be noted that with this system there is no question of balancing transformers since, if the total magnetizing current is, say, 20 per cent of the relay operating current under the worst possible conditions, it is clear that the magnetizing current of any transformer can be several hundred per cent greater than normal without causing instability. Variations of transformer iron will be negligible when compared with the permissible variation under this system, and no great care is required in fixing the relay tapping or point. Equipotential points will not be really relevant to this system, and balancing resistances need never be used.

(G) TESTING WINDINGS.

It is considered desirable by some station engineers to be able to test the performance of current transformers, particularly when installed in position on site. This may be necessary in connection with either the operation of relays or the calibration of meters. Normally this would require the provision of testing equipment capable of giving a very wide range of current values, and if the transformer were installed in position in the switchgear it would also be necessary to disconnect the main primary leads in order to carry out the test. Accordingly, the authors have developed an arrangement whereby a testing winding is incorporated in the current transformer, the former, suitably wound, being energized with some conveniently small value of current (say 10 amperes), and at that current producing an effect on the current transformers exactly equivalent to that produced by rated current on the main primary. This obviates the necessity of removing the transformer from position and breaking circuit connections, and, further, testing equipment need only deliver 10 amperes, corresponding to rated primary load conditions, whatever the rated current of the main primary may be. This permits of considerable saving in the size and cost of testing equipment, besides facilitating portability and improving testing conveniences.

VOLTAGE TRANSFORMERS.

(A) GENERAL FEATURES COMPARED WITH CURRENT TRANSFORMERS.

Voltage transformers do not appear to be readily adaptable to the same advances in design as current transformers. This is perhaps natural in that, being a shunt-connected apparatus, the conditions of operation of a voltage transformer are less varied and there is inherently less difficulty in obtaining the necessary performance. Progress on voltage transformers has accordingly been associated more with improvements in mechanical arrangement, and with special features concerned with the accommodation of the transformer in the switchgear.

A somewhat extreme development has been the elimination of the voltage transformer altogether if particularly high-voltage ratings are concerned; one method now coming into practice in this country with this end in view is described at the end of this section of the paper.

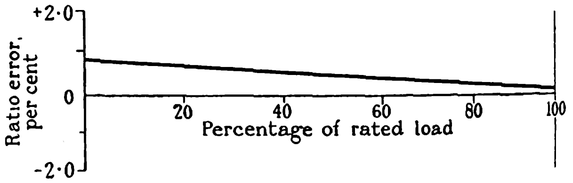

FIG. 17.

(i) *Phase-Angle Correction.*—The voltage transformer operates on the same principle as a power transformer the main difference being that the limitation of secondary burden is one of accuracy instead of heating. The normal accuracy characteristics for a voltage transformer are shown in Fig. 17. The position of the ratio curve is, of course, controllable by turn correction, the "slope" being the true criterion of ratio accuracy. The phase-angle curve is not controllable by turn correction, either as regards position or slope. Fortunately, however, the phase-angle error is not usually the limiting feature in design as in the case of a current transformer, and a design which is economic in the commercial sense gives a phase-angle error of less than 30 minutes from no load to full-load secondary burden. Moreover, the phase-angle error is practically constant and can usually be allowed for in calibration of the meter. If, however, exceedingly high accuracies are required, it is possible to correct the phase-angle error to zero by means of the connections shown in Fig. 18, which, of course, are not applicable in the case of isolated phase transformers. With 3-phase metering, however, requiring at least 2 potential elements, the scheme is generally applicable; the connections of 2 single-phase voltage transformers in open delta are as shown in Fig. 19.

By adopting this means of correcting phase angle in conjunction with suitable turn correction for correcting the ratio, a voltage transformer with practically zero error can readily be produced.

In the authors' opinion, a limiting feature in the design of a voltage transformer is the voltage stress between primary turns, which necessitates a highly sectionalized winding and reinforcement of turns. Even with these precautions the essential use of such finely-dimensioned conductors in the primary winding requires protective measures to disconnect the transformer from the circuit in case of breakdown.

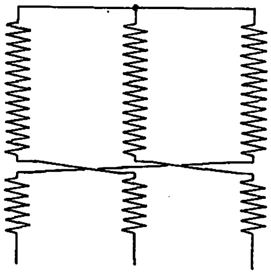

FIG. 18.

Fuses are invariably the means of protection adopted, but, being placed in the high-voltage circuit, they do not afford any protection against overload on the secondary side, and for this latter purpose low-tension fuses also are required.

In view of the magnitude of the fault current which can be fed into a voltage transformer from a modern system of supply, it has become a common practice to provide limiting resistors in series with high-voltage fuses in order to relieve the fuse of the duty otherwise thrown upon it. These resistors may be placed either on the voltage transformer side or on the line side of the fuse, but if the latter position is chosen, care must be taken to ensure that there is no possibility of breakdown on the resistor or its supports. The authors' experience has shown that the safest arrangement is to place the fuse on the line side of the resistor.

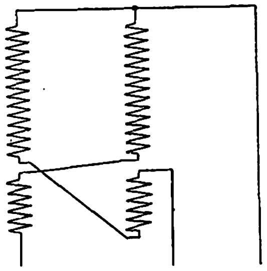

FIG. 19.

(ii) *Improvements in Use of Fuses and Resistors and Isolating Arrangements.*—A recent development is to mount the resistor as part of the voltage transformer, so that the latter, including its fuses, forms a complete unit. For voltages up to and including 11 kV a typical arrangement is to place the fuse across the cover of the voltage transformer and support it on porcelain insulators, the resistor comprising a helix of wire wound on a porcelain bobbin and placed inside one of the supporting insulators. This affords considerable economy in space and retains accessibility of both fuse and resistor, the latter being readily unscrewed from its position.

On circuits above 11 kV, unless otherwise provided against, corona may occur on the fuse wire owing to its very small diameter, and this ultimately corrodes the wire and disconnects the voltage transformer from the line. Shielding the fuse electrostatically is therefore considered essential on the higher voltages, and the authors have devised an arrangement whereby the required shielding effect is automatically provided by the helical winding of the resistor, the fuse being mounted concentrically within the resistor. It should be noted that while the fuse wire is sound the resistor and the whole of the fuse are substantially at the same potential. When the fuse wire blows, however, one end of the fuse may drop to earth potential, while the other remains at line potential. This condition necessitates a liberal spacing between resistor and fuse, and as a rule the necessary diameter of the resistor helix is such that the required spacing is obtained automatically. The same shielding effect is, of course, obtainable by means of an enclosing metallic cylinder maintained at the same potential as the fuse, but the use of the resistor to serve this purpose and to form a unit with the fuse which is readily accessible for inspection or removal, constitutes a great saving in space.

(iii) *Advances in Mechanical Design.*—Access to a fuse and resistor mounted inside the voltage-transformer tank may be afforded by an aperture in the cover of the tank, normally closed by hinged lids; but in general, if a voltage transformer fuse blows, it is necessary to remove the core and coils for overhaul, and accordingly there is actually no necessity for accessibility, although it may be of considerable convenience upon occasions.

The isolating of a voltage transformer for any required purpose may conveniently be afforded by fitting the tank with wheels in order to permit of withdrawal from the line contacts. The arcing which occurs on the relatively slow separating of the contacts while the transformer is being withdrawn is liable, however, to produce high-frequency impulses which may build up on the end turns of the voltage-transformer winding and cause breakdown. On 33 kV the arc may draw out to a length of approximately 2 in. before being extinguished, and means to avoid this are essential. The provision of a small switch inside the tank to break the magnetizing current under oil prior to withdrawal of the voltage transformer is one method, but although this is satisfactory on 22 kV the capacity leakage current of the bushings on 33 kV and above is sufficient to cause arcing on the contacts as serious as that due to magnetizing current. A means by which both magnetizing current and also the capacity leakage current of the bushings can be safely interrupted is to provide a quick-break snap-action switch at the contacts on the end of the bushing. However slowly the voltage transformer may be withdrawn, the speed of break of this switch is the same, the switch holding in until a predetermined amount of withdrawal has been effected, and then suddenly opening and instantaneously extinguishing the arc. When running the voltage transformer back into position this switch, of course, does not function, but with more rapid closing up of the contacts as compared with the opening speed the arcing in this case is so small and of such short duration as to be negligible.

(B) ELIMINATION OF VOLTAGE TRANSFORMERS IN HIGH-VOLTAGE CIRCUITS.

On voltages exceeding 33 kV a modern tendency appears to be to devise means whereby the voltage transformer is eliminated. This is mainly due to considerations of protective gear, for which purposes the majority of voltage transformers for high voltages are employed, the point being that such a transformer is no more reliable than the apparatus it is required to protect, if as reliable.

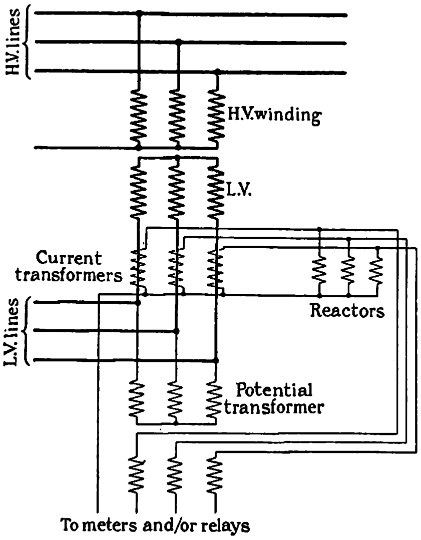

FIG. 20.

The scheme which appears to be developing is to use a power transformer which is already connected to the high-voltage circuit, and provide a voltage transformer for connecting to the low-voltage side of the power transformer, combined with a compensating device for correcting the error in the secondary voltage thus produced due to the regulation of the power transformer.

(i) *Principles of Operation of Compensating Potential Device.*—The compensating device consists of an impedance connected in each phase of the secondary side of the low-voltage transformer, having a value proportional to the impedance of the power transformer both in resistance and reactance, and energized by current proportional to the load current passing through the power transformer so that the compensating circuit is a homologue, at a reduced scale, of the power transformer circuit itself. In this way, a drop of voltage is obtained across the impedance which is proportional to the drop in the power transformer, whatever the conditions of load in the latter, and this voltage-drop across the impedance is accordingly suitable for correcting the error in secondary voltage of the low-voltage transformer due to the regulation of the power transformer, rendering available a compensated secondary voltage which is a true representation both in phase and in magnitude of the potential of the high-voltage circuit.

(ii) *Arrangements for Different Conditions.*—The elementary arrangement for a star/star-connected power transformer is shown in Fig. 20. The compensating impedances here shown are energized by current transformers in the lines of the power-transformer circuit. It is possible, however, and in the majority of cases preferable, to combine the impedances and current transformers into single units, when the connections become simplified as shown in Fig. 21. In general, however, the power transformers will have high-tension windings connected in star and low-tension in delta. In the arrangement of separate current transformers and impedances the connections then become as in Fig. 22,

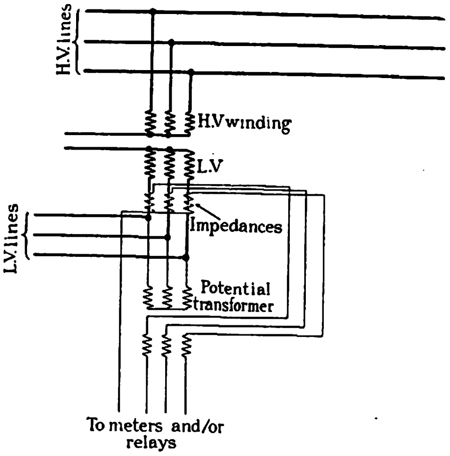

FIG. 21.

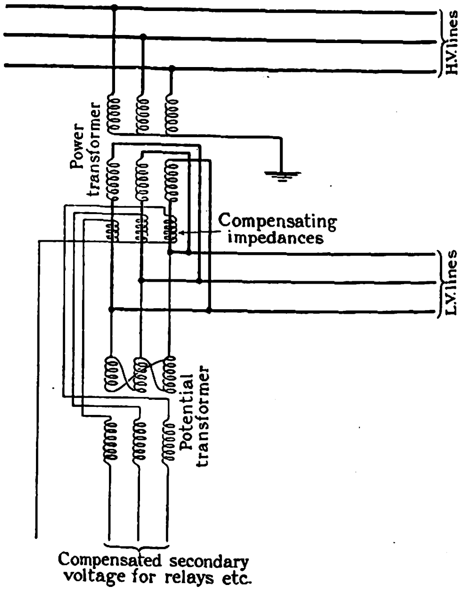

FIG. 22.

when it will be noted that the current transformers have to be inside the delta of the low-tension windings of the power transformer, and the voltage transformer requires delta-connected primary windings and its secondary in open star. The current transformer could still be maintained in the lines if installed on the high-tension side, but usually this is impracticable.

Connecting the current transformers and/or impedances inside the low-tension delta also presents difficulty, and if it is only necessary to indicate line voltage on the high-voltage side the arrangement shown in Fig. 23 can be used, the current transformers and impedances being combined as one unit and themselves delta-connected, although installed in the lines on the low-tension side of the power transformer.

(iii) *Indication of Phase Voltage.*—It will be noted, however, that there is no neutral point available on the secondary side of the low-voltage potential transformer, and hence no means of reading phase voltage. If a meter neutral point is derived from the line currents alone it will be erroneous, since a knowledge of the line currents leaves indeterminate the phase currents and hence the drops of voltage due to phase reactance. The error will be proportional to the residual current (which does not appear in the low-tension line) and since the residual current flows in the high-tension neutral it is possible, by means of a current transformer in this position, to obtain the true meter neutral point. Fig. 24 shows the connections by which this can be done.

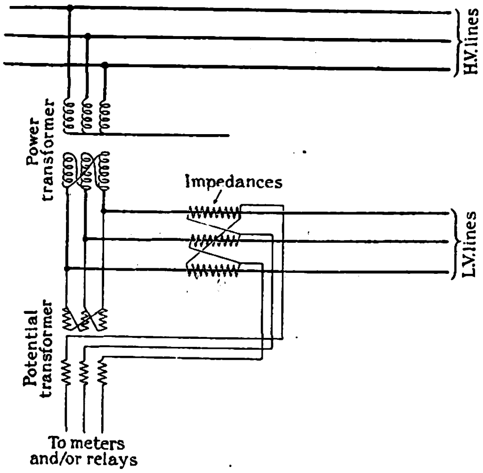

FIG. 23.

(iv) *Requirements to ensure Accuracy.*—Whatever the particular arrangement used, and whether the current transformers and impedances are separate or in single units, the effect is always to introduce a constant value of impedance into the secondary circuit of the voltage transformer, apart altogether from the compensating effect due to load current through the power transformer. This constant impedance effect produces in the secondary circuit of the voltage transformer a ratio and phase-angle change, in the same way as any other impedance connected into the secondary circuit, and accordingly the value of the impedances should be kept as low as possible; the only limit to this is the current which can be conveniently obtained for energizing the impedances, and the lower the value of the latter becomes, the higher is the current required.

In practice it is usual to compromise between these two factors so as to permit the use of a single-turn primary arrangement for the current-transformer effect in all cases. A point to be noted is that the voltage drop produced by the constant impedance effect is vectorial, i.e. there is introduced into the compensated secondary voltage a constant phase displacement, as well as a constant change in magnitude. The effect depends on the power factor of the total secondary burden and the power factor of the impedance. The latter is usually low in order to agree with the reactance and resistance components of the main power transformer impedance, and accordingly the lower the power factor of the total secondary burden becomes, the smaller is the effect due to phase displacement, and vice versa. If desired, the constant effect on magnitude can be adjusted by turn correction on the voltage transformer, and the constant effect on phase displacement may be taken into account in the adjustment of the meters or relays, according to the condition and requirements of individual cases.

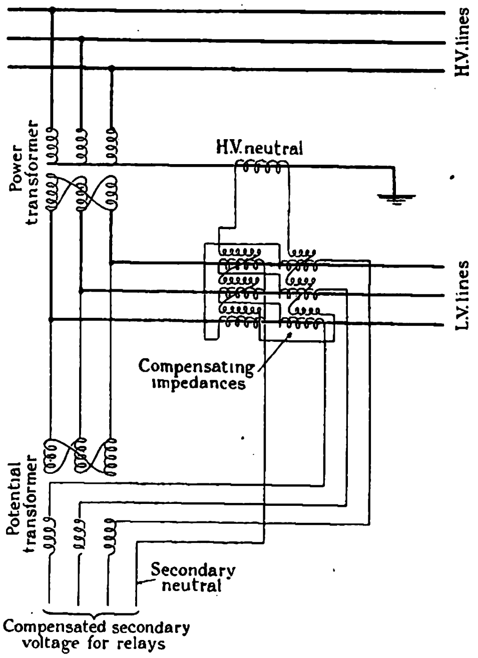

FIG. 24.

It will be seen from the foregoing that the compensated secondary voltage produced by any of the arrangements described depends upon the following:—

(1) The secondary terminal voltage of the voltage transformer.

(2) The compensating voltage as obtained from the impedances energized direct or via current transformers.

(3) The "constant drop" effect produced by the impedances.

The accuracy of the compensated voltage obtained in this way is a function of these three factors and, provided all the apparatus concerned is designed to operate as a whole so as to ensure co-ordination of the component effects, representation of the line and phase voltage system can be obtained with suitable accuracy.

SPECIAL-PURPOSE TRANSFORMERS.

Varying Ratio Features for Special Purposes.—In all the arrangements of current and voltage transformers which the authors have described in this paper the essential feature has been the maintenance of ratio under varying conditions of operation.

There are applications of instrument transformers, however, where it is desirable for the ratio to change with varying conditions of operation. In certain cases it may be required that for a given change in value of the primary current in a current transformer the secondary current shall change at a greater rate than the primary. For example, in a current transformer passing 100 amperes in the primary, the secondary current may be 5 amperes; but with 125 amperes in the primary, i.e. an increase of 25 per cent, an increase to 10 amperes, i.e. a change of 100 per cent, in the secondary current may be required. The authors have developed a current transformer having a performance of this nature which may be utilized with advantage for the operation of relays where response to small changes in primary current is required without the use of delicately set relays.

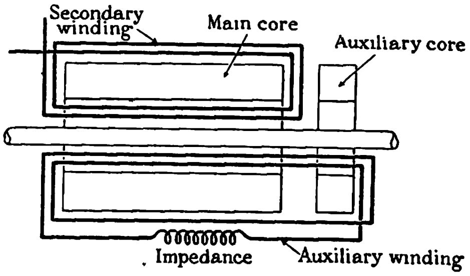

FIG. 25.

The connections are similar to those used in compensated current transformers, but since the auxiliary current is required to affect the ratio the current in the auxiliary winding is limited by an impedance of a reactive nature so that the auxiliary current is brought into phase with the secondary current and subtracts directly from it. The reactance is conveniently obtained by a winding placed circumferentially round the transformer so as to utilize the same core as part of the magnetic circuit for the reactor.

At a predetermined value of primary current the output from the auxiliary core ceases to increase appreciably with increase in the primary current, owing to saturation of the auxiliary core; and since the main-core output increases in proportion to the primary the net output, being approximately the arithmetical difference between the outputs of the two cores, increases at a greater rate than the primary output. The arrangement of this type of current transformer is shown in Fig. 32.

Similar performance is obtainable from a voltage transformer, where the voltage-change amplifying effect is particularly useful in the operation of voltage relays and regulators, since by its use a much closer regulation can be obtained with a given relay.

Alternatively to the current- and voltage-change amplifying effects described above, the opposite feature may also be readily obtained; i.e. for changes in primary voltage or current the secondary voltage or current may remain unchanged. This effect is obtainable with an arrangement of core and winding similar to that shown in Fig. 25, but with the design modified accordingly. A further possibility is that the secondary voltage or current, as the case may be, may be required to increase at a given rate up to a certain point, and then cease to increase any further. This feature also is obtainable with the same arrangement but with variation in the design.

In conclusion the authors wish to acknowledge their indebtedness to the British Thomson-Houston Co., Ltd., for permission to publish the matter contained in this paper, and to thank the company for the opportunities afforded them for research and development on instrument transformer work.

APPENDIX.

TYPICAL TEST-RESULTS ON LOW-RATIO COMPENSATED CURRENT TRANSFORMERS FOR COMMERCIAL CIRCUITS.

TABLE 1.

Ratio 400/5 *amps. Frequency* 50 *cycles per sec.*
Rating 15 *VA.*

Primary current	Ratio error	Phase angle
per cent of rated value	per cent	min.
125	+ 0·12	17
20	+ 0·14	10
10	+ 0·12	11
5	+ 0·17	8

TABLE 2.

Ratio 800/5 *amps. Frequency* 50 *cycles per se*
Rating 15 *VA.*

Primary current	Ratio error	Phase angle
per cent of rated value	per cent	min.
125	+ 0·15	10
20	+ 0·30	9
10	+ 0·40	3
5	+ 0·65	0

NOTE.—This transformer was adjusted to have increased positive ratio error at light loads.

TABLE 3.

Outdoor type 33 000-*volt bar-primary current transformer rated at* 10 *VA. Class* " *B* " (*mumetal core*). *Rated primary current,* 50 *amps.*

Primary current	Ratio error	Phase angle
per cent of rated value	per cent	min.
125	+ 0·7	37
100	+ 0·6	40
20	+ 0·9	47
10	+ 0·9	38
5	+ 0·9	35

TABLE 4.

11 000-*volt bar-primary current transformer rated at* 2 *VA. Rated primary current,* 150 *amps.* (*stalloy core*).

Primary current	Ratio error	Phase angle
per cent of rated value	per cent	min.
100	+ 0·1	28
20	− 0·1	18
10	− 0·1	30

TABLE 5.

Bar-primary transformers for 22 000-*volt compound-filled switchgear, rated at* 50 *VA. Rated primary current,* 200 *amps.* (*stalloy core*).

Primary current	Ratio error	Phase angle
per cent of rated value	per cent	min.
100	+ 0·7	45
20	+ 0·4	36
10	+ 0·7	30

TABLE 6.

Bar-primary transformer for 11 000-*volt circuit, rated at* 15 *VA. Rated primary current,* 300 *amps.* (*stalloy core*).

Primary current, per cent	Phase angle, min.	Ratio error, per cent	Phase angle, min.	Ratio error per cent
Tested at	5-VA burden		15-VA burden	
125	17	+ 0·4	29	+ 0·1
20	7	+ 0·3	23	− 0·1
10	5	+ 0·2	18	0·0
5	10	+ 0·2	26	0·0

TABLE 7.

Bar-primary transformer for 11 000-*volt circuit, rated at* 40 *VA. Rated primary current,* 600 *amps.* (*stalloy core*).

Primary current, per cent	Phase angle, min.	Ratio error, per cent	Phase angle, min.	Ratio error, per cent	Phase angle, min.	Ratio error, per cent
Tested at	5-VA burden		15-VA burden		40-VA burden	
125	9	+0·7	13	+0·6	22	+0·4
20	8	+0·7	13	+0·6	25	+0·3
10	5	+0·8	9	+0·7	22	+0·4
5	0	+0·8	5	+0·7	19	+0·5

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 3RD JANUARY, 1930.

Mr. F. E. J. Ockenden: Most of the devices which have been introduced in an effort to improve current transformers have not succeeded in altering their true figure of merit. Usually such transformers fail to maintain the same high standard if the burden or the frequency is altered. The current transformer which the authors have described in their paper appears at first sight to be rather complicated. It is a little difficult to see what they have done to improve it, yet their figures undoubtedly show that they have achieved that result. Perhaps they have not explained their method of attack in the simplest way. They preface their remarks by stating that an extra primary current should be assumed in addition to the normal primary current in the busbar. Taking the device as a whole, it is obviously impossible to introduce any current other than that which is in the bar; their explanation is for this reason rather difficult to follow. However, let us consider a busbar transformer with a secondary winding connected to some specified load. The trouble with all current transformers, as the authors mention, is that they take a magnetizing current which has two components, the in-phase and the out-of-phase. The variation of the former, and with it the ratio variation of current transformers, is extremely small, but the true magnetizing component is a nuisance; it is large, and in the ordinary way it cannot be dealt with. A very well-known (though imperfect) device for solving the problem makes use of a condenser shunted across the burden. The condenser is adjusted to take a current which is precisely equal to the magnetizing component of the primary current as it would appear in the secondary circuit. Since this is in phase opposition to the current taken by the condenser the two cancel out and the main primary is no longer required to supply a magnetizing component. The phase-angle error of the current transformer therefore disappears Let us suppose that an inductance instead of a condenser is put across the burden. This may be arranged to take a magnetizing current which is precisely the same in magnitude and vector position as that of the original transformer. This current, however, is flowing in the wrong direction; instead of nullifying, it increases the former magnetizing current. The magnetizing current of the inductance must therefore be multiplied by j^2 in order to get the required result. This may be effected by feeding it through another current transformer and this is the origin of the second transformer in the authors' scheme. By thus injecting current into the secondary circuit we can achieve precisely the effect of the condenser, with the advantage that whereas the capacity of the condenser is fixed and, therefore, the compensation is only correct at one burden and frequency, compensation by means of a second transformer should apply over any reasonable variation of burden and frequency. Unfortunately, the second or compensating current transformer has to work at a fairly high density, so that the limiting values of the flux and, therefore, of the true magnetizing current are not those of the main transformer. Thus the compensation is not as perfect as would appear at first sight; it must suffer to some degree from the limitations of frequency and burden which affect the scheme involving the use of a condensive shunt. The crossed-coil device shown in Fig. 10 is very ingenious, but even with this scheme I doubt if the effective permability of a silicon steel core could be raised to the very high value obtained for the initial permeability of nickel-iron, viz. 10 000 to 15 000. My opinion is that the nickel-iron core will produce, in a much simpler way, results equal to those obtained by the authors with their form of compensation, with the additional advantage that the high figure of merit possessed by the nickel-iron core is retained under conditions in which the authors' transformer would be useless. Such a condition would occur if a number of transformers were connected in parallel for protective or summation purposes. It is of the utmost importance in such cases that the impedance of the secondary windings, when the primary is open-circuited, should be as high as possible. The impedance of the transformers described in this paper when so connected would be extremely low and possibly almost negligible. The effect of variation of burden on the phase angle of a transformer compensated by means of a condensive shunt placed across the secondary terminals may be much reduced by a modification which I have employed with considerable success in the design of current transformers of high accuracy. If the condenser is connected across the burden in the well-known manner, the voltage across its terminals varies only with the magnitude of the burden. The capacity current taken by the condenser, which serves to compensate the magnetizing component of the primary, must, therefore, also vary with the voltage across the burden, whereas the magnetizing component in the primary will vary with the flux in the core. The latter, however, will be proportional not to the magnitude of the external burden only but to the total burden of the transformer, that is, to the sum of the external burden and the burden represented by the resistance and reactance of the secondary windings. The capacity current taken by the condenser may be made to vary in a similar manner by connecting the condenser to a tertiary winding wound directly on the core. By this means not only is the compensation due to the condenser made almost independent of the magnitude of the secondary burden, but the capacity of the condenser may be reduced in value by winding the tertiary winding with a larger number of turns than the secondary. By combining this method of compensation with a nickel-iron core I have succeeded in constructing a current transformer having a phase-angle error of only 0·8 minute between full and one-tenth primary current. The ratio variation was less than 1 in 10 000 under the same conditions. The unusually small scale of Fig. 7, where the curve for phase-angle error is shown quite flat, makes it uncertain as to whether the authors intend us to consider the curve to be truly flat within a minute or two. The question of fractional turns is always rather a bugbear for current-transformer designers. The device of drilling a hole through the core and pushing one turn through is certainly quite effective, but I think it would be expensive because the position of the necessary hole would have to be fixed according to the exact fraction of a turn required, and fine adjustment would be impossible. Another scheme mentioned by the authors has the transformer in two sections wound with different numbers of turns. This was the basis of an American device, details of which were published a few months ago. For example, an e.m.f. of 1·0 volt might be induced in one coil and an e.m.f. of 1·1 volts in the other; the circulating current which flows round the transformer windings increases the apparent ratio and is used as the compensating system. The extra winding may be obviated by putting a shunt across the transformer. It is much simpler and it absorbs just that fraction of the current which is not required in the secondary circuit. This method has the defect, however, of allowing the current to vary with the resistance of the burden, but so, in fact, do all the other schemes which have been put forward either by the authors or by previous designers. There is probably no effective way of making a current transformer with fractional turns in which the secondary current is really independent of the secondary burden. In connection with the variable transformer described at the end of the paper, let us consider a normal current transformer operating the coil of a relay. As the primary current increases, so does the secondary current. Suppose the relay arm were held off by a second coil, which tended to prevent the operation of the relay. If this coil were fed from another current transformer which was almost saturated, the effect would be the same as that which the authors obtain; up to a certain point the two transformers would follow the same law and the pull on the tongue tending to operate the relay would be proportional to the current. Above that point the second transformer becomes saturated, the second coil ceases to nullify the effect of the first, and the result is apparently a greatly increased pull on the tongue, since only in the first transformer is the secondary current increasing. Let us suppose that, instead of introducing a second coil, the current from the second current transformer is merely injected into the first. Mechanical opposition is replaced by electrical opposition and we have what is, in effect, the authors' "variable ratio transformer." I think that the use of a relay with two windings, as suggested, would be more adaptable and reliable in practice than the transformer advocated by the authors, but the idea underlying their scheme is undoubtedly capable of considerable development.

Dr. C. V. Drysdale: About 25 years ago I was actively interested in this subject, and made what I believe were the first theoretical and accurate experimental investigations of the behaviour of instrument transformers; it therefore came somewhat as a shock, when I first read the authors' paper, to see that after clearly realizing the source of the errors I had missed an obvious solution. Since the vector difference between the primary and secondary ampere-turns is the no-load ampere-turns made up of the magnetizing and core-loss components, I was led to stress the reduction of the no-load ampere-turns and strongly to advocate the use of permalloy or mumetal, as soon as they became known. I have been much gratified by the remarkable accuracy which Colonel Edgcumbe and Mr. Ockenden have obtained by the use of such alloys. I still think that it is better to reduce the errors as far as possible by using these alloys, but the authors' compensation methods are extremely neat and practicable and they may still be used with advantage to compensate the residual errors in transformers of high-permeability alloys and, possibly, to effect an economy in the amount of alloy required. For switchboard use on constant secondary burden, transformers of stalloy compensated by the authors' method would probably be satisfactory; but it is obvious that the compensation must be adjusted for a particular burden, and that errors will reappear if the burden is changed. It therefore appears desirable to reduce the magnetizing and core-loss excitation to a minimum by the use of high-permeability and low-loss alloys, but this does not detract from the ingenuity of the authors' devices and the skill with which they have put them into practical form.

Mr. E. Fawssett: On page 707 of the paper there is a rather casual remark about low-loss alloys, and I am sorry to have to join with Dr. Drysdale in advocating the use of mumetal because, by doing so, I may be accused of drawing the discussion away from the design of the authors' transformers. On page 709 the authors state: "Even the use of high-permeability alloys for the core material does not provide" the features to which they refer. In my opinion, this statement is too sweeping. Mumetal is easily capable of providing a very high standard of performance. (Mr. Fawssett then exhibited three lantern slides showing the performance of mumetal.) It would be interesting to see some of the authors' test results and to find out how the theoretical conclusions work out in practice on a manufacturing basis. It may not be possible to reproduce the results with the degree of accuracy which is hinted at in the paper when (as is not unlikely) a slight change of burden occurs. Current transformers ought not to be very sensitive to burden change, for it is very difficult to forecast the burden to close limits in modern power-station lay-outs with long runs of secondary leads and where small additions to it are often made later on. The provision of testing windings [Section (G)] is a notable feature. However, if a transformer is as precise as the authors suggest, with variations of 1, 2, 3, or 4 minutes, one is bound to be critical of using anything but the real circuit. It is very doubtful whether a testing winding can really be made to reproduce exactly the main primary winding with a small variety of secondary burdens, and over the whole range of load of primary current. If, as the authors suggest, this is possible, further proof should be given. With regard to voltage transformers, the 3-phase potential transformer is not, in my opinion, ordinarily a very accurate piece of apparatus. The single-phase type is preferable, especially from the points of view of performance and safety, and it is therefore very inadvisable to mix up the phases. The single-phase transformer should not need any additional compensation and it is, in general, a much better piece of apparatus than the 3-phase transformer. On page 716 the authors suggest that voltage transformers are scarcely, if at all, more reliable than the apparatus which they are required to protect. They are definitely not as reliable, and are, in fact, nearly always the weak point in a system. The section dealing with elimination of voltage transformers in high-voltage circuits is of interest in regard to the general question of very high-accuracy metering requirements. In my opinion, if supplies are to be cheapened, it is wrong practice to insist on such extremely close limits of accuracy as those to which we are approaching. Surely the cost and complication of the gear, if very much enhanced, may not be justifiable. The statement on page 713 of the paper that "As a principle of general design, the authors submit that in any arrangement of apparatus each individual part should be made as perfect as possible," is an excellent piece of advice. (Mr. Fawssett then exhibited a lantern slide showing one way of compensating for the power transformer losses.)

Mr. R. S. J. Spilsbury: I wish that fuller experimental results had been given in the paper. For instance, no figures are quoted for the variation of the transformer characteristics with burden or with frequency; and although the compensation is specially advocated for single-turn transformers of low current rating the paper contains no results for such transformers. Another interesting point is the effect of wave-form. Since the auxiliary core must operate at quite a high magnetic density it is possible that the characteristics of the transformer might be rather seriously affected by variation of the primary wave-form. Have the authors any data on this point? On the question of the relative merits of compensation and mumetal cores, the authors state that transformers with the latter do not give a flat characteristic. Flatness is, of course, a relative term, but the ratio characteristic of a mumetal transformer can be flat within 1 part in 10 000 from full to one-tenth normal current. Probably the question will settle itself on an economic basis: other things being equal, I should prefer the mumetal transformer on the score of simplicity, but the authors' design will undoubtedly be very valuable for certain applications. The authors define the sensitivity of a relay as the current required to operate it: hence when they wish to speak of making a relay work at a very low current they refer to this operation as "minimizing the sensitivity." This seems to be rather a misleading usage and it is not supported by the B.E.S.A. "Glossary."

Mr. C. W. Marshall: This paper tends to show that the calibration of current transformers in conjunction with meters will, fortunately, soon be a thing of the past. With regard to the relative merits of mumetal and compensated current transformers, it would be interesting to hear the views of experienced engineers on the stability of the former. Its simplicity is a point in its favour, and possibly the economic side has to be considered just now, but stability is the most important factor of all. Mr. Fawssett referred to the testing winding, and I agree with him that it is undesirable to introduce that complication. It appears to me to be quite easy to ascertain whether or not a core or winding has changed, by applying a separate potential and measuring the magnetizing current in magnitude and phase at a definite point. If there has been no change, further action is unnecessary. The weak point in both the mumetal and the compensated type of current transformers is that at extremely light loads neither helps very much, and it appears that the only method of overcoming the difficulty must rely upon excitation from a parallel potential source which is independent of the current. I should be interested to hear what the authors have to say regarding the theoretical possibility of that suggestion. In actual practice the secondary circuit is just as liable to failures as the primary circuit. It should be recognized that great care must be taken in design to avoid thermal troubles. We are aiming at the greatest possible simplification of the instrument equipment, and it is my hope that a system employing one current transformer per phase and serving all purposes will eventually be achieved. With regard to potential transformers, the issue is very broad. It is generally agreed that it is difficult, if not impossible, to introduce potential transformers without considerably reducing the factor of safety. The possibilities of condenser potential measurements with or without low-voltage potential transformers, and even of the use of resistances, have been suggested as alternatives. It is, however, more hopeful to anticipate improvement on the lines which have been suggested by the authors. In the grid system we have definitely departed from the use of pilot wires in the longer sections and are thus dependent, to a great extent, on accurate reproduction of the high-voltage magnitude and phase by measurements which come through the power transformers. It is expected that a degree of accuracy sufficient for the purpose will be obtained without the introduction of 132-kV potential transformers.

Mr. W. A. Burgess: Switchgear makers are frequently requested, on the one hand, to give extremely close accuracies for metering on very small primary currents and, on the other, to provide for very heavy short-circuit conditions. The authors have shown that those two conditions are distinct, and that under normal circumstances one has to be sacrificed for the other. The extension of the range of the single-turn primary suggested by the authors is a proposition which should be very attractive to switchgear makers. The authors are inclined to investigate a number of different methods of obtaining stability in connection with protective gear. Stability is the main essential in protective gear; the setting is only incidental. The only way to attack the problem of protective gear stability is accurately to balance the current transformers, in characteristic at least. There seems to be no reference in the paper to this balancing of the characteristics in so far as it affects the attainment of a straight-line voltage relation. Whether the authors' form of current transformer compensation can be made easily, or at all, to produce a straight-line characteristic, is not clear from their paper. Such a characteristic is, in my opinion, absolutely essential for the pilot forms of feeder protection. The only form of protection to which reference is made in the paper is transformer protection; feeder protection appears to be ignored. I agree with the authors on the question of the reduction of the secondary current, but I do not think that they go far enough. Many meter engineers would agree that instruments can be provided to give on ½-ampere secondaries the accuracies required within commercial manufacturing limits, and I think that, particularly on the higher voltages, one would be better off with ½-ampere secondaries. I am rather disappointed, moreover, to find that there is no mention in the paper of the very ingenious core which, I believe, the authors' firm use for their current transformers, namely the rolled-strip core. I should like to know whether there is any appreciable difference in the phase-angle or ratio error or actual loss, between the rolled-strip core and the stamped core (for equal weight). I should also like to know how the weight of iron on a compensated current transformer with a bar primary compares with that in a multi-turn current transformer, either of the rolled-strip or stamped-type core having, say, a 100-ampere primary, a voltage of the order of 33 000 or 66 000, and a normal 15-VA output with both Class B and "precision" accuracies. The potential-transformer correction method due to the authors—for I think it is in large measure due to them in its final stage—is of great interest. I can say from first-hand experience that the accuracies obtained are very good. While accuracies with this form of potential-transformer compensation—or reproduction of e.h.t. voltage on the low-tension side—are extremely good, yet with the present tendency to use tapped transformers for voltage regulation (such as on the national "grid") considerable complication arises owing to the necessity for tapping everything. It is a nuisance, but it cannot be avoided if the method of compensation used by the authors is adopted. I suggest that the much simpler expedient of providing a low-voltage coil on the main transformer in a suitable position be adopted instead.

Lieut.-Col. K. Edgcumbe: With regard to the serious trouble which arises with an accidentally opened secondary, it seems to me that since the short-circuited winding which forms a part of the authors' current transformer is unlikely to be open-circuited at the same time as the main secondary, it may form, to some extent, a protection against undue rise of voltage. The authors state that they doubt if mumetal is truly stable. Mumetal has now been used for 4 or 5 years, and I have never heard of any instance of a definite change of characteristics. It is very susceptible to mechanical damage, so that special precautions have to be taken in making up transformers with it; but apart from that I do not know of any reason for supposing that it undergoes a change, either from age, temperature, or over-magnetization. We may expect some more figures on the subject very shortly, as a good deal of work is being done on that particular point, which is, of course, a very important one. Mr. Burgess referred to the 0·5-amp. secondary, and said that he thought that instrument engineers would agree that it was perfectly easy to construct instruments to work with such a secondary. There seems to be some idea that the secondary current affects the burden as far as the instruments are concerned. That is not so. It does not affect the burden imposed by the instruments, whether the secondary current is 5 amperes or 0·5 amp. The only advantage of 0·5 ampere (and, as the authors point out, it is a very important one) is that it reduces the losses in the connecting leads to about 1 per cent of the value at 5 amperes. The instruments behave equally well with either and are as easy to construct. A serious disadvantage of the 0·5-ampere secondary as compared with the 1-ampere is the very much higher voltage induced in the secondary in the event of an open-circuit. I hope the authors will amplify the figures of performance in their reply. At present they are very meagre and do not tell us, for example, the size of the transformers, whether their cores were small or large, or even what was the magnitude of the burden. The idea of putting on an auxiliary test winding when the transformers are first installed has, I believe, been employed before. I remember seeing a description of it some years ago. I do not see why some of the speakers have doubted whether it was a true reproduction of the primary. In a ring transformer it should reproduce the primary very accurately. Probably the same result could be obtained by subdividing the secondary into two halves and comparing them when the transformer was new. If they retained the same relative characteristics one might presume that nothing had happened to the transformer.

Mr. C. L. Lipman : In my opinion, the ½-ampere rating of the secondary current of bushing-type current transformers has rendered possible improved apparatus and instruments. The winding for ½-ampere full-load secondary current improves the performance of the "straight through" type of current transformer, as it permits a finer turn adjustment. Modern measuring instruments, including ammeters, wattmeters, reactive kVA-meters and power-factor meters consume less power when wound for 0·5-ampere than the earlier types of instrument wound for 5 amperes (other conditions such as strength of springs, etc., remaining the same). In 0·5-amp. coils it is, for example, possible to use enamelled wire with single silk covering instead of wire of large overall diameter with double cotton covering: a considerable improvement in the space and copper factors for a given winding space and hence a reduced power consumption are thus obtained. At the present time instruments are available which require a smaller electrical input, have lighter moving systems, give the same or an improved mechanical output and have a higher performance than earlier designs. One of the reasons for this improvement is the use of the 0·5-amp. secondary current.

Mr. A. J. Gibbons : Some years ago I was connected with the work of revising the metering on some 6 000-volt switchgear on high-capacity and small-current circuits. The switchgear was made by the firm with which the authors are associated, and after some demonstration tests it was decided to try some of these compensated current transformers. From the practical point of view, the results obtained in connection with meter accuracy have been all that could be desired in view of the fact that not precision accuracy, but merely first-rate commercial accuracy, was the primary consideration. The following are actual test figures taken from a watt-hour meter working on 200 : 5 current transformers:—

Load, VA	Percentage error on unity power factor	Percentage error on 0·5 (lag) power factor
full	0·8 −	0·6 −
¾	0·2 −	0·2 +
½	0·2 +	0·8 −
¼	0·3 −	1·0 −
1/10	0·5 −	
1/20	0·4 −	

I think that the figures substantiate very well the claims for enhanced accuracy on the bar-primary compensated transformers. With regard to the use of current transformers on protective gear, the authors point out that difficulty is sometimes experienced when current transformers require different ratios, presumably for protecting transformers with Merz-Price circulating-current gear. This trouble can easily be overcome by omitting the circulating-current protection and substituting core-balanced earth leakage, which is practically immune from operation on a through fault and can readily be adapted to give almost any sensitivity desired (certainly down to 20 per cent of the transformer rating). Back-up inverse time-lag overload protection will cover the exceedingly rare case of a fault between phases. I notice that the authors have in mind the provision of testing windings, and in some cases I consider that these would be a great advantage. It is frequently a matter of some difficulty to obtain a check on the performance of a current transformer. I think these testing windings will enable the check to be made very rapidly. I do not agree with the authors in regard to voltage transformers. They state (page 716) that there is no necessity for access to the high-tension fuses. On looking through some records which deal with some 90 22 000-volt potential transformers, I found that 9 fuses had blown and in no case had there been a transformer fault; the trouble was merely due to deterioration of the very fine fuse wire. So far I have yet to experience an actual transformer fault on these particular instruments.

Mr. A. E. Quenzer : The last speaker referred to testing windings. There is one point which is not in their favour and that is the danger of the terminals being short-circuited; this would obviously introduce serious errors in the main secondary winding. I am not certain as to the utility of testing windings and, from my own experience, I have found portable testing apparatus to be quite satisfactory, provided that the testing current is applied direct to the secondary terminals without disconnecting any secondary leads. This method takes into account possible errors in transformer ratios. Are the testing windings to be a feature of the general design? Referring to Tables 1 and 2 in the appendix, I should like to know the power factor of the burden and whether the tests were carried out on the rated burden of 15 VA. Some particulars of the performance of these transformers on a frequency of 25 cycles per sec. would also be welcome.

Mr. E. W. Hill: I have noticed in the paper and also in the speakers' remarks what I consider to be incorrect methods of expressing current transformer errors; they are ambiguous and unintelligible to anyone who does not know the convention upon which they are based. It so happens that the error in the ratio of a current transformer is one which has an inverse relation as regards sign to the error in the magnitude of the current delivered from the secondary windings. If the current transformer has an error and the ratio is too high, for instance, it means that the secondary current is low. All our attention is centred upon the secondary side of the current transformer. From the point of view of accuracy, we are interested in how a meter or other instrument will perform when connected up to the secondary winding of the current transformer. Therefore, any way of expressing the error of the current transformer should have some consistent relation in respect of sign to the way in which the instrument connected to the current transformer will be working. The statement that a current transformer has an error of minus 1 per cent should mean that the current delivery from the secondary winding is 1 per cent low; but it is never quite clear. I should like to appeal for an intelligible way of specifying current-transformer errors. If in one column the loadings—full, $\frac{3}{4}$, $\frac{1}{2}$, etc.—were set out, and in an adjoining column figures were set forth expressing "secondary-current magnitude percentage error," the meaning would be clear to everyone. If the error against any particular load were expressed as $+1$ per cent, it would mean that the magnitude of the secondary current was 1 per cent high. There would be no ambiguity, and no need to infer from the known characteristics of current transformers the sign of a particular set of errors. When the authors' ideas come into full effect and we find the inflection of the current-transformer characteristic curve inverted, matters will be more difficult. We shall not then be able to infer the sign of errors merely from an inspection of the curve presented to us. If under present conditions we see a current-transformer curve with positive errors at the top and negative errors at the bottom, we can, it is true, interpret what is meant, but only by inference from the shape of that curve. The method which I have indicated would, however, obviate any chance of mistake in such a case. In any event I should like to see references to current-transformers' "ratio errors" entirely suppressed, since they are bound to be misleading. As regards phase-angle errors, these could be set out against loadings so as to have, in the second column of the table, the "secondary-current phase-angle error" expressed as "degrees of lead" or "degrees of lag," thus avoiding the use of the terms "positive error" and "negative error."

Mr. W. J. Minton (*communicated*): I am sorry that Mr. Fawssett seems to have withdrawn his plea for a high degree of accuracy. I believe I have heard him say that a decrease of 0·5 per cent in the registration of the meters is sufficient to annul the profits of many concerns. I wish to draw attention to the loose way in which accuracies are stated and to express the opinion that these figures should refer back to the quantity which is to be measured. The terms "positive" and "negative" should also, in my opinion, be eliminated and accuracy should be stated in terms of registration, as a fraction or percentage. Thus, for too great a registration 1·03 or 103 per cent would be given, whereas 0·97 or 97 per cent would be obtained if the registration were inadequate. The chief advantage of this suggestion is that it enables accuracies, which are usually read off from a slide rule, to be entered up without the trouble of converting once again to the usual form. When several accuracies have to be allowed for, as, for example, when two potential transformers are used, this involves a considerable saving of labour.

Mr. H. Trencham (*communicated*): There is a good deal of evidence that the operation of instrument transformers is not as well understood as is desirable, even amongst engineers responsible for electric power distribution. Since current transformers are series-connected they form an essential part of the supply equipment in which they are used, notwithstanding that their function is ancillary; they frequently constitute part of the bus system, as in bulk-metering arrangements and on most incoming feeders. The authors' contention (page 704) that there is a tendency to regard instrument transformers purely from the meter or from the switchgear point of view is important, and its truth has been instanced on more than one occasion by specialist switchgear manufacturers who have found it necessary to undertake the design and production of their own instrument and protective transformers. A recognition of broader claims than those of metering or switchgear work alone would surely be of value. The statement on page 705 ["Current Transformers" type (1)] is open to amplification, as a range up to 50 per cent overload cannot be considered sufficient to meet requirements of relays or trip coils which may be calibrated to twice and three times normal load. The benefits to be derived from the use of current transformers of few ampere-turns (of the straight-through or bushing type) are so great and so much needed in the industry that their application to plain overload protection, which is after all by far the most usual type, should not be left in any uncertainty. The authors' statement appears to mean that at loads in excess of 150 per cent of normal there may occur a falling-off in ratio which would vitiate the correct operation of relays or trip coils calibrated in terms of secondary currents up to 10 and 15 amperes. As primary current is the true criterion, however, the case might have to be met by special calibration of such relays or trip coils with their own or representative transformers, a practice which would not be welcomed where large production is the aim. Some further thought on this subject may be found profitable. In regard to short-circuit capacity, it should be remarked that oil circuit-breakers are frequently applied in locations where they may be subjected to short-circuits well above their rated breaking capacity. It is advisable to bear this in mind if the breaker rating be used as a basis for the selection of current transformers, and this rating should definitely err on the conservative side. Concerning secondary-current rating (page 711), there is a good deal of interest attaching to the suggested 1-ampere secondary; apart from the technical issues involved, the cost of secondary wiring for large power-station equipments is considerable and it is frequently necessary to use quite large cables with 5 amperes of secondary current because of the long runs involved. The limit of a 300-ampere primary for 1-ampere secondary design would not, however, be very helpful in this problem as the majority of power-station circuits nowadays carry considerably more than 300 amperes. The special devices which have been developed by the authors to reduce and compensate for errors exhibit an interesting degree of resource and are, in the main, of a sufficiently simple character to ensure their ready application in practice. It will be of interest to note their progress in the immediate future.

[The authors' reply to this discussion will be found on page 730.]

North-Western Centre, at Manchester, 18th March, 1930.

Mr. J. Randle: On first reading the paper it appears that the ratio error correction follows logically upon the authors' ingenious method of phase-angle correction. A second reading reveals a distinct break in the method, and I wish to ask whether the ratio error correction was rendered necessary by the increase in ratio error introduced by the phase-angle correction. It is interesting to note that the correction of ratio error involves an increase in phase-angle error. The authors claim to have reduced the current in bar-primary transformers from above 1 000 amperes down to above 100 amperes. What are the considerations fixing the figure of 100 amperes? If the authors' recommendation of a 1-ampere standard burden is adopted, will this extend the range even further? An acquaintance with the manufacture of the cumbersome 2-turn primary with specially shaped copper and hand insulation, makes one welcome an extension of the range of bar-primary transformers. In the variation of the compensated current transformer employing a split main core, the increased flux density will lead to high core losses. When such transformers are used in a circulating-current system of protection a large " through " fault will cause considerable heating. I should like to know whether, in this type of transformer, thermal considerations prove to be a limiting feature in design.

Mr. W. Holmes: The paper is entitled " Instrument Transformers." I do not expect that all types of instrument transformers could be reviewed in one paper, but this paper is rather confined to the description of another compensated type of instrument transformer. I mention this particularly because the authors state that this particular type of compensated transformer has changed the whole outlook of current-transformer design. I cannot see any difference in principle between the transformer designed by the authors and the 2-stage current transformer designed by Brooks and Holtz over 10 years ago. This transformer is put on the market by the British Sangamo Meter Co. and is fully described in the *Transactions of the American I.E.E.* (1922, vol. 41, p. 382), and it is also mentioned in the *I.E.E. Journal* (1927, vol. 65, p. 576). It consists of a core divided into two parts, a compensating winding from one part to the other, but instead of using a resistance inside the transformer this method uses another winding on the meter. This makes a rather simpler transformer, and there is no difficulty in giving the meter a double winding. Another type of compensated current transformer was described by Wilson in a paper read before the American I.E.E. in January 1929. It is made by the General Electric Co. of America. In this transformer one leg of the iron core is split into two parts, and a lagging coil is placed round one part in the same way that the quadrature band is put on an induction meter. Surprising results are claimed for this transformer. Curves of phase-angle errors are shown on the zero line from full to 1/10th load current, and the errors are only 2 minutes at 1/20th load current. Compensated current transformers introduce unnecessary complications, viz. the extra windings; the two cores; the joints in the windings; and the wrapped up resistances or shunts introducing weak links which in time give trouble. The current transformer has been, and still can be, a very simple piece of apparatus. By using cores of nickel iron such as mumetal and permalloy, it is possible to get an almost perfect transformer. On page 707 the authors dismiss low-loss alloys in 6 lines, but in reply to their remarks I would say that the cost now is not extremely high—it has been reduced in a few years by two-thirds. I admit that saturation occurs at a density of about 3 000, but this is unimportant when current transformers usually work at densities below 1 000. In fact it has a definite advantage—it helps the short-circuit characteristics. Time has proved that mumetal and permalloy are now very stable under service conditions. In Tables 1 and 2 the authors give tables of phase-angle errors reaching 10 and 17 minutes. This is rather disappointing after all the complicated compensation involved. With a simple mumetal transformer having the same number of ampere-turns the errors are well within half this value. The last paragraph on page 709 reads:—" A transformer compensated in this way, if sold on a commercial basis and not operated exactly at its rated burden, may have errors, etc., at some other value of secondary burden." Is the method of further compensation for this, shown in Fig. 10, where a further third-stage transformer is used, only for laboratory use? The reason for all this compensation is to obtain a bar-primary construction, and the reason of the bar-primary construction is to make the transformer safe on short-circuits, with which I entirely agree. The information about short-circuits, given on page 706, paragraph 3, is very interesting. There is just one point, however, on which the authors might have been more precise. They mention a factor of 150, based on thermal effects. Time should, however, be coupled with this factor. When considering thermal effects, for instance, a transformer would easily withstand 150 times full load for a fraction of a second, and it would be easy to calculate how long would elapse before the copper melted.

Mr. H. C. Turner: The design of the bushing transformer with which the paper largely deals is of great importance in these days of the National Grid, and although I do not think that the methods of correction employed by the authors are final, the solution may be found along the line of thought which they have started. The correction of a current transformer by injecting into its secondary a current equal and opposite to the primary magnetizing and iron-loss current has been thought of before. It has been impossible, I have always understood, to find a suitable source of current to balance the magnetizing and iron losses, but the authors have solved this to a degree by employing the auxiliary core which, in order to do its work, must be run at a fairly high density. This core, whilst capable of providing sufficient current by its secondary winding, unfortunately does not provide it in the right direction. In Fig. 5 the current vector lags behind the main core vector, with the result that whilst the phase angle is corrected it is corrected at the expense of the ratio. The method of correcting the ratio shown in Fig. 9 cannot, I think, be employed concurrently with the above-mentioned method of power-factor correction, as the lengthening of the reversed secondary vector is caused by the magnetizing vector which lags more than 90° and which, owing to the impossibility of it being in line with the secondary current vector, must increase the phase angle. The last paragraph but one in col. 2 on page 708 should, I think, state that either phase or ratio correction can be provided but not both. The use of an auxiliary core at a higher density than the main core is rather unsatisfactory as it means that the correcting current will remain constant over a part of the range where the total magnetizing current is growing—in other words, the currents will not match. The method of correction which employs the auxiliary and crossed windings and in which the density in the main core (or rather cores, as it is now split) has a set-up zero, is not fully described and it would be interesting to know what results the authors have obtained. This is important as they have apparently discarded the previous methods in its favour. The use of other phases to provide the correcting current is not, in my opinion, to be encouraged, as the load cannot always be balanced and fault conditions may cause grave errors in reading and in the control of protective gear. The transformer figures mentioned in Tables 1 and 2 are good, but the load is reasonably low and the primary ampere-turns are higher than those in the worst cases. It would be interesting to see figures for 80/5-ampere and possibly 40/5-ampere transformers. The method of obtaining fractional turns is not simple and would perhaps be better replaced by that of winding all low-primary transformers with ½-ampere secondaries. This is another instance of the illusions of youth disappearing. We used to be told that it was just as impossible to have less than one turn as it is to make a clock strike less than once—yet instrument engineers frequently have to provide 100 or 200 ampere-turns with a current of 500 or 1 000 amperes, and have no difficulty in doing so. For protective schemes a more satisfactory practice than that of designing special balancing transformers is to use absolutely standard and cheap transformers and rely on biasing these as is done in the case of the McColl scheme in which, under normal conditions, the relays are held open by the secondary current, and in which the unbalance of current transformers does not affect the operation. Except for the most exacting conditions the present design of potential transformers gives all the accuracy demanded, and I do not think that improvements in this direction are necessary. The improvement of insulation is of greater moment. A point recently arose in connection with transformers where the frequency varies. With voice-frequency apparatus and picture telegraphy, frequencies range from 50 to 12 000 cycles per sec., and we find that iron powder solves the difficulty. Have the authors tried the use of powder instead of laminations?

Mr. M. W. Sheppard: The authors lay great stress on the advantages of bar-type current transformers over the wound type, but although I agree in general I think they overstress the point. The percentage of wound-type current transformers which break down owing to short-circuits on the line is extremely small and it should be noted that multi-turn current transformers are still extensively used in America, notwithstanding the fact that the compensated type of current transformer has been available for a number of years, and I believe large blocks of power are dealt with. In the authors' comments upon high-permeability iron they mention the disadvantage of its comparatively low magnetic saturation value, yet a few lines further on they claim that by using a compensated winding a reduction in core area may be effected. This would seem to accentuate this apparent disadvantage and hardly seems consistent. My view is that for ordinary purposes this is not a real disadvantage and, should the secondary be inadvertently open-circuited and the flux rise to an extremely high value, the iron losses under these conditions are so low when compared with those inherent to stalloy that the heating effect would not be sufficiently great to damage the core or windings. I note that in the compensated current transformer an auxiliary core is used which operates at a comparatively high flux density. I should like to have the authors' assurance that after a few years' service or a heavy short-circuit this core will maintain its magnetic characteristics. If this is not so it appears to me that its value as a compensating device is rather problematical, as it should be remembered that the inherent phase-angle of each individual current transformer may be of the order of, say, 200 minutes at low values of current. Therefore a 10 per cent variation in either current transformer represents an unbalance of 20 minutes, whereas when a current transformer with a nickel-iron core having an error of, say, 10 minutes, varies 10 per cent, this represents a difference of only 1 minute. I fail to see the relationship between Figs. 3 and 6; in one case current is taken from separate circuits and added vectorially, whilst in the other the flux in the main core is controlled by means of a current taken from the same primary circuit. It is not clear to me how the conditions contained in the text with regard to Fig. 10 are obtained. From the diagram it appears that half the main core is supplied with an additive flux, while the other half has a subtractive flux applied. Thus the respective resultant fluxes are very different, and from this I fail to see how the authors can substantiate their claims to be operating the core at its point of maximum permeability. I should like to see the tables giving actual test figures extended to cover the effect of a change of VA burden or frequency, as the necessity of calibrating for one particular burden or frequency is a distinct disadvantage, and even with a standard design the variations in different consignments of iron makes this imperative. I also note the authors' remarks regarding the losses in the leads, but from the above it seems essential either to allow for this extra burden when calibrating, or to keep it extremely low. The use of fractional turns to effect ratio compensation has been in use for many years, but I agree with the authors that a lower value of secondary current might be an advantage for the lower ranges. Turning to transformer protection, I am of the opinion that the best conditions are obtained when current transformers having similar characteristics are used. To meet this, it is necessary to have a wound type on one side at least, but the current transformers can be made to withstand a heavier overload than the transformer to be protected, and the " switching in " surge may be guarded against by the use of " kick fuse " relays. My view is that the current transformers should not balance under normal conditions, owing to the effect of the magnetizing current of the power transformer. If this is compensated for, as is often the case, a serious out-of-balance will obtain on a through fault. The authors' connections for voltage transformers show considerable ingenuity and appear to be a modification of the customary inter-star connection. With regard to the general aspect of design, apart from the minor improvements effected by shunts and turns compensation there are three definite lines of approach. The first is to compensate the errors of the main current transformer by means of an auxiliary current transformer, (*a*) by adding the secondary currents magnetically in the manner described by the authors, or (*b*) by adding both secondary currents vectorially, a method which has been in use in America for many years. The principle of the two above methods appears to be identical, but the application is slightly different. The second method is to control the shape of the magnetizing and iron-loss curve by means of a magnetic shunt, making it approximate to a square law. This practically ensures a constant-ratio error which can be adjusted by turn compensation. The phase angle is corrected by means of a lag band encircling part of the core. The above methods are very ingenious and at the time of their introduction marked a decided advance in design, but one must not lose sight of the fact that they are only palliatives and the error is still inherent in the transformer. The third method goes to the root of this error, and is to use a core of high-permeability, low-loss alloy. By the use of this metal a transformer may be built having a bar-primary and having all the advantages of a wound-type current transformer as regards reliability, simplicity and ease of manufacture and test, and yet having a greater accuracy than either the wound type or compensated bar-type current transformer. Moreover, it will have a performance which is not seriously affected by change of burden or frequency. My partiality to current transformers with nickel-iron cores is due to the fact that they are the nearest approach to a perfect transformer yet obtained—that is, a transformer having a current ratio corresponding to the turn ratio and without phase displacement under all normal conditions, yet simple to manufacture and test, which can be put to stock and used as required without the necessity of calibration or an uneasy feeling that all is not well. A transformer having a nickel-iron core is particularly applicable as a bushing-type current transformer for use on high voltages and low currents, as it should be remembered that a compensated current transformer takes a comparatively large volt-ampere load to magnetize it, and this power is not available under the above conditions. A disadvantage of this alloy is its relatively high cost, but no doubt this will be considerably reduced with greater demand. To set against this is the distinct saving in manufacture and testing due to the simplicity of design.

Mr. V. A. Brown : The use of high-permeability, low-loss core materials such as mumetal, etc., in the construction of current transformers has enabled the absolute values of error to be reduced, but the ingenious methods of compensation invented by the authors have brought the variations of error under the control of the designer. To my mind, the simultaneous use of the lower and upper bends in the magnetization curve is very unusual practice, and it is surprising that no one has previously visualized the use of the upper bend as a corrective against the lower bend. It is a pity that more detailed information concerning the special-purpose instrument transformers, dealt with at the end of the paper, is not given, and I hope that the authors will amplify this in their reply. It is with the questions of short-circuit ratings and protective transformers that my only real criticism of the paper is concerned. Under headings (i) and (iii) of the Summary the authors claim responsibility for certain views which are also held by other instrument transformer designers. For example, under heading (i) the short-circuit limitations of current transformers and the view that a reduction of ampere-turns is the only real means of increasing the short-circuit capacity, have been well appreciated for some time. With reference to heading (iii), it has long been my practice to limit the core density in protective transformers to a safe figure at the maximum " through " short-circuit current for which they are designed. Of course, at low values of rated primary current this has meant generous physical dimensions of the current transformers, combined with a reduction in the volt-ampere burden imposed by the pilot wires. I have never regarded biasing arrangements as a good method of getting stability and, so far as the reduction of spill current by the balancing of transformers is concerned, I am firmly convinced that the provision of large transformers does not cost any more when the expense of balancing smaller transformers is considered. Nevertheless, I do not advocate the abolition of a single balance test as a check against errors of design or workmanship. I agree with the authors when they say that a current transformer should be rated according to its service burden and not at an increased burden as is frequently specified. There is no point in calling for the higher value of volt-ampere rating if the required limits of error, corresponding to the service burden, be specified. I endorse the authors' view that, strictly speaking, the secondary burden of a current transformer should be expressed as an impedance, and I hope that the British Engineering Standards Association will consider this suggestion when next they revise B.S.S. No. 81. The expression of secondary burden in volt-amperes is a snare when the burden of secondary apparatus is expressed in volt-amperes at a current differing from the rated secondary current of the transformer. I have in mind the case of a user who was attempting to check the performance of a current transformer at 1/10th rated primary current with a 0·5-ampere meter having a consumption of 2 volt-amperes at full-scale deflection. He complained that the transformer was reading badly low and had failed to appreciate that this ammeter imposed a burden of 200 volt-amperes on the current transformer by virtue of its high impedance, namely 8 ohms. The above case also explains why some users fail to see that they cannot have very low leakage settings from a bar-primary current transformer with a leakage relay (or trip coil) that is capable of being set at the desired low values. There is an optimum number of turns on the relay (or trip coil) which will give a minimum value of primary tripping current, and this point is well illustrated by Fig. 15 of the paper. The methods of compensating voltage transformers, when fed from the lower-voltage side of power transformers, should eliminate the necessity for such transformers rated higher than 33 kV. Any indication of voltage for synchronizing purposes on circuits at the higher voltages can be catered for by low-voltage tappings on the terminal bushings of oil circuit-breakers.

Mr. O. Howarth : I endorse the authors' statements that the subject of instrument transformers deserves more specialized attention and more general publicity than it has hitherto received. Mr. Wellings mentioned that a poor current transformer is put into a vital position and disappears when faults occur. Well, the mistake we make is in putting a poor current transformer in a vital position; we should see that a really good current transformer is put into that vital position. I have in mind certain current transformers in this district with wound primaries, which have been subjected to very heavy short-circuit currents and to fairly severe transients, and have given good service for many years without showing any signs of distress or breakdown. The compensated current transformer is of more use for the higher ratings, so far as achievement of satisfactory performance is concerned, than for the lower ratings. A compensated current transformer rated as low as 100 amperes will probably not be satisfactory for operating a meter. Whilst it may be nominally within some class appearing in B.S.S. No. 81 I think that in practice its performance will not be good. The lowest limit for a really accurate metering transformer with a bar primary, even when compensated, is about 300 amperes. I have tested some transformers of this type rated at 3 000 amperes and the compensation certainly gave very good features. A 3 000-ampere transformer should be fairly accurate without compensation, but in these compensation was a decided advantage. I should like the authors to give some information on one point: How does the secondary impedance on a compensated current transformer compare with the secondary impedance on a straight transformer of the same ratio and primary ampere-turns? This is rather important when summating two circuits by means of current transformers in each circuit operating the same meter, because the magnetizing current of an idle transformer may be taken from the transformer supplying the current going through the meter. It has some bearing on the meter accuracy. The higher the impedance of the secondary, the better. It would be interesting to hear how the design of protective transformers which reduces the magnetizing current to a negligible value is achieved. With regard to voltage transformers, the authors justify putting the fuses inside the tank by saying that if a voltage transformer fuse blows it is necessary to remove the core and coils for overhaul, and accordingly there is actually no necessity for accessibility although it may be of considerable convenience upon occasions. I do not agree, however. I think that the voltage-transformer fuse is the most wonderful time-lag fuse ever invented. After 12 months' service it blows without any fault occurring on the potential transformer. Manufacturers can supply good, accurate transformers; the trouble is that, from the users' point of view, manufacturers usually do not. Take the case of meters. The British Standard Specification—and manufacturers have some hand in the drafting of these specifications—says that Class C current and potential transformers are for ordinary industrial purposes, and Class B is for metering equipments where close accuracy is required. Close accuracy is required on all ordinary metering equipments on which accounts are based. Meter manufacturers who also make instrument transformers will persist in supplying Class C current transformers with their meters. The authors tell us that we ought not to ask for transformers rated for a volt-ampere burden higher than that with which they are to work, but we do get a more accurate transformer if it is rated for a higher burden than is actually imposed.

Mr. T. W. Ross : There is one important point to which I should like to refer in connection with the use of current transformers in compound-filled armour-clad switchgear, and that is the desirability of such transformers being of the single-turn primary type. I have seen switchgear specifications in which 20/5-ampere current transformers with an output of 15 VA were specified. It will be obvious that to obtain such an output several primary turns would be required, and in order to accommodate these turns in the space available the cross-section of the conductor would be limited. The current transformer being covered with the compound and the normal rating of the circuit breaker being, say, 300 amperes—which rating is marked on the name plate —the current transformer would have to carry such currents if at any time the switch was loaded up to its rated capacity. This seems to me to be a real danger and should be kept in mind when considering the application of current transformers in compound-filled gear. It would surely be preferable to have a reduced accuracy from the current transformer and get a more robust equipment both from the point of view of short-circuit stress and thermal rating. Although in certain cases it is desirable and probably necessary to provide special current transformers such as those described by the authors (in order to obtain the accuracy required for watt-hour meters), I would suggest that in many cases it would be better practice to measure the energy on the low-tension side of the power transformers and so be in a position to make use of the larger currents available. It seems to me that we very often depart from the ideal, that is to employ extra-high tension for transmitting power between two points with the least possible complication, by including metering equipment when the metering could just as well be carried out on the low-tension side. The authors make a strong claim for what they consider to be the desirability of designing current transformers to suit any conditions in their application to protective apparatus. Whilst agreeing that this is one method of ensuring stability of balanced protection on " through " faults, I have always made a point of testing protective current transformers for balance before despatch from the factory. The test is made with primary currents up to 15 000 amperes, and I consider that it is justified, because it will most probably indicate any defect in the construction of the current transformers. The excellent results which have been obtained with protective gear after these tests are a practical proof of their usefulness, and because of the great importance of satisfactory protective gear it seems desirable that they should be carried out.

Mr. J. H. Buchanan: I am wholly in agreement with the claim as to the merits of transformers constructed according to the ideas put forward in the paper. I believe that, on the whole, the split core with a " figure 8 " winding will be found to be sufficient in itself for most practical purposes. It gives a remarkably flat characteristic both for ratio and phase-angle errors at any particular burden, and furthermore a transformer constructed on those lines, in contrast with many compensated transformers, is insensitive to variations in burden. It has also the merit of being insensitive to variations in the power factor on the secondary side. In some current transformers of conventional design the performance is very much affected by variations in power factor. While that is to some extent the case in these transformers with " figure 8 " windings, they are only affected in a very much slighter degree. I am glad the authors have drawn attention to the fact that instrument transformers have not in the past always received the attention they deserve, but in my opinion the users themselves are largely to blame for that. I know one case where six transformers—quite expensive ones—were delivered on site but the buyers were not ready to use them and they were, apparently, left out of doors for weeks, with the result they were rendered unusable. They were sent back to the makers for overhaul. They were put right and returned to site, when the same thing happened a second time. They had to be overhauled a second time before they could be put into service. With regard to short-circuit limitations, I think that enough distinction has not been made between primaries which have 2, 3 or 4 turns and what are admittedly weak windings having a very considerable number of turns. I consider that a good design can be made with 2 or 3 primary turns to be substantially as secure against short-circuit effects as most bar-primary designs, as regards both electrical and mechanical limitations. The advantages gained by doubling or trebling the ampere-turns, in the case of low ratios, are so great that I think that in the future more attention will be given than has been the practice in the past to 2- or 3-turn primaries designed specially to resist severe short-circuit conditions.

Mr. E. H. W. Banner (*communicated*): It is difficult for anyone not thoroughly conversant with modern facts and figures of all types of instrument transformers to appreciate fully the importance of the compensated transformer. I suggest that a summary in the form of a table or curves showing for stalloy, nickel-iron and compensated transformers the connection between costs, accuracy obtainable, ampere-turns, total weight and minimum range for a bar-primary, would be extremely valuable in order to enable engineers to realize the improvement in accuracy and how this varies with cost of each type, together with the other less important factors mentioned above.

Mr. S. Farrer (*communicated*): The amount of compensation required to correct for ratio and phase-angle errors, due to the main core of a current transformer, will be roughly inversely proportional to the size of that core. Thus the size of the auxiliary core must be greater, the less is the size of the main core. A definite optimum relationship between the sizes of the two cores might, therefore, be expected for a current transformer of any rating, from the point of view of accuracy for either given total space or given total cost. I should be very interested to know whether the authors have found any definite ratios to exist between the lengths of the two cores and whether it has ever been necessary in practice to use stampings for the auxiliary core of different size from those for the main core. In the design of a current transformer for minimum phase-angle error, it seems evident that some definite portion of the B–H curve for the material of the core would have to be chosen, i.e. that by working on some portion of the B–H curve optimum correction for all loads would be obtained; similarly some portion of the curve would be best adapted for use in obtaining a minimum range of ratio errors. It is unlikely that these two portions of the curve could be arranged to coincide and therefore, in obtaining maximum correction for one error, a suitable range of values of B would be chosen and this would greatly limit the possible compensation for the other error by means of a winding on the same auxiliary core. It seems probable, then, that in order to obtain, in a current transformer, precision accuracy from the points of view of phase angle and ratio, the use of two auxiliary cores would be indicated. I should be glad to know whether the authors have found it necessary in practice to employ separate cores for ratio and phase-angle correction. On page 710 a scheme of cross-magnetization of a divided main core for a current transformer is described. As the two equal portions of the core are magnetized in opposite senses by a winding energized by the auxiliary core, it is stated that there would be no resultant effect on the secondary winding; it seems to me that this would only be the case if the main core were being worked on a perfectly straight portion of the *B–H* curve. I should be very grateful if the authors would explain in a little more detail their scheme of cross-magnetization.

Mr. S. R. Mellonie (*communicated*): Dealing with current transformers for the operation of overload coils on page 705, the authors imply that the performance above 50 per cent overload is not important, but B.S.S. No. 116 requires a setting at 300 per cent of load. The limit of 40 times the secondary current quoted on page 707 shows how such values may vary, and is of great importance when considering protective devices. This should be compared with a figure of 14 times which was given in the *Journal* (1927, vol. 65, p. 583). Dealing with potential transformers, the authors rightly emphasize the danger of failure which exists owing to the use of very fine wires for the high-tension windings. These wires are difficult to insulate and are mechanically weak and therefore susceptible to corrosion. It is suggested that a minimum value of 0·01 in. diameter is a practical compromise. Troubles due to coronæ on fuse wires have been eliminated by coating the wire with insulating material. I have designed and tested a fuse fitted with electrostatic shields, but this gave trouble due to flashing over when the fuse blew. A very compact and sound job is made by enclosing the transformer limiting resistance and fuse in the same oil tank. The authors recommend that potential-transformer fuses should be coupled on the line side of the limiting resistance, but I should like to know their reasons for this. From theoretical considerations the resistance should be coupled to the busbar or heavy-current circuit. In this way the entire length of conductor associated with the potential transformer circuit is protected. In fact, the resistance should be regarded as protecting the fuse, and not vice versa.

Mr. A. M. Strickland (*communicated*): For some time past there has been a demand for improved performance of current transformers for use with metering equipments, and the paper gives an excellent exposition of one method of making such improvement. It would perhaps at first sight appear that their design, which entails some complication, is not now warranted owing to the more recent introduction of low-loss irons which appear to give very good results. However it is evident that, with a combination of the two, in the future the production of reasonably accurate bar-type current transformers for primary currents as low as possibly 20 amperes will not be out of the question. It is suggested that the authors have omitted one argument in favour of the simple ring current transformer, that is its convenience for use on ordinary power consumers' metering in sizes up to 50–500 primary amperes. They have great advantages for this work as they require little mounting and can be easily changed at any time with the minimum of interruption to service, inconvenience and cost. At the same time, with improved characteristics metering accuracy at low loads and low power factors should be improved. Another use to which current transformers of the authors' design have been put is in connection with meter-testing equipments. Here high accuracy is essential. The transformers are used with multi-turn primary winding ranges and with a polyphase wattmeter on the secondaries, and as the phase-angle error is practically nil the resultant simplification in routine testing is a matter to be considered. It would be of interest to know whether, in view of their statement that it is doubtful whether the new low-loss irons are stable in service, the authors anticipate any trouble with the auxiliary core iron which, they state, is run at fairly high flux density. The suggested methods of obtaining partial turn adjustments are exceedingly interesting; in view of this is it necessary to advocate 1-ampere secondary metering when it is borne in mind that the usual VA load for induction-meter series coils is about 2 VA at the most, and it is not considered good practice to load metering current transformers with other apparatus than the above. As rapid improvements are evident in current transformers it would appear questionable whether, apart from special cases, in the near future the wound primary transformer will not be used. Do the authors consider their type of transformer to be less liable to damage by accidental open-circuiting of secondaries?

THE AUTHORS' REPLY TO THE DISCUSSIONS.

Messrs. J. G. Wellings and **C. G. Mayo** (*in reply*): In replying to the many points raised by the various speakers, we should like to express our appreciation of the way in which the paper has been received, and the interest taken in the various views expressed in it.

Meter and Instrument Section.

Mr. Ockenden mentions true figure of merit, and we take it that by this he means not only performance under rated burden but also performance with any burden up to rated burden. In this connection we have added an Appendix giving test results at burdens of 5, 15 and 40 VA on a 40-VA transformer in which precision accuracy is maintained throughout. Nevertheless, it should be pointed out that still higher accuracies may be obtained with the transformer if designed to give its best performance at a stated burden. Again we would emphasize that the conventional type of current transformer can only give its highest accuracy at zero burden, which condition is not realized in practice.

The similarity which Mr. Ockenden draws to the use of a condenser in shunt is not strictly true, as the compensating effect produced in such a way does not lend itself to varying values of primary current and secondary burden as regards power factor. The way in which Mr. Ockenden describes his theory of the compensated current transformer is not, in our opinion, so clear as the way described in the paper, and is also subject to correction as described above.

Mr. Ockenden states that it is difficult to follow our explanation of the source of the separate excitation provided by the auxiliary core, and that it is impossible to introduce into the primary any current other than that which is in the bar. We would point out that it is possible to obtain any amount of additional exciting ampere-turns once the provision of separate cores is visualized. In this connection the question of flatness may conveniently be raised. Flatness is, of course, a relative term, and any degree of flatness can be secured by using sufficient ampere-turns and/or using mumetal, but to secure adequate flatness it will be found that the absolute errors must be so reduced that the transformer is unnecessarily bulky and costly. In other words, the change of error becomes the limiting feature. With compensated current transformers using stalloy the permeability is not increased to the same maximum as mumetal, but is increased to a large value which remains substantially constant at varying primary currents, a feature which, in our opinion, is superior to an extremely high permeability at one value of primary current, coupled with much lower values of permeability at other values of primary current. Furthermore, it should not be overlooked that our type of compensating windings are not restricted to silicon-steel cores, but are equally applicable and effective where used with cores of such materials as mumetal, i.e. the use of compensating windings is such as to improve the permeability and maintain it substantially constant over a wide range of primary currents.

As regards the operation of current transformers in parallel for summation metering equipments, undoubtedly the compensated current transformer has a lower shunt impedance than a transformer with equivalent accuracy, obtained either by the use of liberal ampere-turns or by the use of nickel-alloy cores. It has been our experience, however, in the majority of such metering equipments that the length of the pilot leads from all the various circuits which have to be metered brings up the total impedance very considerably, so that the mutual impedance is comparatively small, and as a matter of fact the figures given by Mr. Gibbons in his contribution to the discussion refer to an equipment of this nature. On the other hand, this same feature of the comparatively lower transformer impedance compared with the more conventional type is advantageous in giving a reduced value of open-circuit voltage should the secondary windings be disconnected.

As regards Mr. Ockenden's remarks on the fractional-turn arrangement, he appears to be under the misapprehension that a circulating current flows round the transformer windings. Actually the effect of the use of two cores in parallel may be regarded as equivalent to that obtained by using two independent current transformers, the one for 2·5 amperes, and the other to give, say, 2·525 amperes, so that the total current is 5·025, and hence giving a closer degree of correction than would otherwise be possible if there were only one core. Our preferred method, however, is the use of one or more turns linking only a portion of the total core section, and this, as described in the paper, has the added advantage of improving the permeability of the core material, and is both convenient and effective. We appreciate the interest shown by Mr. Ockenden in our paper, and for bringing to light other aspects of the matter which may not have been sufficiently described in the paper.

Dr. Drysdale appreciates the advantages of our methods of compensation, particularly that they can be applied to cores of nickel alloys as well as those of silicon steel. This is a point which it is certainly desirable to emphasize. By these means we have been able to produce bar-primary transformers with a rated current as low as 50 amperes without the cores being of other than usual proportions, and with an accuracy practically equal to that obtainable with class "A" (B.S.S. 81—1927). Dr. Drysdale mentions the same point as Mr. Ockenden, viz. that the accuracy will be changed if the burden is changed. While this is definitely so, and applies to transformers of all types, we would again stress the point made in our paper that with a compensated design the minimum errors can be made to occur at rated burden instead of only at zero burden, and, therefore, under operating conditions a higher degree of accuracy is obtainable.

Mr. Fawssett begins his remarks by advocating the use of mumetal. Towards the end of his remarks, however, he refers to the high cost of obtaining the accuracies at present being specified, and we would here point out that the compensated transformer is capable of giving those high degrees of accuracy without the use of a highly expensive metal such as mumetal, although, as mentioned in our reply to Dr. Drysdale, in extreme cases we recommend a combination of both mumetal and compensated windings. Mr. Fawssett again refers to the question of change in burden, and we would refer him to replies made to other speakers on this matter. In our experience with many switchgear developments, there is very little difficulty in forecasting approximately the burden which will occur in service, and it is our understanding that when meters are calibrated with their current transformers it is invariably metering practice to request definite information of the total impedance in the secondary circuit, and to test only under those prescribed conditions. As regards the use of testing windings, we have made exhaustive tests proving that, provided a ring core is used and the secondary winding is evenly distributed over it, the performance obtained when the testing winding is used is exactly the same as when the main primary is used. Col. Edgcumbe's remarks confirm this result.

Mr. Spilsbury's queries with regard to the variation of errors with burden are dealt with in our reply to Dr. Drysdale and in the Appendix now attached to the paper. Compensated current transformers have been built to give precision accuracy at any frequency from 25 to 100 cycles. As regards wave-form, this is a matter which has had our attention, and variations due to wave-form can be rendered negligible by proper design. The flatness of characteristic curves was dealt with in our reply to Mr. Ockenden.

Mr. Marshall's suggestion that, in order to overcome the weakness of all known types of current transformers at extremely light loads, excitation should be derived from a separate source of potential, is extremely interesting, and by this means it would be possible to make the effective permeability almost constant at all values of primary current, and this permeability would be very high. There is, however, a weakness as follows:—Suppose the flux density to be maintained by separate potential at a point corresponding to the point of inflexion of the magnetization curve for the material. If then the superposed working flux were out of phase with this flux and relatively small the effective permeability would be that corresponding to the working point. If, however, the superposed working flux were in phase with the original flux the effective permeability would be that corresponding to the slope of the inflexional tangent to the magnetization curve, and many times greater than in the above case. Thus, although the errors would be practically independent of the magnitude of the primary current they would be affected by the phase of the primary current. They would, however, be considerably less than those in a plain transformer at light loads. We do not agree that in practice the secondary is just as liable to failure as the primary, and, moreover, a failure on the primary winding has far greater consequential effect than a failure in the secondary winding of a current transformer.

We do not agree with Mr. Burgess that balancing of transformers is the only way to achieve stability in balanced protective gear. We do not even believe that it is a satisfactory way. In protective-gear transformers the critical point for accuracy is at primary currents of the order 10 to 20 times rated primary, and what is required is high permeability not so much at low flux densities as at moderately high flux densities. Compensated current transformers would, therefore, not be used for protective gear, although the same methods may be used to secure improved sensitivity without sacrifice of stability. With regard to the rolled strip core, the characteristics obtained with such cores are substantially the same, bulk for bulk, as those obtained from cores of stamped rings over the range of flux density usually employed in current-transformer design. With regard to the weight of cores for compensated current transformers compared with the conventional multi-turn types, in general the size of core is greater, but the overall dimensions of the transformer are in general less, particularly when allowance is made for clearances around the primary windings and its terminals. As regards the question of lower rated secondary currents than the usual standard of 5 amperes, it is our opinion that 1 ampere is exceedingly desirable as an alternative rating, and in some cases 0·5 ampere as well, according to pilot burden and the characteristics of the transformers concerned.

In reply to Col. Edgcumbe, an Appendix has been added giving further results on compensated current transformers of various ratios. We are interested in the remarks of Col. Edgcumbe and those of other speakers as regards the stability of mumetal and, as described in the paper and emphasized in our reply to another speaker, there is a very definite application in the use of mumetal in extremely low ratios, combined with compensating windings to reduce the quantity of material required and also to improve the performance obtained from it.

Mr. Lipman deals with the 0·5-ampere secondary winding of a current transformer. It is true that the increased number of secondary turns provides extremely fine adjustment in turn correction, but in our opinion sufficiently fine adjustment is obtained with 1-ampere secondary current, which avoids other difficulties such as high open-circuit voltage, low space factor of windings, etc.

We are indebted to Mr. Gibbons for the performance figures he gives in regard to a metering equipment employing compensated current transformers tested by him. With reference to his statement as regards certain advantages of earth protection as against circulating current, it must not be overlooked that circulating-current conditions may apply to the transformers used in certain forms of core-balance protection. We appreciate Mr. Gibbons's comments on the question of accessibility of fuses. These would appear to justify ready accessibility being provided in all cases.

Mr. Quenzer queries the necessity of testing windings, and considers it satisfactory to connect the testing leads to the secondary terminals of the current transformer. This, however, does not check the transformation performance of the current transformer. Other points raised by Mr. Quenzer are dealt with in our replies to other speakers.

We are fairly in agreement with Mr. Hill on the question of statement of current-transformer errors, and would go even further and advocate the statement of phase-angle error in radians.

The points raised by Mr. Minton have been dealt with in our replies to Mr. Fawssett and Mr. Hill.

We are glad to have the support of Mr. Trencham in advocating the proper correlation of switchgear and metering requirements. Mr. Trencham also emphasizes the need for current transformers to be as reliable as the bus connections, a point which is not necessarily taken care of in the ordinary use of multi-turn current transformers.

Manchester Discussion.

Mr. Randle surmises that the ratio-error correction was rendered necessary by the fact that phase-angle correction increases the ratio error. This is to some extent true, but it must be noted that this vitiation of ratio error is not large enough to make ratio error the limiting feature, were it not for the fact that the phase-angle error is so greatly improved. In other words, the reduction of the phase angle by our method of compensation so improves the accuracy of the transformer in this respect that ratio error becomes the limiting feature, and accordingly it appeared desirable to find some means by which ratio error could be similarly compensated so that this feature became in keeping with the reduced phase-angle error. The ratio-error correction neither necessarily nor generally causes an increase of phase angle, and it may even be arranged to reduce phase-angle error. This is because ratio-error correction is due roughly to the rotation of a vector already approximately normal to the secondary vector, i.e. phase-angle change due to ratio correction is, therefore, usually of the second order. With inductive burdens the exciting current vector is no longer approximately at right angles to the secondary vector, and in this case ratio-error correction tends to prevent the usual increase of ratio error with reduction of phase-angle error. Col. Edgcumbe has pointed out in his contribution that reduction of secondary current does not *per se* reduce the burden. It should be borne in mind that to operate any given instrument or relay the power required mechanically is independent of the current rating of its operating coil. The flux density in the auxiliary core is high only from the usual current-transformer point of view, and does not necessitate consideration of core heating.

Mr. Holmes states that he cannot see any difference in principle between our compensated transformer and the Brooks two-stage transformer. We would point out that there is a fundamental difference, both in principle and in application. The Brooks transformer, it is true, has a main core and an auxiliary core, but beyond this all similarity ceases. The Brooks transformer operates on the principle of supplying the " error current " electrically to the instrument being operated by providing the instrument with an additional winding energized from the auxiliary core, which in turn operates on the difference of the input and the output ampere-turns of the main core. Our type of compensated transformer has the " error current " supplied, in effect, magnetically to the main core by specific design of the auxiliary core, and accordingly the output of the transformer, so far as the meter is concerned, is inherently compensated, and the meter only requires the one usual winding. That is to say, our compensated transformer can be regarded as an ordinary plain transformer requiring an ordinary plain meter; and even to a non-technical man there is no difficulty in distinguishing between this and a current transformer requiring double pilots and double-element meters. With regard to the comparison of our transformer with the Wilson transformer as produced in the United States, it is more difficult to draw any fundamental difference as regards the methods of ratio and phase-angle compensation compared with our compensated transformer. However, we would point out that this transformer was developed in the United States subsequently to our work in England, the first compensated transformers of our design being supplied as far back as 1923. As regards comparison of our transformer with the transformers with mumetal cores, this point has already been referred to in our reply to other speakers. As regards the query as to whether the compensation shown in Fig. 10 is for laboratory use, we would point out that our designs of compensated transformers are primarily intended for use on commercial metering circuits where extremely high accuracy is required, such as is specified for the Central Electricity Board, etc. The form of compensation shown in Fig. 10 is used for special purposes, sometimes by itself and at other times in conjunction with the methods shown in Fig. 8, according to conditions. So far we have not attempted to produce transformers for laboratory use, but have concentrated on producing transformers to meet certain specific high grades of accuracy with the transformers as small as possible physically and with the bar-type primary down to the very minimum primary current. Large numbers of transformers have been supplied and have been operating in service under these conditions for many years where the use of the bar primary instead of the multi-turn, which would otherwise be required, has enabled the lay-out of the switchgear and likewise its reliability to be improved to a greater extent. With regard to the short-circuit factor of 150 based on thermal effects, this of course involves a time factor, and the duration of the short-circuit is assumed to be the average time which a circuit breaker takes to clear, namely, about 0·25 sec. This assumption for the duration of the short-circuit period, and also other assumptions as the average symmetrical effect, were intended to be covered by the statement of " average conditions " of short-circuit as quoted in the paper. Since the publication of the paper we have been most interested to see expressions of short-circuit capacity in technical papers published in France and America, which agree very closely with the short-circuit limitations as determined by us.

Mr. Turner's idea that phase-angle and ratio compensation cannot be used together is entirely erroneous and this point is dealt with more fully in the reply to Mr. Randle. The fact that the correcting current tends to remain substantially constant over a part of the range is a decided advantage, and intentionally so, and means that the correcting current is a greater percentage of the primary at lower values of primary current, and this is precisely what is required. As stated in the paper, the use of the crossed-winding method of Fig. 10 increases the effective permeability from 3 to 4 times, depending on the burden and primary current, the improvement being greater with smaller burdens and values of primary current. Very approximately, with a transformer of this type, halving the burden halves the phase-angle error. The previously described methods are very simply and effectively superposed on this to give even better results. An Appendix giving further test-results has been added to the paper.

We cannot agree with Mr. Sheppard that the advantages of bar-primary transformers may be over-stressed. From the experience from which we have had with large station switchgear we are convinced that the requirement for current transformers to be of the bar-primary type is of an importance practically overruling every other consideration. It should be borne in mind that every piece of apparatus in a large system has some form of protection, and the current transformers themselves have to be assumed beyond reproach, and accordingly anything in the form of a coil for the primary winding should be avoided wherever possible. As regards the point as to permanence and performance after years of service with frequent heavy short-circuit duty, we would point out that we have had this type of compensated transformer in service now for many years, and there has been no indication as to any change in performance nor would any such change be expected as the density, although high from an ordinary current transformer point of view, is not high intrinsically. As regards the arrangement shown on Fig. 10 and queried by Mr. Sheppard, we would refer Mr. Sheppard to the paragraph at the top of page 710. We can only amplify this by stating that the alternation of flux density as required by the secondary burden is so small compared with the alternation of the flux produced by the figure-of-eight winding that the permeability is very approximately a differential permeability. Roughly speaking, transformers compensated solely by the method shown in Fig. 10 may have their errors reduced to approximately one-quarter of what they would otherwise be for the same size of core operating uncompensated. Furthermore, the arrangement of

Fig. 10 is extremely effective in producing the flat characteristic, as mentioned by another speaker who is familiar with this type of transformer. We would refer Mr. Sheppard to the Appendix, now added to the paper, which gives typical performance of compensated current transformers under varying conditions of burden and ratio, etc. As regards Mr. Sheppard's statement that certain schemes of compensation are only palliatives and that the error is still inherent in the transformer, we would refer him to our reply to Mr. Ockenden in the discussion before the Institution.

We are glad to note that Mr. Brown is so fully in agreement with us on the general views expressed in the paper and particularly with regard to balanced protective gear, where we note that Mr. Brown's practice and views have for some time been those put forward in the paper.

We thank Mr. Howarth for his favourable comments on the 3 000/5 transformer which he has tested. The question of secondary impedance has been dealt with in the reply to Mr. Ockenden. The magnetizing current of protective transformers is reduced mainly (*a*) by generous iron section of the cores, and (*b*) by reduction of pilot burden by such methods as magnetic balance or using smaller rated secondary currents. On the question of potential-transformer fuses, it would appear that there is good reason for accessibility of fuses. As regards the blowing of fuses, our experience has been that, since the provision of electrostatic shields, corona on the fuse wire is avoided, so that on higher-voltage designs failures after about 12 months' service have practically been eliminated. We agree with Mr. Howarth's inference that the present British Standard Specification for Instrument Transformers is not in accordance with present-day practice, and we hope that shortly a revision will be made, when the users will no doubt have ample opportunity for specifying their requirements. In this respect we feel that the users should more definitely state their requirements. That is to say, if they require a certain grade of accuracy, that accuracy should be mentioned to the maker instead of ordering a transformer of a higher volt-ampere burden at a lower accuracy and trusting that such a transformer on a lower burden will give the higher accuracy which the user really has in mind.

We are glad to note Mr. Ross's general agreement on the question of the short-circuit capacity. Particularly do we feel that more use should be made of the installation of transformers on the low-tension side of power transformers so as to avoid the complications and comparative weakness of the high-tension transformers, unless these latter windings can, by means of compensating windings, be made to give the required accuracy with the single-turn primary construction.

Mr. Buchanan mentions that the construction shown in Fig. 10 may be found sufficient in itself for most practical purposes. We have perhaps hardly emphasized sufficiently in the paper the remarkably flat characteristic which transformers compensated in this way give in spite of variations in burden. As mentioned in the paper, however, still higher grades of accuracy can be obtained by the combination of the arrangements shown in Figs. 10 and 8. We are in agreement with Mr. Buchanan that there should be a distinction between transformers having 2, 3 or 4 turns and those having a very considerable number of primary turns. Nevertheless, a transformer even with only 2 turns is in a fundamentally different category from those which have only a straight-through primary. It must be borne in mind that the circuit frequency has only to be high enough on even a 2-turn primary to build up sufficient voltage to break down the insulation between those two turns. Provided, however, that such 2- or 3-turn primary transformers are given liberal insulation between turns, they have an exceedingly useful field of application, and we are all in favour of their use.

In reply to Mr. Banner, an Appendix showing the performance of compensated transformers with varying burdens and ampere-turns has now been added to the paper.

As Mr. Farrer suggests, there is an optimum relation between the sizes of the main and auxiliary cores, and this has been determined in a large number of cases by calculation. It has not so far been necessary to use different sizes of stampings for main and auxiliary core. So far, the need of separate cores for ratio and phase-angle compensation has not arisen, and transformers in practice are constructed in which the same auxiliary core serves: (*a*) for compensation in accordance with Fig. 10, (*b*) for phase-angle correction in accordance with Fig. 6, and (*c*) for ratio correction in accordance with Fig. 8. It should be noted that the magnetizing forces on the two halves of the main core are equal and, therefore, in the absence of magnetizing ampere-turns due to the effect of the burden on the transformer the flux densities on the two half-cores, and therefore the induced e.m.f.'s, must be equal and opposite and therefore there is no resultant e.m.f. in the secondary. This would be the case were the transformer short-circuited at its terminals and without secondary resistance. As soon as resistance is introduced in the secondary circuit the secondary ampere-turns differ from the primary ampere-turns, this difference increasing the flux density numerically on one-half core and decreasing it on the other half, the two fluxes now no longer cancelling but combining to give the required secondary e.m.f. at, however, a much reduced cost of magnetizing current or difference between secondary ampere-turns and primary ampere-turns, owing to the permeability being, in effect, differential.

We thank Mr. Mellonie for drawing our attention to an apparent error in the statement of overload capacity of metering current transformers. Our statement should have read that metering accuracy should be maintained up to, say, 25 per cent overload but that the transformers should still maintain sufficient accuracy for relay operation up to 300 per cent load. We are interested to note that Mr. Mellonie has designed and tested fuses fitted with electrostatic shields, but that his arrangement gave trouble due to flashing-over when the fuse blew. In our combined arrangement of fuse and resistor development, in which the resistor acts as an electrostatic shield to the fuse, particular care has been given to prevent arc-over when the fuse blows. We have a large number of these combined fuses and resistors operating under service conditions, but so far every satisfaction has been obtained and there has been no cases of arcing-over when the fuse blows. As to whether the fuse should be on the line side of the resistor or vice versa, it is our experience that there are advantages and disadvantages either way. A decision as to which is the better method must in our opinion, be based on the particular arrangement of the connections involved. We have known of one case where with the resistor mounted in front of the fuse of one of the supporting insulators of the resistor failed and the fuse was of course unable to clear the fault. With the fuse installed in front of the resistor the fuse could have cleared the fault.

We are glad to note that Mr. Strickland appreciates the possibilities of using nickel-iron alloy in conjunction with the methods of compensation described in the paper. The question of the flux density of the auxiliary core has been dealt with in the replies to the other speakers. We thank Mr. Strickland for drawing our attention to the possibilities in connection with meter-testing equipment. As regards the effect of accidental open-circuiting of the secondary of a compensated transformer, we would state that the presence of the compensating windings reduces the value of the open-circuit voltage which would otherwise occur.

AN INVESTIGATION OF EARTHING RESISTANCES.*

By P. J. Higgs, B.Sc.

[From the National Physical Laboratory.]

(*Paper first received 16th August, 1929, and in final form 20th February, 1930.*)

SUMMARY.

The phenomena of polarization and endosmose which accompany the flow of direct current in soil were investigated in various laboratory experiments. Polarization was an effect of gas bubbles on the measured soil resistance—bubbles which formed owing to a small electrolytic decomposition of the soil moisture by the current and which accumulated at the electrodes. Endosmose was extensive and occurred even against an appreciable hydraulic back-pressure. The earthing resistances of electrodes of inextensive area depend directly on the resistivity of the surrounding soil, and so relations were obtained showing the effect of moisture, temperature and salt on soil resistivity. The resistivities of coal, coke, ashes, chalk and dried soil were also obtained.

Various types of electrodes of inextensive area, viz. pipes, plates and strips, were installed in a plot of ground and tested over a period covering one year. The results are important as being typical of what may be obtained in practice, but not as criteria of comparative utility of the various electrode types on account of the soil resistivity being—there were reasons to presume—appreciably non-uniform. The earthing resistances of the various electrode types were, however, calculated theoretically, a soil of uniform resistivity being assumed, and the results obtained may be used as criteria. The seasonal variations in resistance were determined during the year, and the effect of moisture in this respect was greater than that of temperature.

Some electrodes of extensive area, viz. water pipes, the lead sheath of a large size cable and the steel structures of buildings, that were in the vicinity of the other electrodes, were also tested. Their earthing resistances were much smaller than those of the other types, and the smallest resistance was that of a water pipe. The possible differences between alternating-current and direct-current measurements made on electrodes in the field were investigated. The greatest difference obtained was an increase in resistance of about 20 per cent with direct current and with the positive electrode one of inextensive area.

The various types of electrodes of inextensive area are considered theoretically in an Appendix.

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Appendix. A theoretical consideration of the earthing resistances of various electrodes of inextensive area.

SECTION (1). AN INVESTIGATION OF SOIL RESISTIVITY UNDER DIRECT-CURRENT AND LOW-FREQUENCY ALTERNATING-CURRENT CONDITIONS.

Earthing in electrical practice is carried out to mitigate primarily the dangers of shock to persons and of leakage currents with regard to starting fires. To make them effective, earthing resistances are generally made as small as possible. An earth connection may be made either for alternating or direct current, and its resistance may not be the same with each on account of the effects of polarization and endosmose with direct current. These effects were investigated in some preliminary experiments.

(A) DIRECT-CURRENT POLARIZATION OF SOIL.

A sample of sandy loam taken from the ground and containing about 15 per cent by weight of moisture was placed between copper disc electrodes in a glass tube 10·5 cm in diameter and 15 cm long, in order to investigate the direct-current polarization of soil. The arrangement of the apparatus is shown in Fig. 1. It includes various switches by means of which resistance measurements were made as required, either with alternating current or with direct current flowing in either direction. The electrodes were lightly pressed against the soil in order to ensure good contact. Each kind of measurement was made with 140 volts and the soil resistance was taken to be the ratio of the voltage to the current.

Polarization was investigated by making various switch operations in a considered sequence and observing the resultant changes in soil resistance. To investigate the effect of the nature of the electrode contacts on polarization, tests were also made with tinfoil placed between the copper discs and the soil, and with the tinfoil replaced by carbon powder.

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The results of the tests and notes bearing mainly on the effects of polarization are given below.

(i) The primary effect of polarization was a decrease of direct current with time at constant voltage. The rate of the increase of apparent resistance was greatest initially and decreased gradually to zero, and the magnitude of the total change was in some cases such that the final value was about three times the initial. The actual range of resistance measured in this way was from about 2 000 ohms to 6 000 ohms. The measurements were somewhat inconsistent, as shown by repeat tests, under apparently similar conditions, giving sometimes appreciably different results. A possible explanation of the inconsistency is given below.

The soil being visible in the glass containing-vessel, it was noted that an effect of the flow of direct current was a slow electrolytic decomposition of the contained moisture, for gas bubbles were continually forming. As the gas bubbles formed they accumulated in the interstices at the electrode contacts and the direct current decreased in value. When the interstices, which were small in volume, were filled with gas the current was more or less steady, on account of the production of gas being balanced by its escape.

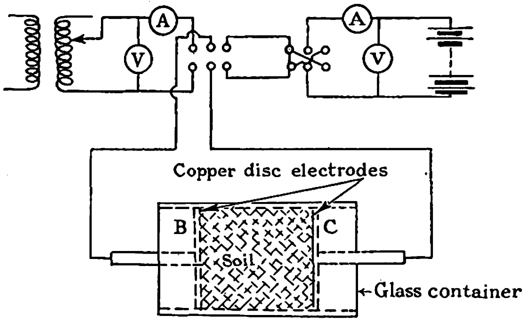

FIG. 1.—Soil resistivity tests. Direct-current polarization in soil.

The increase of soil resistance to a final steady value with the flow of direct current appeared, therefore, to be primarily owing to the accumulation of gases at the electrodes. On the current ceasing to flow, the soil resistance would slowly decrease to its former initial value as the gases became gradually dissipated, and this feature was observed in the tests.

(ii) The resistance of the soil was slightly greater with an initial direct current than with alternating current. The difference was probably due to a small back electromotive force of electrolysis with direct current as in the electrolysis of water.

(iii) The increase in the resistance of the soil owing to the polarization effect of direct current of one direction of flow was apparent in measurements made with alternating current or with direct current flowing in the reverse direction. This feature is in accordance with the supposition that the increase in resistance, or polarization effect, is mainly a pure resistance due to the accumulation of gas at the electrode contacts.

(iv) With tinfoil between the copper discs and the soil, the resistance of the soil with alternating current or with an initial direct current was about 80 per cent of its respective value measured with the plain copper electrodes. The decrease in resistance was presumably owing to improved electrode contact, but the increase in resistance on account of polarization was proportionately about the same as before.

(v) With carbon powder instead of tinfoil between the copper discs and the soil, the initial resistance of the soil was further slightly decreased, presumably owing to still better electrode contact. The increase in resistance owing to polarization was, however, comparatively small, possibly on account of the fine carbon particles preventing the accumulation of gas either by absorption or by themselves simply occupying the interstices.

(B) EXPERIMENTS IN ELECTRICAL ENDOSMOSE.

When the direct current flowed continuously for several minutes in the tests described previously, it was noted that the soil near the positive electrode was getting wetter and that near the negative electrode drier. The effect, which was one of movement of moisture in the direction of the current-flow, was investigated by the experiments described below.

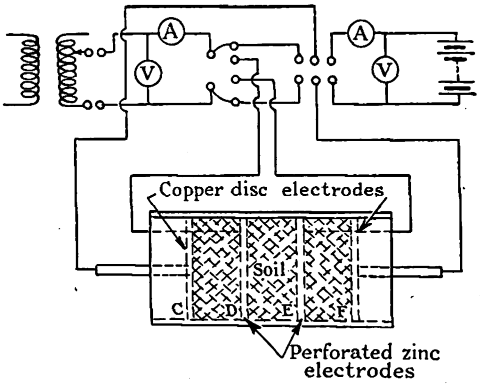

FIG. 2.—First electrical endosmose experiment.

First Electrical Endosmose Experiment.—A sample of sandy loam, containing about 12 per cent by weight of moisture, was placed in a glass tube with four metal disc electrodes, as shown in Fig. 2. The outer electrodes C and F were made of copper and the inner, D and E, of commercial perforated zinc. The soil was divided by the electrodes into three approximately equal parts. The electrical connections to D and E were rubber-insulated conductors, and to C and F brass rods. The outer electrodes were lightly pressed against the soil when the measurements were made, in order to ensure good contact.

Endosmose was produced in the soil by means of a small direct current which flowed continuously during the experiment, except for periodic short intervals of time when measurements were made with alternating current to ascertain the effect of endosmose on the various sections, and on the whole of the soil.

The results obtained are given by curves in Figs. 3 and 4. Fig. 3 shows the relations between voltage-drop and time for the individual sections. The voltage-drop across a particular section would increase or decrease with decrease or increase of moisture, and the curves may be taken to indicate approximately the movement of moisture among the sections during the experiment. There was no net loss of moisture, except possibly a little owing to electrolysis.

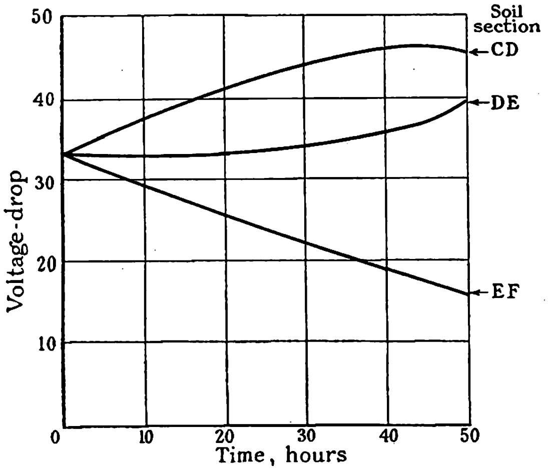

FIG. 3.—Variation of voltage-drop across the individual soil sections with time (see Fig. 2).

Fig. 4 shows the relation between the resistance of the whole of the soil and time, and it indicates that the endosmose increased the resistance considerably. After the experiment the mean moisture content of each section was determined: that of section CD, next to the negative electrode, was 7·1 per cent, that of the middle section DE 9·8 per cent, and that of section EF, next to the positive electrode, 16·5 per cent, the percentages being by weight of soil.

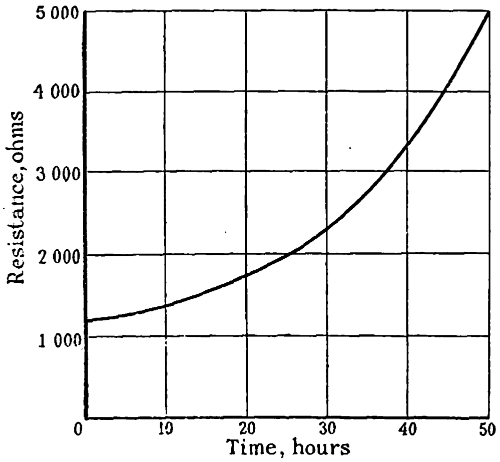

FIG. 4.—Variation of resistance of whole soil with time (see Fig. 2).

Second Electrical Endosmose Experiment.—The arrangement of the apparatus used in the second electrical endosmose experiment is shown in Fig. 5. It consists of sandy loam between two electrodes in a glass funnel, the electrodes being connected in a direct-current circuit. The top electrode was a brass piece that fitted in the neck of the funnel, as shown. It was soldered to the end of a brass rod which passed with appreciable clearance through the funnel tube portion or small end. The bottom electrode was a tin cover that fitted the big end.

A preliminary test was made with the arrangement of Fig. 5(*a*). A direct-current voltage of 200 was applied across the electrodes, the bottom one being positive, and a current of about 0·1 ampere flowed. The moisture of the soil accumulated slowly around the top electrode and rose in the tube portion to a height of about 3 in. It was, therefore, considered interesting to investigate the height to which the water would rise if the soil were supplied with an unlimited amount. For this purpose the arrangement of Fig. 5(*b*) was used. The funnel was placed in a flat dish containing water and its small end was extended upwards with glass tubing and rubber connecting-pieces. A lead weight was placed on the funnel to counteract the lifting effect of water in the tubing.

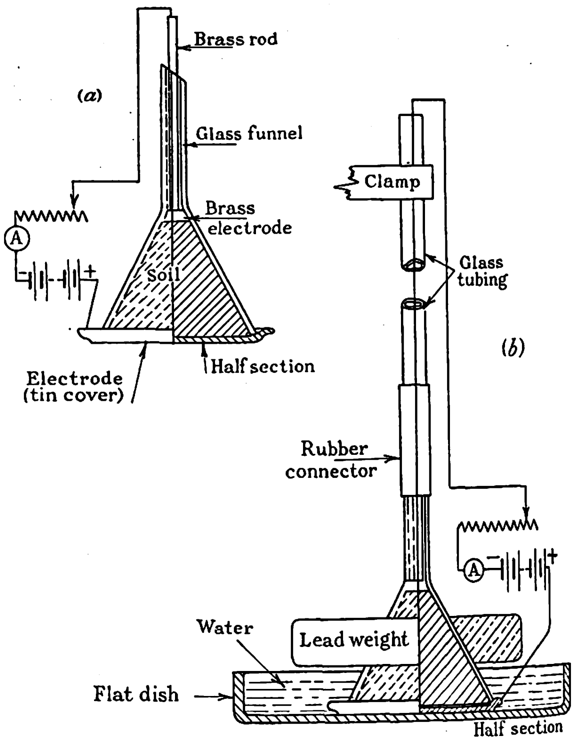

FIG. 5.—Second electrical endosmose experiment.

On applying the voltage of 200, about 0·1 ampere flowed and water rose slowly in the tubing. The results of the experiment are given in Fig. 6 in the form of curves showing relations between head of water and time, and between current and time. The curves indicate that the current decreased, or, in other words, that the soil resistance increased as the head of water increased. Because there were no changes in the soil, either of temperature or of moisture content, it seemed that the increase in soil resistance was due to the head of water, or that the hydraulic back-pressure, which would increase the resistance to the movement of the moisture of endosmose through the soil, had also increased the electrical resistance. The phenomenon was one of a mechanical back-pressure affecting electrical resistance in the same way as an electrical back-voltage.

The conditions were apparently steady after 15 hours with the head of water about 9 ft. and the current about 36 per cent of its initial value. This head of water gives at its base a pressure of 3·9 lb. per sq. in., which indicates that endosmose occurs even against considerable hydraulic back-pressure. Subsequently it was noted that the water would rise higher than 9 ft. without change of conditions except that the counterweight on the funnel was increased. When the applied voltage was removed the water descended slowly in the tube. While the current flowed some electrolytic decomposition of the moisture in the soil occurred, for gas bubbles were continually forming and escaping at the rate of a few a minute through the head of water.

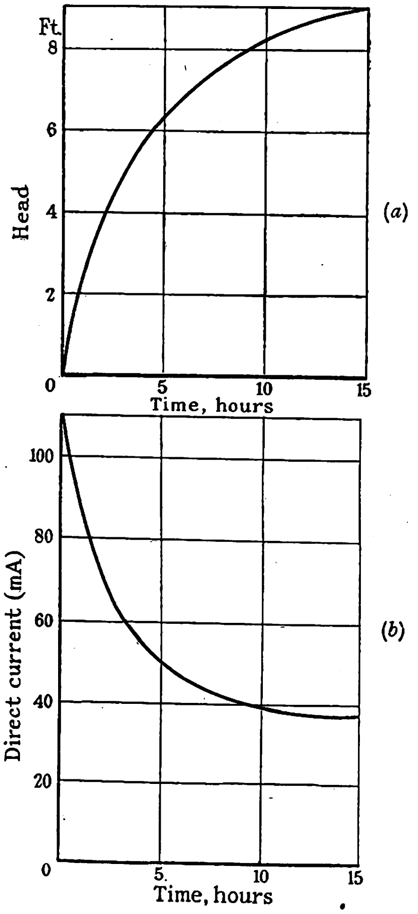

FIG. 6.—Variation of (*a*) head of water, and (*b*) current, with time (see Fig. 5*b*).

(C) RESISTIVITY AND MOISTURE CONTENT.

The relation between resistivity and moisture content was determined for two kinds of soil which are prevalent in the vicinity of the National Physical Laboratory. One kind is top soil having a greyish black colour like garden loam and occurring to a depth of about 2 ft., and the other is bottom soil having a sandy yellow colour. The former is referred to as "top soil" and the latter as "sandy loam."

Samples of the soils, having different moisture contents, were tested by means of the alternating-current ammeter-voltmeter method. The results given in Table 1 indicate the relation between moisture content and resistivity—an important factor, since the resistance of inextensive electrodes, such as driven pipes or buried plates, is proportional to the resistivity of the surrounding soil.

TABLE 1.

Resistivity and Moisture Content of Top Soil and Sandy Loam. Temperature 17° *C.*

Moisture content per cent by weight	Resistivity		Ratio to resistivity at 15 per cent of moisture	
	Top soil	Sandy loam	Top soil	Sandy loam
	ohms per cm cube			
2·5	250 000	150 000	13·2	14·3
5	165 000	43 000	8·7	4·1
7·5	100 000	26 000	5·3	2·5
10	53 000	18 500	2·8	1·75
12·5	27 000	14 000	1·42	1·33
15	19 000	10 500	1·00	1·00
17·5	14 700	7 900	0·77	0·75
20	12 000	6 300	0·63	0·60
25	8 500	4 800	0·45	0·46
30	6 400	4 200	0·34	0·40

(D) RESISTIVITY AND TEMPERATURE.

The relation between resistivity and temperature was determined for sandy loam containing 15·2 per cent by weight of moisture. The tests were made with the alternating-current ammeter-voltmeter method. Temperatures between 0° C. and 20° C. were obtained in a special chamber, and those at and below 0° C. in an ice box. The results obtained are given in Table 2.

TABLE 2.

Resistivity and Temperature of Sandy Loam. Moisture Content 15·2 *per cent by Weight of Soil.*

Temperature	Resistivity	Ratio to resistivity at 20° C.
° C.	ohms per cm cube	
20	7 200	1·0
10	9 900	1·4
0 (water)	13 800	1·9
0 (ice)	30 000	4·2
– 5	79 000	11·0
– 15	330 000	45·9

The soil resistivity increased steadily with fall of temperature until freezing point was reached, when a relatively large increase occurred at constant temperature, presumably owing to the moisture in the soil freezing. Below 0° C. it continued to increase steadily with fall of temperature but at a much greater rate. The results indicate that to obtain reliable earth connections with inextensive electrodes they should be buried at depths greater than that to which freezing conditions penetrate.

(E) RESISTIVITY AND ADDED SALT.

The relation between resistivity and added salt was determined for sandy loam containing 15 per cent by weight of moisture. The salt added was measured as a percentage by weight of the contained moisture. The results obtained are given in Table 3.

TABLE 3.

Resistivity of Sandy Loam with Added Salt. Moisture Content 15·0 *per cent by Weight of Soil. Temperature* 17° *C.*

Added salt (per cent by weight of moisture)	Resistivity	Resistivity as percentage of original value
	ohms per cm cube	
0	10 700	100
0·1	1 800	16·8
1	460	4·3
5	190	1·8
10	130	1·2
20	100	0·95

The first additions of salt were most effective; e.g. the first 0·1 per cent of added salt decreased the soil resistivity by about 80 per cent.

(F) RESISTIVITY AND TEMPERATURE OF SANDY LOAM WITH ADDED SALT.

The relation between resistivity and temperature was determined for sandy loam containing 20 per cent by weight of moisture to which 5 per cent by weight of salt was added. The results are given in Table 4.

TABLE 4.

Resistivity and Temperature of Sandy Loam with Added Salt. Moisture Content 20 *per cent by Weight of Soil. Salt* 5 *per cent by Weight of Moisture.*

Temperature	Resistivity	Ratio to resistivity at 20 °C.
° C.	ohms per cm cube	
20	110	1·0
10	142	1·3
0	190	1·7
– 5	312	2·9
– 15	1 440	13·0

The results of Table 4 for salted soil indicate quite small resistivities over the whole temperature range and no large increase under freezing conditions at 0° C.

(G) RESISTIVITIES OF VARIOUS MATERIALS.

Various materials were tested for resistivity as a matter of interest in connection with the general problem of earthing. The tests made and the results obtained are given in Table 5.

The resistivity of the soils dried at oven temperatures was of the same order of magnitude as that of an insulating material. Soils in their naturally driest condition would, however, contain some moisture and would be

TABLE 5.

Resistivities of Various Materials.

Material	Moisture content (per cent by weight)	Resistivity	Remarks
		ohms per cm cube	
Sandy loam	0	> 1 000 × 10⁶ *	Well dried in oven
Top soil	0	> 1 000 × 10⁶ *	Well dried in oven
Coal	—	> 1 000 × 10⁶ *	Natural lump
Coal	Saturated	34 000 †	Powdered, placed in glass jar and water added to coal surface
Coal	5·5	1·7 × 10⁶ *	Powdered, placed in glass jar but free water drained off
Coke	18·2	800 ‡	Powdered, placed in glass jar but not compressed
Coke	18·2	250	Powdered, placed in glass jar but compressed
Ashes	0	215	Not compressed
Ashes	0	100	Compressed
Ashes	15	350	Not compressed, water added
Ashes	15	100	Compressed
Chalk	0·72	97 × 10⁶ *	Natural slab
Chalk	0	> 1 000 × 10⁶ *	Natural slab dried in oven
Chalk	14·2	12 800 †	Natural slab after immersion in water for 4 days

* The test voltage was about 500 volts (d.c.). † The test voltage was about 100 volts (d.c.). ‡ The test voltage was about 100 volts (a.c.).

partially conducting. A sample of top soil, in a very dry condition, was taken from the ground surface after several weeks of summer without rain, and was found to contain about 5 per cent of moisture by weight.

The resistivity of coal in the natural lump was of the same order of magnitude as that of an insulating material. That of the coal powdered and saturated with water was high in comparison with values common to soils.

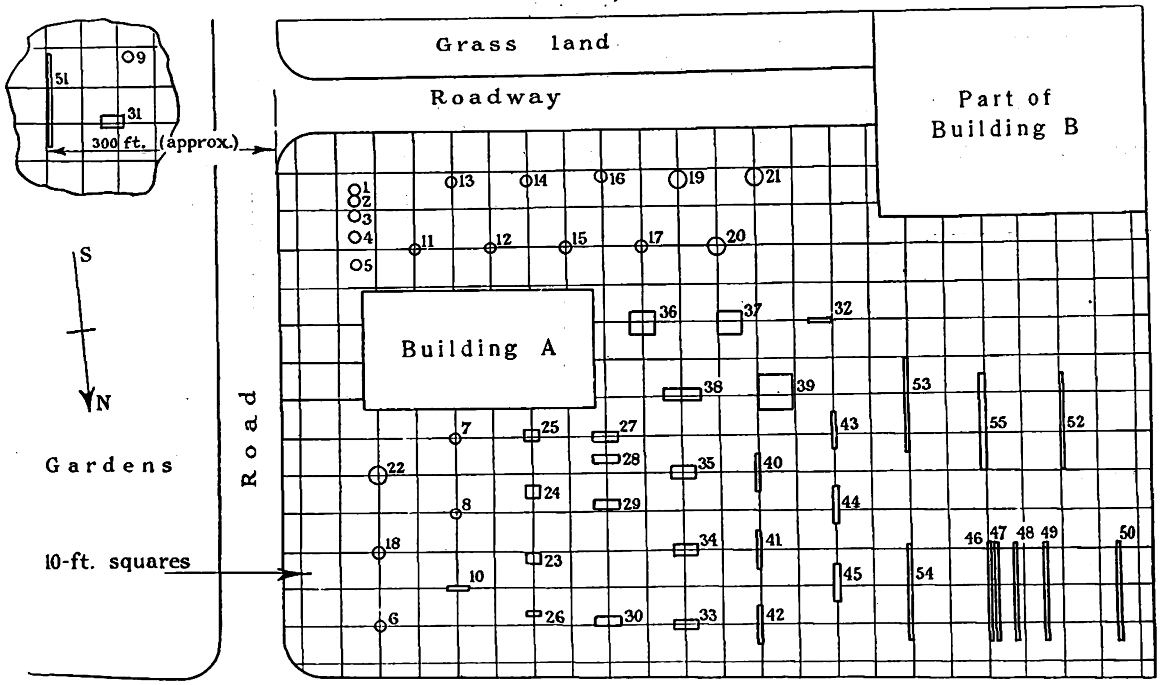

FIG. 7.—Plan of lay-out of earthing electrodes.

The resistivity of coke and ashes was very low compared with soil and was practically independent of moisture content. That of chalk in the natural lump was high, but when the chalk was saturated with water it was of the same order of magnitude as that of soil.

SECTION (2). EXPERIMENTAL MEASUREMENTS OF THE RESISTANCE OF VARIOUS TYPES OF EARTH CONNECTIONS.

(A) VARIOUS ELECTRODES OF INEXTENSIVE AREA.

Various electrodes of inextensive area were placed in a plot of ground and tested in order to determine typical earthing resistances. They were galvanized-iron pipes, wrought-iron plates and copper strips in various sizes, and were tested generally to determine their individual resistances, but in a few cases to determine the effect of distance apart on the resistances of pairs connected in series and in parallel. The individual electrodes were spaced about 20 ft. apart in order that there should be little effect due to proximity, and the pairs were spaced at definite distances apart. All the electrodes were buried except the pipes of 2 in. or less in diameter, which were driven. A pipe and a strip were placed each in a coke bed, and another pipe was salted down with 10 lb. of salt dissolved in water. A plan of the general lay-out of the electrodes is shown in Fig. 7.

The resistance of an electrode of inextensive area depends on (*a*) its shape, dimensions and depth in the ground, and (*b*) the soil resistivity. To obtain earth connections of low resistance the various electrodes would be compared either theoretically or practically as regards (*a*), (*b*) being uniform. Uniform resistivity is assumed in theory as described in the next paragraph, but it could be only very approximately obtainable in practice where the method of comparing the various electrodes would be that of installation and test. Further, the degree of divergence in practice could be hardly determinable. The practical comparison of

TABLE 6.

Particulars of Test.

Month of test (1925–1926)	Condition of soil	Temperature of top soil
		° F.
September * ..	Moist	†
November ..	Very wet	†
January ‡ ..	Wet	36
February ..	Wet	46
May	Moist	61
July	Dry	70
September ..	Top soil, moist. Sandy loam, very dry	62

* The electrodes had just been installed.
† No records taken.
‡ Melting snow on the ground surface.

electrodes can, therefore, in any case be only roughly approximate, natural undisturbed ground being more suitable in this respect than that which has been "made" or worked for garden purposes.

The resistance of an electrode of known dimensions and position in the ground can be determined theoretically by means of the formula

$$R = \rho/(2\pi C)\ *$$

where ρ is the soil resistivity (assumed uniform), and C is the electrostatic capacity in free space of the electrode with its image above the ground. The formula shows that earthing conductance is directly proportional to C which, being calculable, is valuable as a means of comparing various types of electrodes of inextensive area.

Ground Used.—The plot of ground used is situated within the area of the National Physical Laboratory. It was at one time a garden but at the time of the tests was covered with rough grass.

There were reasons to suppose that the soil resistivity was appreciably non-uniform. The ground had been considerably disturbed for purposes of cultivation. There were the two kinds of soil, viz. top soil and sandy loam, and the results given in Table 1 indicate that the resistivity of the former was rather greater than that of the latter for similar conditions of moisture content and temperature. When the excavations were made to bury the plates, it was noted that the soil moisture increased with depth. Each of these features interfered with the condition of uniform resistivity. The two kinds of soil and the increased moisture content both decreased the soil resistivity with depth.

If an electrode of inextensive area were placed in the ground within a few feet of a metal body such as a

TABLE 7.

Earthing Resistances of Driven Pipes. Mean and Calculated Values and Seasonal Changes.

Electrode No.	Length	External diameter	Resistance: Measured, covering one year: Maximum §	Minimum §	Mean §	Calculated for ρ=10 000 ohms per cm cube	Maximum / Minimum
	ft.	in.	ohms	ohms	ohms	ohms	
6	6	1	43	36	39	46	1·2
7 *	6	1	20	17	18	46	1·2
8 †	6	1	21	17	18	46	1·3
9	6	1	—	—	330 ‖	46	—
10 ‡	9	1	63	33	41	34	1·9
11	1	1	1 450	690	1 030	187	2·1
12	2	1	1 450	440	710	112	3·3
13	4	1	103	74	85	65	1·4
14	10	1	28	23	26	31	1·2
15	1	2	1 870	570	940	152	3·3
16	3	2	380	200	260	73	1·9
17	6	2	54	45	49	46	1·2
18	6	2	49	41	45	46	1·2
19	1	6	870	410	550	99	2·1
20	3	6	182	101	127	52	1·8
21	6	6	51	39	44	32	1·3
22	6	6	30	26	28	32	1·1
6 ft. × 1 in. Pipes connected in Series.							
1 and 2	Distance apart, ft.	1	84	64	70	54	1·3
1 and 3		3	109	84	90	70	1·3
1 and 4		6	114	95	100	77	1·2
1 and 5		12	170	142	148	84	1·2
6 ft. × 1 in. Pipes connected in Parallel.							
1 and 2	Distance apart, ft.	1	37	31	34	36	1·2
1 and 3		3	37	29	33	29	1·3
1 and 4		6	35	29	32	27	1·2
1 and 5		12	44	34	39	25	1·3

* Placed in a coke bed about 6 ft. long and 1 ft. radius.
† Treated with 10 lb. of salt dissolved in water.
‡ Bent so that 6 ft. was buried 3 ft. deep.
§ Maximum, minimum and mean of 7 measurements (see Table 6).
‖ Tested once only, in February 1926.

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* See Appendix.

water pipe or the steel framework of a building, its resistance would probably be decreased on account of the proximity. The only body of that kind in close proximity to the electrodes was the steel framework of building A shown in Fig. 7. No electrode was, however, placed nearer to it than about 10 ft.

TABLE 8.

Earthing Resistances of Buried Plates. Mean and Calculated Values, and Seasonal Changes.

Electrode No.	Size (length × breadth)	Depth in ground	Resistance				Maximum/Minimum
			Measured, covering one year			Calculated for $\rho = 10\,000$ ohms per cm cube	
			Maximum †	Minimum †	Mean †		
	ft. ft.	ft.	ohms	ohms	ohms	ohms	
23	3 × 3	1	201	118	141	38	1·7
24	3 × 3	3	60	30	39	30	2·0
25	3 × 3	6	27	21	24	28	1·3
26 *	3 × 3	6	30	20	24	27	1·5
30	6 × 3	6	18·4	14·2	16·4	20	1·3
31	6 × 3	6	—	—	116 ‡	20	—
32 *	6 × 3	6	14·5	11·2	13·1	20	1·3
33	6 × 3	1	77	48	60	37	1·6
34	6 × 3	3	28·0	19	22·9	22	1·5
35	6 × 3	8	15·6	13·0	13·8	20	1·2
36	6 × 6	3	27·0	16·0	20·1	17	1·7
37	6 × 6	6	18·6	11·5	15·0	15	1·6
38	9 × 3	6	13·7	11·3	12·5	17	1·2
39	9 × 9	6	10·5	8·1	9·1	11	1·3
6 ft. × 3 ft. Plates buried 6 ft. Deep and connected in Series.							
27 and 28	Distance between centres, feet	6	32	26	28	28	1·2
27 and 29		18	37	33	36	35	1·1
27 and 30		48	36	32	35	38	1·1
6 ft. × 3 ft. Plates buried 6 ft. Deep and connected in Parallel.							
27 and 28	Distance between centres, feet	6	12·0	10·8	11·4	12·9	1·1
27 and 29		18	11·0	9·3	10·4	11·3	1·2
27 and 30		48	9·4	7·9	8·9	10·5	1·2

* Plate buried vertically, mean depth 6 ft. † Maximum, minimum and mean of 7 measurements (see Table 6). ‡ Tested once only, in February 1926.

Seasonal Changes in Earthing Resistance.—The resistance of electrodes of inextensive area is affected by the seasonal changes of climate on account of the influence of the weather on the soil resistivity. Wet or warm conditions will decrease it owing to increasing soil moisture content or temperature. To investigate the magnitude of the seasonal effects on the resistance of the various types of electrodes shown in Fig. 7, tests were made at approximately 2-monthly intervals covering a complete year, September 1925 to September 1926. Particulars of the tests are given in Table 6.

Method of Measurement.—The tests were made by means of the alternating-current ammeter-voltmeter method, the current being obtained from a direct-current supply through a rotary convertor and a transformer. The arrangement of apparatus is shown in Fig. 8. The transformer windings were insulated from one another. The secondary voltage of the transformer, which was variable between 50 and 500 volts, was adjusted in each test to give good meter readings.

The measurement of the resistance of one electrode A requires two other electrodes B and C, the three being spaced not less than about 10 ft. apart. Let the resistances between the electrodes in pairs be respectively R_{AB}, R_{BC}, and R_{CA}. Then the required resistance R_A is given by

$$R_A = \tfrac{1}{2}(R_{AB} - R_{BC} + R_{CA})$$

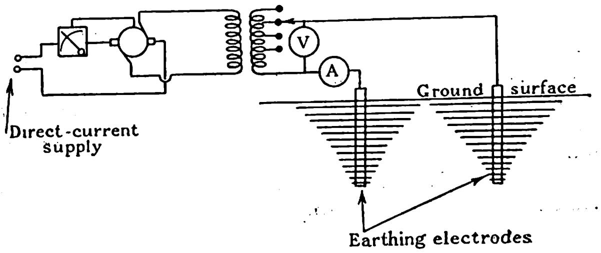

FIG. 8.—Earthing resistance tests. Method of measurement.

The earthing resistance R_1 of the steel framework of building A was first determined by this method. The resistance R_2 of any electrode was thereafter determined by measuring the resistance R between it and the building, the required value being

$$R_2 = R - R_1$$

The resistance R was in many cases quite large compared with R_1, so that R_2 was practically equal to R.

Results.—The results of the tests are given in Table 7 for pipes, Table 8 for plates and Table 9 for strips. The tables give the following particulars of the electrodes:—Their index numbers corresponding to those of Fig. 7; their dimensions and depths in the ground; the measured maximum, minimum and mean resistances covering the year of test; the theoretical resistances calculated on the assumption of a soil resistivity of 10 000 ohms per cm cube; and the ratios of the maximum values to the minimum.

TABLE 9.

Earthing Resistances of Buried Strips. Mean and Calculated Values, and Seasonal Changes.*

Electrode No.	Size (width × length)	Depth in ground	Resistance				Maximum/Minimum
			Measured, covering one year			Calculated for $\rho = 10\,000$ ohms per cm cube	
			Maximum ‡	Minimum ‡	Mean ‡		
	in. ft.	ft.	ohms	ohms	ohms	ohms	
40	2 × 10	1	131	82	98	36	1·6
41	2 × 10	3	55	23	37	32	2·3
42	2 × 10	6	26	20	24	30	1·3
43	1 × 10	1	254	115	155	40	2·2
44	4 × 10	1	98	50	64	33	2·0
45	8 × 10	1	87	38	50	28	2·3
50	2 × 25	1	52	18·5	27	18	2·8
51	2 × 25	1	—	—	32 §	18	—
52 †	2 × 25	1	16	10·7	12·8	18	1·5
53	2 × 25	3	37	18·3	25	16	2·0
54	2 × 25	6	14·2	11·8	13·3	15	1·2
55	6 × 25	1	29	19·5	22	13·5	1·5
2 in. × 25 ft. Strips buried 1 ft. Deep and connected in Series.							
46 and 47	Distance between centres, feet	1	56	23	34	15	2·4
46 and 48		6	80	35	48	26	2·3
46 and 49		16	87	38	51	29	2·3
46 and 50		36	94	39	53	34	2·4
2 in. × 25 ft. Strips buried 1 ft. Deep and connected in Parallel.							
6 and 47	Distance between centres, feet	1	29·6	16·4	21·9	14	1·8
46 and 48		6	25·6	12·8	18·5	12	2·0
46 and 49		16	24·8	11·2	17·1	11	2·2
46 and 50		36	25·0	10·9	17·0	9	2·3

* Copper strip $\frac{1}{16}$ in. thick.
‡ Maximum, minimum and mean of 7 measurements (see Table 6).
† Placed in a coke bed.
§ Tested once only, in February 1926.

Discussion of the Results.—That the results are somewhat irregular was probably due to the soil resistivity being appreciably non-uniform, as has previously been mentioned. The resistances of electrodes 9 and 31 were, for example, particularly high. They were installed in a small plot of ground away from the main plot and the soil of the former was more sandy in character than that of the latter. The more sandy the soil the greater would be its resistivity and the greater the resistances of electrodes placed in it.

The smallest mean resistance obtained was about 10 ohms and the greatest about 1 000 ohms, which indicates that it is possible to obtain a wide range of values even within a comparatively small area where the soil is roughly of the same nature throughout. The effect of the coke or salt was in each case approximately to halve the resistance. The measured resistances of the electrodes buried shallow were generally greater than the respective calculated values, whereas those of the electrodes buried deep were more nearly in agreement, this being probably due to the soil resistivity decreasing with depth.

The minimum values occurred mostly in November when the ground was very wet after a period of heavy rains, and the maximum in September when the ground was very dry after a period of warm weather without rain. The lowest temperature was noted in January when the ground was covered with melting snow, and the highest in July when the ground was somewhat dry. It appears in the former case that the effect of low temperature in increasing resistance was largely offset by the then very wet condition of the soil and, in the latter case, that contrary conditions prevailed. During the test period no severe freezing conditions were experienced, and the effect of moisture on resistance was greater than that of temperature.

The seasonal variations in resistance of electrodes buried deep were less than those of electrodes buried shallow. The variations were not definitely decreased by the use of coke or salt, the advantage of either being mainly in reducing mean resistances. If freezing conditions had, however, been experienced, the advantage of salt on the variations would probably have been definite. The smallest ratio of the maximum resistance to the minimum was 1·1 and the greatest 3·3, the latter indicating that seasonal changes even under relatively mild conditions may be quite large.

The resistances of electrodes may change owing to causes other than seasonal. After an electrode has been installed the soil takes time to settle around it, and its resistance may decrease on account of improvement of contact. An electrode in soil slowly corrodes and the corrosion may increase the resistance. Tests for the former effect would be complicated by the seasonal variations, and for the latter, apart from similar complications, would necessarily have to be continued over several years.

(B) Various Electrodes of Extensive Area.

Situated near the place of the tests on the inextensive electrodes were two buildings indicated respectively by A and B in Fig. 7, where the former and a part of the latter are shown. Each had a steel framework: the former had also an electric steel-conduit system the tubes of which were in places laid along and clipped to the steel framework, and the latter had also water pipes and a large lead-covered cable. These various types of electrodes of extensive area were tested and the results are given in Table 10.

Table 10.

Various Types of Electrodes of Extensive Area.

Electrode	Earthing resistance
Building A.	ohms
Conduit	2·4
Steel framework	2·4
Building B.	
Water pipe	0·76
Waste-water pipe	7·3
Lead sheath of cable	1·5
Steel framework	2·2

The results indicate that where an electrode is in contact with soil dispersed throughout an extensive tract of land, as it was more or less in each of the cases given in the table, except possibly that of the waste-water pipe, the resistance is considerably smaller than that readily obtainable by means of electrodes of inextensive area. The lowest resistance was 0·76 ohm and was given by the water pipe.

(C) Direct-Current Tests.

Tests were made on electrodes of inextensive and extensive areas with alternating current and with direct current at different voltages in order to investigate the effect of direct-current polarization on field measurements. They were made along lines similar to those of the laboratory experiment made to investigate polarization in soil, as described in Section (1). The various switch operations were made as required and when the current changed with time at constant voltage its initial and final values were noted. The voltages of the direct current were respectively about 50, 6 and 2, and were obtained from a battery which was not earth-connected except through the electrodes during the tests.

The measurements were somewhat inconsistent, as shown by repeat tests giving somewhat different results. Apart from the inconsistency, however, the results generally indicated the following points. The resistances measured with initial values of direct current were about the same as those measured with alternating current. Direct-current polarization was negligible when the positive electrode was extensive in area, but it increased the resistance when the positive electrode was inextensive; the increases were roughly from 10 to 20 per cent of the initial values. The initial direct-current resistance was roughly 5 per cent greater with 2 volts than with 50, but the polarization effect was practically independent of the magnitude of the voltage.

The author thanks Mr. S. W. Melsom for his kindly co-operation in planning the work, and Dr. E. H. Rayner, M.A., for his assistance in preparing this paper.

APPENDIX.

A Theoretical Consideration of the Earthing Resistances of Various Electrodes of Inextensive Area.

Fundamentals.—Let A, Fig. 9, be a body in an infinite medium of specific inductive capacity ϵ and specific resistance ρ.

If A be given a charge Q and C be its capacity to infinity,

$$V = \frac{Q}{C} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If A be a source of current and R its resistance to infinity,

$$V = IR \quad . \quad . \quad . \quad . \quad . \quad (2$$

Eliminating V, we obtain

$$R = \frac{Q}{CI} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

A relation between Q and I is now required.

Let A be enclosed by a spherical surface of radius r; AB the axis of a small conical pencil; ds the area where the pencil cuts the surface; dr a short distance from ds

along AB; $-dv$ the drop in potential along dr; and di the element of current flowing out through ds.

By Ohm's law,

$$\rho di = -\frac{dv}{dr}ds \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

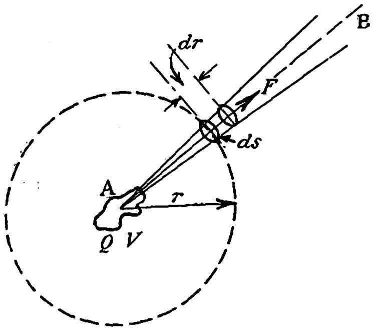

FIG. 9.

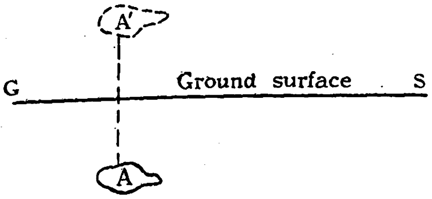

FIG. 10.

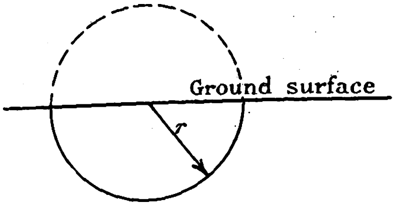

FIG. 11.

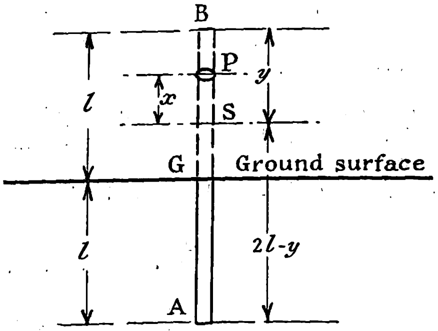

FIG. 12.

The electric force F at ds, by definition, is either

$$-\frac{dv}{dr}\cdot\frac{1}{\epsilon} \quad \text{or} \quad \frac{Q}{r^2}\cdot\frac{1}{\epsilon}$$

that is,

$$-\frac{dv}{dr} = \frac{Q}{r^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

From (4) and (5),

$$\rho di = \frac{Q}{r^2}ds \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Integrating (6) we obtain

$$\rho I = \frac{Q}{r^2}4\pi r^2 = 4\pi Q$$

that is,

$$\frac{Q}{I} = \frac{\rho}{4\pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

From (3) and (7) we have

$$R = \frac{\rho}{4\pi C} \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Equation (8) is the general formula relating resistance, resistivity and capacity for a body in free space.

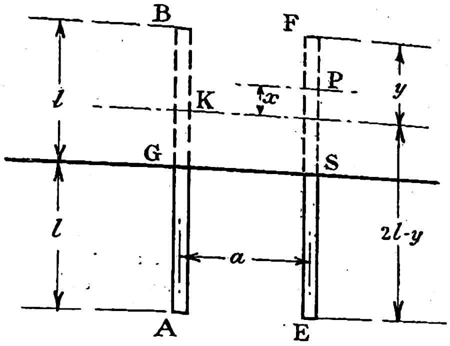

FIG. 13.

If A be considered with respect to another body B instead of to infinity, then (8) would still apply, R being the resistance between A and B, and C their capacity as oppositely charged bodies.

Practical Applications.—Let A, Fig. 10, be an electrode in the ground and A′ its image above the ground surface GS. If A and A′ connected together be considered as one body in free space, then their resistance to infinity would be given by equation (8), where C is their capacity to infinity. Because the conditions above and below GS are symmetrical, the resistance of A alone to infinity is

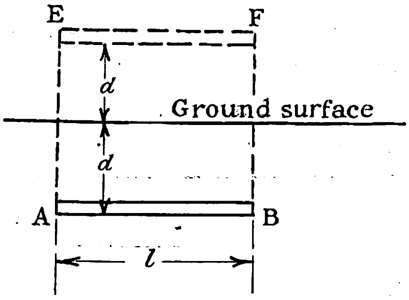

FIG. 14.

$$R = \frac{\rho}{2\pi C} \quad . \quad . \quad . \quad . \quad . \quad (9)$$

Equation (9) is the general formula for calculating the resistances of electrodes of inextensive area, the units of measurement being in centimetres.

Hemispherical Electrode.—A hemispherical electrode with its flat side level with the ground surface is shown in Fig. 11. It with its image is a sphere the capacity of which is equal to the radius or

$$C = r \quad . \; . \; . \; . \; . \; . \; . \quad (10)$$

Driven Pipes.—Owing to the particular geometrical form of a pipe, capacity is not readily calculable. The calculation is simplified, however, by making an initial assumption which, leading to results that are correct within a few per cent of error, is sufficiently accurate for practical purposes. The method of treatment and the assumption given below are due to Prof. G. W. O. Howe.*

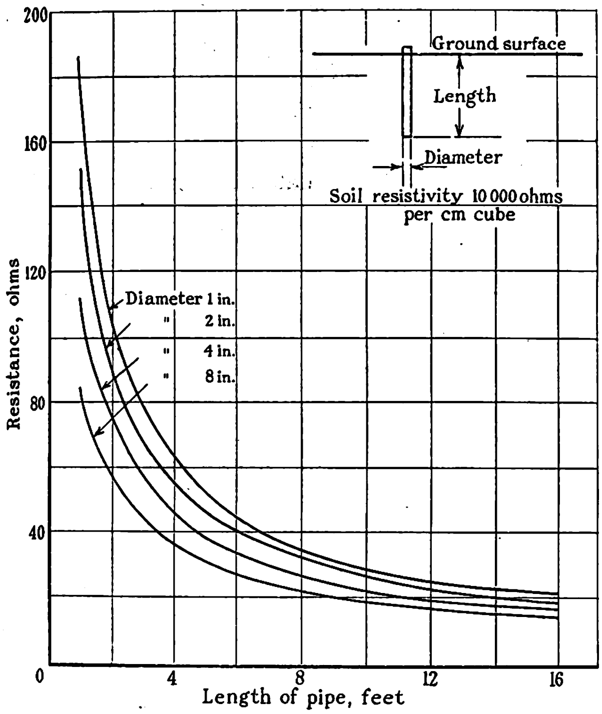

FIG. 15.—Change in resistance of driven pipes with length and diameter.

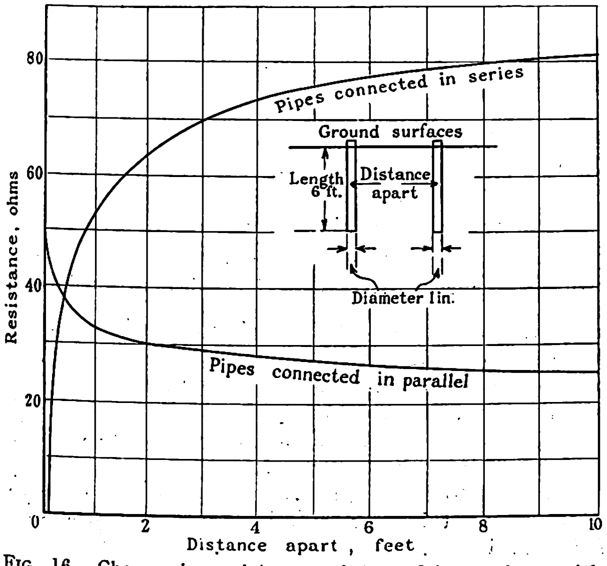

FIG. 16.—Change in resistance of two driven pipes with distance apart.

Let GA, Fig. 12, be a pipe and GB its image. To determine the resistance of GA it is necessary to calculate the capacity of AB in free space.

If AB be a charged body in free space, it is wholly at a certain potential and its charge is unevenly distributed over its surface, being of greatest density at the ends. This condition is difficult to consider mathematically. The assumption mentioned above is that the density of charge is uniform, from which the mean potential of AB may be calculated; the result will be the actual potential very nearly. The charge and potential being known, the capacity of AB is the charge per unit potential.

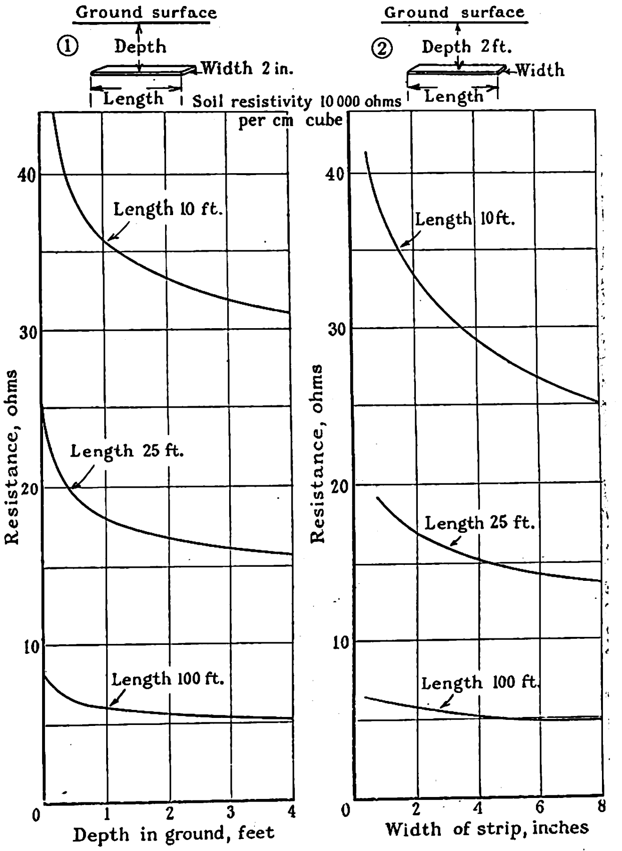

FIG. 17.—Change in resistance of buried strip with (1) length and depth in ground, and (2) length and width.

In Fig. 12, let GA $= l$, BS $= y$, SP $= x$, D be the diameter of the pipe and σ the assumed uniform charge per unit length.

The charge on a length dx at P is σdx.

The potential at S owing to element of charge at P

$$dV_s = \frac{\sigma dx}{\sqrt{\left[\frac{D^2}{4} + x^2\right]}} \quad . \; . \; . \; . \quad (11)$$

---

* "On the Capacity of Radio-Telegraphic Antennæ," *Electrician*, 1924, vol. 73, pp. 829, 859 and 906; "The Calculation of the Effective Resistance of Earth Plates," *Electrician*, 1915–16, vol. 76, p. 353; "The Capacity of Rectangular Plates and a Suggested Formula for the Capacity of Aerials," *Radio Review*, 1919–20, vol. 1, p. 710.

and, owing to the whole of charge, is equation (11) integrated between the limits of y and 0, and $(2l - y)$ and 0, from which

$$V_s = \sigma\left[\operatorname{arc\,sinh}\frac{2y}{D} + \operatorname{arc\,sinh}\frac{2(2l - y)}{D}\right] . \tag{12}$$

The mean potential of AB is equation (12) integrated between the limits of $2l$ and 0, divided by $2l$, from which

$$V_{m1} = 2\sigma\left[\operatorname{arc\,sinh}\frac{4l}{D} + \frac{D}{4l} - \sqrt{\left\{1 + \frac{D^2}{16l^2}\right\}}\right] \tag{13}$$

The total charge on AB

$$Q = 2l\sigma \quad . \quad . \quad . \quad . \quad . \tag{14}$$

The capacity C is the ratio of (14) and (13).

Driven Pipes connected in Series or Parallel.—Let GA and SE (Fig. 13) be two similar pipes at a distance a apart, each being of length l, diameter D, and charge per unit length σ. The mean potential of AB due to its own charge is given by V_{m1}, equation (13). The potential of AB is, however, affected by the charge on EF.

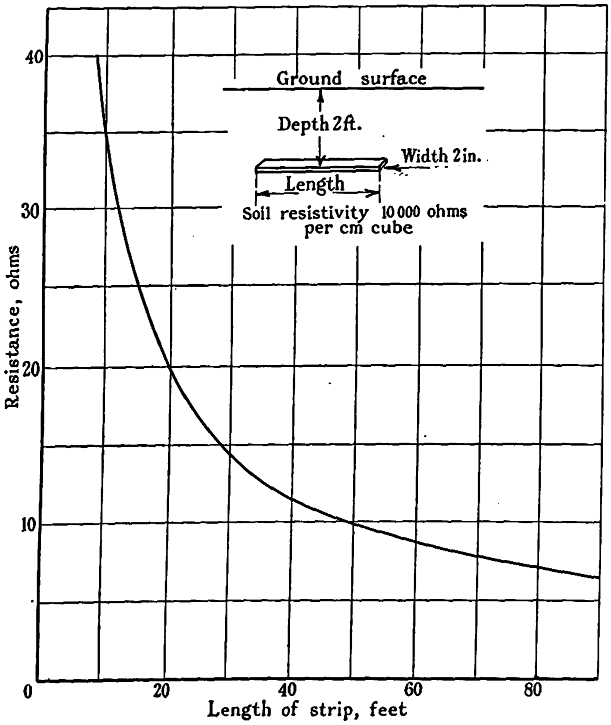

FIG. 18.—Change in resistance of buried strip with length.

The potential at K (Fig. 13) due to element of charge at P

$$dV_K = \frac{\sigma dx}{\sqrt{[a^2 + x^2]}} \quad . \quad . \quad . \quad . \tag{15}$$

Equation (15) being similar to (11) except that $\frac{1}{2}D$ is replaced by a, the mean potential of AB due to charge on EF is, from equation (13),

$$V_{m2} = 2\sigma\left[\operatorname{arc\,sinh}\frac{2l}{a} + \frac{a}{2l} - \sqrt{\left\{1 + \frac{a^2}{4l^2}\right\}}\right] . \tag{16}$$

For two pipes connected in *parallel*:—

$$\text{Total mean potential} \quad V_m = V_{m1} + V_{m2} \quad . \quad . \quad . \tag{17}$$

$$\text{Total charge} \quad Q = 4l\sigma \quad . \quad . \quad . \quad . \quad . \tag{18}$$

$$\text{For } n \text{ pipes} \quad V_m = V_{m1} + V_{m2} + V_{m3} \ldots (n \text{ terms}) \tag{19}$$

$$Q = 2nl\sigma \quad . \quad . \quad . \quad . \quad . \tag{20}$$

For two pipes connected in *series*:—

Total mean potential difference between them

$$V_m = 2(V_{m1} - V_{m2}) \quad . \quad . \quad . \quad . \tag{21}$$

$$\text{Total charge} \quad Q = 2l\sigma \quad . \quad . \quad . \quad . \quad . \quad . \quad . \tag{22}$$

Buried Strips.—To calculate the capacity of a buried strip, the method of treatment is to substitute for the strip a pipe having the same length of periphery, to obtain the mean potential of the pipe by means of the given formulæ and to multiply the result by a correction factor, which is about 1·11 when the width of the strip is about 17 times its thickness.

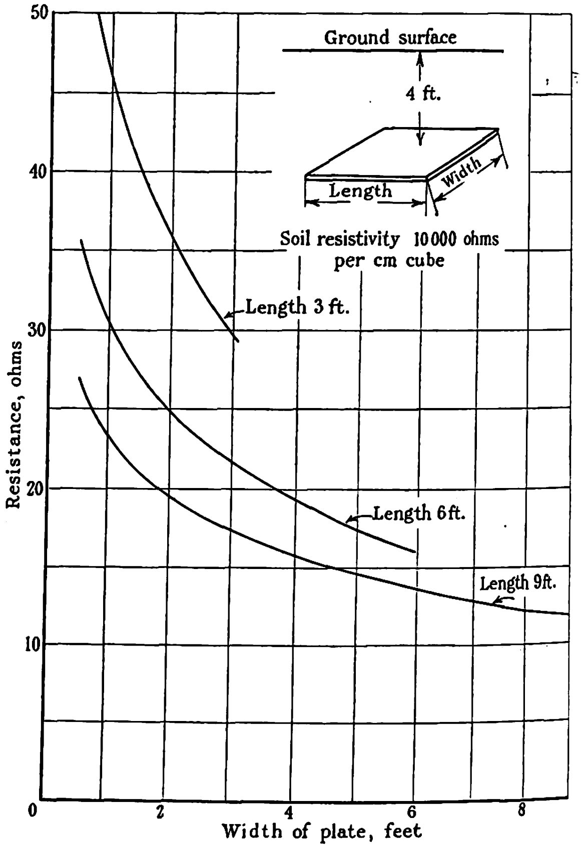

FIG. 19.—Change in resistance of plates with length and width.

Referring to Fig. 14, let AB be the strip of length l, width w and thickness t, buried at a depth d, and let EF be its image.

$$\text{Diameter of equivalent pipe} \quad D = \frac{2(w + t)}{\pi} \quad . \quad . \tag{23}$$

Potential of AB due to its own charge, from equation (13),

$$V_{m1} = 2\sigma K\left[\operatorname{arc\,sinh}\frac{2l}{D} + \frac{D}{2l} - \sqrt{\left\{1 + \frac{D^2}{4l^2}\right\}}\right] \tag{24}$$

K being the correction factor.

Potential of AB due to charge on image EF, from equation (16)

$$V_{m_2} = 2\sigma\left[\operatorname{arc\,sinh}\frac{l}{2d} + \frac{2d}{l} - \sqrt{\left\{1 + \frac{4d^2}{l^2}\right\}}\right] \quad (25)$$

Total potential $V_m = V_{m_1} + V_{m_2}$ . . . . (26)

Total charge $Q = 2\sigma l$ . . . . (27)

Buried Plates.—To calculate the capacity of a buried plate, the method of treatment is to consider the plate as a large number of strips connected in parallel, to obtain by integration the potential of any one strip due to the charge on the whole plate and to obtain, by integrating over the whole width of the plate and dividing by the width, the mean potential of the plate. The result obtained may be given as

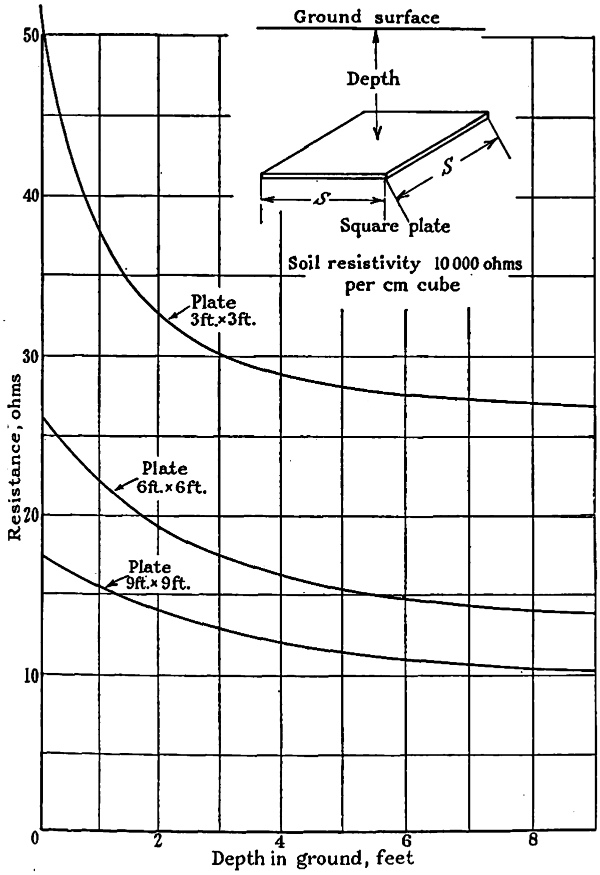

FIG. 20.—Change in resistance of square plates with size and depth in ground.

$$V_{m_1} = 3\cdot 1\sigma\sqrt{(wl_1)}\left(1 + 0\cdot 0375\frac{l_1}{w}\right)^{-1} \quad . \quad (28)$$

where l_1 is the length of the plate and w its width, the formula being approximately applicable between the limits of $l_1/w = 1$ and $l_1/w = 12$.

The total charge $Q = \sigma w l_1$ . . . . . . (29)

The potential of a buried plate due to the charge on its image may be approximately obtained as follows:—

When the plate is in the plane of the ground surface, equations (28) and (29) apply.

When the plate is at a depth d in the ground that is large compared with l_1, the image may be taken to be at a distance of $2d$ from the plate, and

$$V_{m_2} = \frac{\sigma w l_1}{2d} \quad . \quad . \quad . \quad . \quad . \quad (30)$$

When d is neither large nor small compared with l_1, the plate with image may be considered as a strip with image, in which case equation (25) would apply.

$$V_{m_2} = 2\sigma w\left[\operatorname{arc\,sinh}\frac{l_1}{2d} + \frac{2d}{l_1} - \sqrt{\left\{1 + \frac{4d^2}{l_1^2}\right\}}\right] \quad (31)$$

Total potential of plate $V = V_{m_1} + V_{m_2}$ . . (32)

Total charge $Q = 2\sigma w l_1$ . . . (33)

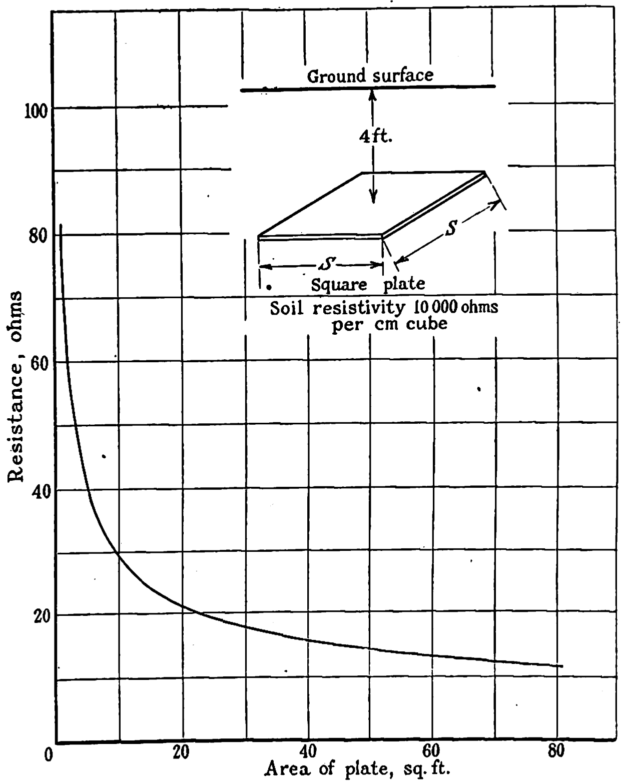

FIG. 21.—Change in resistance of square plate with area.

The method of calculation of either strips or plates connected in parallel or series is similar to that described for pipes.

Theoretical Resistance Curves.—Curves showing relations between the earthing resistances (calculated by means of the various theoretical formulæ), the dimensions and depths in the ground of various types of electrodes, are given in Figs. 15 to 21.

Discussion of the Various Types of Electrodes of Inextensive Area.—The various types of electrodes of inextensive area are compared in Table 11, the relative earthing resistances given in col. 6 of the table being obtained from the curves of Figs. 15 to 21.

The values given in the table suggest the following points:—

(i) Pipes and strips are about equally efficient and are much more efficient than plates. Pipes, which are simply driven in the ground, would, however, be more commonly used than strips, which require a considerable amount of ground excavation for their installation, on account of the low first costs of the former.

(ii) An electrode consisting of two pipes spaced about 5 ft. apart and connected in parallel is much more efficient than one pipe of diameter equal to the sum of the two. A number of small electrodes dispersed in the ground and connected in parallel is more efficient than the same amount of metal less widely dispersed.

(iii) A plate of a given amount of metal becomes more efficient the more it is elongated like a strip.

(iv) The efficiency of a strip or plate is only slightly increased by burying at depths greater than about 2 ft. or 4 ft. respectively, the soil resistivity being assumed to be uniform. It appears, therefore, that the possible variations in soil resistivity with depth are relatively more important with regard to earthing efficiencies than the actual depths of burying. A strip or plate should, when practicable, be buried where the soil resistivity is lowest, if not too shallow.

The sizes of electrodes and the depths of burying are, for practical reasons, generally confined within limits. The dispersion of a number of small electrodes connected in parallel to obtain a low resistance would, for example, be limited by the installation cost or by a minimum size of electrode as regards mechanical strength and durability. The length of a pipe would be limited to that which may be easily driven, and the depth of burying a strip or plate to a moderate amount of ground excavation. Although the thickness of metal of an electrode has no appreciable effect on earthing resistance, yet it should be sufficient to give the electrode a reasonable mechanical strength and service life in the presence of possible corrosion.

TABLE 11.

A Comparison of Various Electrodes.

Electrode	Length	Width or diameter	Depth in ground	Soil excavation †	Relative	
					Earthing resistance	Efficiency §
	ft.	in.	ft.	cub. ft.		
Pipe	6	1	—	—	1 ‡	1 ‡
Strip	10	2	4	80	0·68	1·04
Strip	10	2	2	30	0·72	0·97
Pipe	12	1	—	—	0·54	0·92
2 Pipes *	6	1	—	—	0·59	0·85
Strip	25	2	2	75	0·37	0·77
Pipe	6	2	—	—	0·86	0·58
Strip	10	5	2	30	0·61	0·46
Plate	9	6	4	72	0·59	0·44
		(feet)				
Plate	3	3	8	72	0·59	0·22
Plate	3	3	4	36	0·63	0·21
Plate	6	6	4	144	0·35	0·10

* Two pipes each 6 ft. in length and 1 in. in diameter, spaced 5 ft. apart and connected in parallel.

† The soil excavation has been calculated on the basis that pipes being driven require none; the minimum width of a trench 2 ft. deep is 1·5 ft. and of one 4 ft. deep is 2 ft.

‡ A driven pipe 6 ft. long and 1 in. in diameter has been taken as a standard for the purpose of the comparison.

§ Efficiency is taken to be inversely proportional to earthing resistance and to the volume of the electrode; i.e. efficiency is proportional to the earthing conductance of an electrode per unit volume of metal. The thickness of the metal of each electrode has been taken as 0·25 in.

REPORT OF THE COUNCIL FOR THE YEAR 1929–1930, PRESENTED AT THE ANNUAL GENERAL MEETING OF 15TH MAY, 1930.

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REPORT.

The Council, at the Fifty-eighth Annual General Meeting of The Institution of Electrical Engineers, present to the members their Report for the year 1929–30, covering approximately the period from the 1st April, 1929, to the 31st March, 1930. In this connection, the Council desire once more to express the Institution's grateful thanks to its many members who have given their time so freely in promoting its work and activities.

(1) MEMBERSHIP OF THE INSTITUTION.

The changes in the membership since the 1st April, 1929, are shown in a table included in Appendix A.

The following table shows the growth of membership for the last 10 years:—

Year	Membership	Increase
1921	9 449	1 303
1922	10 275	826
1923	10 911	636
1924	11 415	504
1925	11 743	328
1926	12 142	399
1927	12 647	505
1928	13 043	396
1929	13 561	518
1930	14 200	639

(2) EXAMINATIONS.

The Graduateship Examination was held in May and November, 1929, in London, Belfast, Birmingham, Cardiff, Dublin, Glasgow, Hull, Manchester, Newcastle-on-Tyne, Plymouth and Portsmouth, and also in Australia, China, East Africa, India, Malta, New Zealand, South Africa and the Straits Settlements.

During the year a number of candidates were granted permission to satisfy the educational requirements for Associate Membership by the submission of satisfactory written papers or theses in lieu of an Examination.

(3) NATIONAL CERTIFICATES AND DIPLOMAS IN ELECTRICAL ENGINEERING.

England and Wales.—In 1929 the Joint Standing Committee, representing the Board of Education and the Institution, was associated with the final examinations of 120 courses at colleges and schools in England and Wales approved in connection with the above certificates and diplomas.

The final examinations were held during the summer of 1929 and the number of awards was as follows:—

433 Ordinary Certificates.
209 Higher Certificates (including 4 Post-Higher Certificates).
10 Ordinary Diplomas.
4 Higher Diplomas.

Scotland.—The Institution, in conjunction with the Scottish Education Department, has drawn up a scheme for the award of the above certificates and diplomas in Scotland. Final examinations will be held in 1930 for the first time under the scheme.

(4) HONORARY MEMBER.

The Council have pleasure in recording that, as announced at the Ordinary Meeting on the 9th January, 1930, they have elected Sir Richard Tetley Glazebrook, K.C.B., D.Sc., F.R.S., to be an Honorary Member of the Institution.

(5) FARADAY MEDAL.

The ninth award of the Faraday Medal was made by the Council to Sir Ernest Rutherford, O.M., F.R.S.

(6) HONOURS AND DISTINCTIONS CONFERRED ON MEMBERS.

Knighthood.

Page, Archibald (Past President).

C.M.G.

Pitkeathley, Lt.-Col. J. S., C.V.O., C.I.E., C.B.E., D.S.O., R.E. (Associate Member).

M.B.E.

Rogers, E. E. (Associate Member).

(7) DEATHS.

The Council regret to have to record the death of the following 80 members of the Institution during the year:—

Honorary Member.

Ferranti, S. Z. de, D.Sc., F.R.S.

Members.

Angold, A. E.
Baxendale, T.
Baylor, A. K.
Baynes, S. W.
Beaumont, W. W.
Blascheck, C. A.
Cockburn, A. C.
de Warburg, C. H.
Fargues, J., O.B.E.
Field, M. B., O.B.E.
Fynn, V. A.
Hansford, R. V., D.Sc.
Hill, C. W.
Hutchinson, Sir S. H. C.
Irvine, F.
Jackson, Admiral Sir H. B., G.C.B., K.C.V.O., F.R.S.
Jeffery, J.
Jones, J. C. D.
Judd, W.
Kolkhorst, A. O.
Leach, H. L.
Lieb, J. W.
McCarthy-Jones, C. H.
Malcolm, Col. E. D., C.B., R.E.
Marshall, R.
Mayston, W. H.
Mudford, F. J.
Orchiston, J.
Pearson, G. A.
Reid, E. J.
Richardson, J.
Semenza, G.
Sinclair, Col. A.
Swinton, A. A. C., F.R.S.
Thomson, J. S.
Toplis, W. S.

Associate Members.

Amor, F.
Barton, T., B.Sc. Tech.
Beddoe, J. S., M.B.E.
Blagden, A. H.
Cooper, G. P.
Cursetjee, N. J.
Fox, J. T.
Gerhardi, C. H. W.
Higgins, C. H.
Huber, A. J.
Jackson, H. Y. V., M.C.
Ker, D. W.
Lewsley, J. W.
McMahon, J. F.
Malcolm, G. D.
Neff, W. A.
O'Brien, C. C.
Randles, J. T. T.
Rogers, W. R.
Simpson, A. J. G.
Smith, W. W.
Tarby, J. E.
Thomson, H. L.
Warner, H. T.
Webb, S. H.

Companions.

Alabaster, H.
French, Sir S. R., K.C.M.G.
Jameson, C. G.

Associates.

Henderson, J. A.
King, W. F., F.R.S.E.
Mackenna, J.
Porter, E. B.

Graduates.

Atherton, J. F.
Bagchi, K. P.
Cressey, J. A.
Penny, J. C.
Watkinson, J. E.
Wyatt, E.

Students.

Allan, James.
Pocock, C. J. D.
Porteus, T. A.
Reddy. P. J.
Willis, W. S.

(8) REVISION OF BYE-LAWS.

The revision of the Bye-laws, to which brief reference was made in the last Annual Report, was completed during the year. The alterations, which principally affect the qualifications for the non-corporate classes of membership, were duly approved at a Special General Meeting of Corporate Members on the 9th May, 1929, and were subsequently allowed by the Privy Council on the 2nd August, 1929.

Such regrading of the membership as became necessary as a result of the alterations has been completed.

(9) INSTITUTION BUILDING.

The Institution continues as in the past to grant facilities for the free use of its Building to kindred societies for the purposes of their meetings, and during the past year nearly 200 such meetings were held.

(10) OIL PAINTINGS.

The collection of paintings in the Lecture Theatre has during the past year been further augmented by generous gifts by Mr. Ll. B. Atkinson, Sir Thomas Callender and The Hon. Sir Charles Parsons, O.M., K.C.B., F.R.S., of oil paintings of Clerk Maxwell, Hopkinson and Swan respectively.

The portraits of Maxwell and Hopkinson are by Mr. R. H. Campbell, and that of Swan by Mr. W. Paget.

The paintings of Ampère and Graham Bell, which, as stated in the last Annual Report, are being given by Mr. E. Garcke and Sir Hugo Hirst respectively, will, it is hoped, be ready for hanging early next Session. The Council have also gratefully accepted from Mr. H. Marryat an offer of a portrait of Ferranti.

(11) MEETINGS.

During the past twelve months, 431 meetings have been held in London and the Local Centres by the members, the Council and the various Committees. A detailed statement is given in Appendix B.

The Premiums awarded by the Council for papers will be announced about the time of the Annual General Meeting.*

(12) INAUGURAL ADDRESS OF SIR THOMAS PURVES.

The delivering of the President's Inaugural Address on the 24th October, 1929, was marked by the fact that by means of telephone land-lines and loud-speakers it was heard simultaneously at meetings of members in London, Birmingham, Cardiff, Glasgow, Leeds, Liverpool, Manchester, Newcastle-on-Tyne, Portsmouth and Southampton. At the commencement of the proceedings the Chairmen of all the meetings spoke in succession and were clearly heard by the 10 audiences.

The vote of thanks to the President for his Address was proposed by Mr. J. Harcourt Williams, who spoke from Manchester, and was seconded by Prof. Magnus Maclean, who spoke from Glasgow.

The Council are much indebted to the Post Office Engineering Department for having made the necessary arrangements and also to Messrs. Graham Amplion, Ltd., for the loan of the loud-speakers used.

(13) LOCAL CENTRES AND SUB-CENTRES.

Reports from the Committees of the Centres and Sub-Centres indicate that the attendances at the meetings and the interest in the discussions, etc., have been well sustained.

In view of the continued increase in local activities which necessarily entails larger expenditure, the Council have found it necessary to increase the scale of grants to the Centres.

The President attended functions and meetings at the Centres at Birmingham, Cardiff, Glasgow, Leeds, Liverpool, Manchester, and Newcastle-on-Tyne, as well as at the Sheffield and Tees-Side Sub-Centres.

On each occasion he addressed those present and was very gratified to note the activities of the various Centres and the evidence of appreciation by the members of the opportunities offered for discussion and intercourse.

Last Session, authority was given for the setting up of a Local Sub-Centre for Hampshire, to function directly under the Council. The inaugural meeting was held at Portsmouth on the 27th June, 1929, when Colonel Edgcumbe, who was then President, addressed the meeting and the first Committee was elected. Meetings are being held alternately at Portsmouth and Southampton.

Full details of the meetings and other activities of the Local Centres and Sub-Centres are contained in the Annual Reports presented each year to the local members.

Local technical libraries, the setting up of which was approved by the Council in 1922, have for some time been in existence at Dublin, Glasgow, Leeds, Manchester and Newcastle. The past year has seen the extension of the scheme to Loughborough and Middlesbrough.

Full particulars of the arrangements for borrowing or referring to the books at these libraries can be obtained on application to the Local Honorary Secretaries.

(14) WIRELESS SECTION.

The interest and activities of the Wireless Section have been well maintained. Seven meetings have been held, at which 12 papers were read. In addition, 5 papers have been published or accepted for publication in the *Journal*. The average attendance at the meetings was 118.

(15) METER AND INSTRUMENT SECTION.

The Meter and Instrument Section is now well established, and seven meetings have been held during the past year, the average attendance being 77. The quality of the papers has been high, and the discussions have been well sustained. The meetings included an informal debate, which was organized with the object of encouraging the junior members to speak.

It is felt that there is still a large number of members who are qualified to join the Section and have, so far, failed to make application for membership. It is therefore desired to remind members of the Institution that the Section has been formed for the reading and discussion of papers on meters, instruments and cognate subjects, and to stimulate interest in these subjects, and it is hoped that all members whose work comes within the scope of the Section will give it their active support.

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* See page 795.

(16) INFORMAL MEETINGS.

Twelve meetings have been held during the Session, the average attendance being 74 as against 69 last year.

The Informal Meetings Committee again cordially invite members to write to the Secretary indicating subjects which they wish to suggest for discussion. Offers from members to open discussions will also be welcomed and carefully considered by the Committee.

(17) STUDENTS' SECTIONS.

There are at present 3 095 Students on the register of the Institution, and a very full programme of meetings, visits to works and social functions was carried out by the eight Students' Sections, viz. those at London, Birmingham, Glasgow, Leeds, Liverpool, Manchester, Newcastle, and Sheffield. The membership of these Sections has during the Session been augmented by the inclusion of some 980 Graduates under the age of 28, who, as mentioned elsewhere in this Report, are now entitled under the Bye-laws to the same privileges as Students.

It was stated in the last Report that the Council had approved of a Lecture, to be known as "The Students' Lecture," to be delivered annually at each of the Students' Sections. For this purpose it was decided to appoint two Lecturers every other year, each of whom would visit four of the Sections in one Session and the remaining four in the following Session. The first two Lecturers, their subjects and the Sections which have been visited by them this Session, are as follows:—

Lecturer	*Subject*	*Sections*
Lt.-Col. H. E. O'Brien, D.S.O.	"Electric Traction"	Glasgow Leeds Newcastle Sheffield
Mr. F. J. Baldwin	"Overhead Line Work, with special reference to the 'Grid'"	Birmingham Liverpool London Manchester

The Lectures were much appreciated, although the attendance at some of the meetings was disappointing. The aggregate attendances were approximately 480.

In August last a Summer Meeting was organized by the London Students' Section. The party numbered 26 and included, in addition to London Students, members of the Students' Sections in the provinces.

The first part of the meeting was in Northern France, where the party spent two days inspecting the rural electrification schemes of the Société Béthunoise. The party then proceeded to Rheims where the High Tension laboratories of Messrs. Verrières Charbonneaux and the cellars of Messrs. Heidsieck were visited.

The remainder of the meeting was spent in Paris, the programme including visits to the following places:—

- The Ivry Port power station (Électricité de la Seine).
- The factory of the Compagnie Électro-Mécanique.
- Le Bourget Aerodrome.
- The research laboratories of the International Standard Electric Corporation.
- The factory of Le Matériel Téléphonique.
- The Eiffel Tower radio station.
- The repair shops of the Paris–Orleans Railway.

In addition, there were excursions to the battlefields area in Northern France and an all-day visit to the Palace of Versailles.

The Council desire to express their thanks for the hospitable welcome extended to the party on the occasion of the visits to works, etc. The meeting was very successful and thanks are due to Mr. J. Grosselin (Local Hon. Secretary for France) and Major T. Rich, Member, who accompanied the party, for their valuable assistance in arranging the visits, and also to the Hon. Secretary (Mr. L. S. Crutch) and the Committee of the London Students' Section for organizing the Meeting.

(18) STUDENTS' JOURNAL.

The Council have decided, as an experiment over a period of 12 months, to publish a quarterly *Journal* devoted exclusively to the meetings and other activities of the Students' Sections, in regard to which, under the new Bye-laws, Graduates under the age of 28 have the same privileges as Students. It is expected that the first number will be issued in the autumn.

(19) LOCAL AWARDS FOR STUDENTS' PAPERS.

The Council have approved a recommendation of the Papers and Local Centres Committees that one local award be made each year by each Local Centre from its funds for the best local Students' paper. These awards must be regarded as strictly unofficial and will not be recorded by the Institution.

(20) SUMMER MEETING.

A cordial invitation was accepted from the Société Française des Électriciens for the Summer Meeting for 1929 to be held in France, and it duly took place there from the 12th to the 22nd June, the party of visitors including some 135 members and ladies.

The programme arranged by the French society consisted of a stay of four days in Paris and an excursion to the Pyrenees.

The Paris portion of the meeting (12th to 15th June) included visits to—

- The generating station at Saint Ouen of the Compagnie Parisienne de Distribution d'Électricité.
- The generating station at Gennevilliers of the Union d'Électricité.
- The generating station at Ivry of Électricité de la Seine.

The million-volt laboratory at Ivry of the Compagnie Générale Électro-céramique.
The École Supérieure d'Électricité.
The Sainte Assise wireless station of the Compagnie Générale de T.S.F.
The Établissements Belin (tele-photography).
The new generating station at Issy-les-Moulineaux of the Compagnie Parisienne de Distribution d'Électricité.
The 46,000-gauss electromagnet at the Office National des Recherches Scientifiques et Industrielles et des Inventions, at Bellevue.

There were excursions to Versailles, Trianon and Chantilly, and some visits were especially arranged for the ladies, including the Sèvres porcelain factory.

The party were also the guests of the French society, the Compagnie Parisienne de Distribution d'Électricité and the Groupement des Secteurs de la Region Parisienne at a banquet at the Hôtel Continental on the 12th June.

The remainder of the visit consisted of an excursion to the Pyrenees, for which a special train was provided free of charge by the Compagnie des Chemins de Fer de Paris à Orléans and the Compagnie des Chemins de Fer du Midi. The route followed was Paris—Bordeaux—Pau—Lourdes—Toulouse—Paris, with subsidiary excursions to Eaux-Bonnes and the Col d'Aubisque, Gavarnie and Carcassonne. The following works were also inspected:—

The dam and generating station at Eguzon of the Union Hydro-Électrique.
The works at Hourat and the rectifier station at Pau of the Compagnie des Chemins de Fer du Midi.
The Soulom works of the Société des Phosphates Tunisiens.
The works at Luz of the Société Hydro-Électrique de la Cere.
The works at Lannemezan of the Société des Produits Azotés.

At Pau the visitors were entertained at a banquet offered by the South-Western Centre of the Société Française des Électriciens, and at Toulouse they were received at the Capitol by the Mayor and City Councillors and the Toulouse Centre of the French Society.

The Meeting concluded with the return of the party to Paris on the 22nd June.

The thanks of the Institution have been conveyed to all those named above, and the Council wish to place on record their appreciation of the generosity and cordiality with which the party were received throughout the Meeting. The Council especially desire to record their appreciation of all that was done by Mr. Paul Bunet and Mr. J. Grosselin, the President and Director respectively of the French society, who accompanied the party throughout the Meeting and who, through their unfailing tact and courtesy and excellent organization, did so much to make the Meeting the great success it undoubtedly was.

(21) FARADAY LECTURE.

The Faraday Lecture this Session was delivered by Captain P. P. Eckersley, his subject being "Broadcasting by Electric Waves." The Lecture was given at London, Birmingham, Edinburgh, Leeds, Liverpool, Manchester, Newcastle-on-Tyne, Plymouth and Sheffield.

The nine Lectures were attended by a total audience of approximately 7 500, of whom over 5 500 were non-members. The latter figure is a satisfactory indication that the Lectures continue to fulfil their object of bringing electrical science to the attention of the public.

(22) REVIEWS OF PROGRESS.

Continuing the series of reviews of progress in electrical engineering which were published in the *Journal* in 1926, 1927, 1928 and 1929, reviews on the following subjects have been or will be published during 1930:—

Domestic Applications of Electricity.
Electrical Equipment of Automobiles.
Electricity Supply Tariffs.
Electrical Plant and Machinery.
Electro-Physics.
Electric Traction.
Transmission and Distribution.

The reviews to be published in 1931 will be on the following subjects:—

Electrical Measuring Instruments and Sensitive Controlling Apparatus.
Electrical Standardization.
Electricity in Mines.
Electricity Meters.
Electro-Chemistry and Electro-Metallurgy.

(23) SCHOLARSHIPS.

The following Scholarships have been awarded by the Council:—

David Hughes Scholarship.
(Value £50; tenable for one year.)
P. F. Soper (East London College).

Paul Scholarship.
(Value £100; tenable for two years.)
K. H. Gillanders (Brockley County School, London).

Salomons Scholarships.
(Value £50 each; tenable for one year.)
R. B. Smith (Leeds University).
F. W. L. Horner (Municipal Technical College, Belfast).

War Thanksgiving Education and Research Fund (No. 1).

The Council have made grants of £50 from the above Fund for research purposes to each of the following:—

J. A. Clegg (University College, London).
A. F. Wilkins (Cambridge University).

In order further to extend the educational work of the Institution, the Council have decided to establish two Institution Scholarships, which will ultimately involve an annual expenditure of £950.*

A bequest of £1 000 has been received by the Institution under the Will of the late Mr. W. J. Thorrowgood,

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* See page 796.

Member, the income of which is to be devoted to the establishment of a Scholarship affording training in connection with electrical railway signalling, a branch of engineering with which the benefactor was particularly associated.

The Council have set up a Scholarships Committee, representative of education and industry, to settle the method and conditions of award of these new scholarships and also to deal with all scholarships and similar awards administered by the Institution.

(24) Activities of Overseas Members.

The possibility of increasing the Institution's activities in India and the Dominions has had the careful consideration of the Council, and, as a result of information which has been obtained from the Local Hon. Secretaries in the countries concerned, the Council have decided to encourage the holding of meetings abroad for the reading and discussion of selected Institution papers. Where this, or the holding of social functions, is found practicable, the Council have sanctioned the setting up of Local Advisory Committees, which, it is considered, will be of great value, not only in organizing meetings, but in acting as local sources of information on Institution matters. Financial assistance will be provided by the Institution so as to enable the Committees to carry out their duties more efficiently.

(25) Professional Engineers' Act (Queensland).

Under the provisions of the above Act, which was passed in 1929, Corporate Membership of the Institution is one of the qualifications entitling to registration as a professional engineer in Queensland, Australia.

(26) Local Hon. Secretary for Italy.

In place of the late Mr. Guido Semenza, who was Hon. Secretary of the Institution for Italy from 1903 until his death in 1929, the Council have appointed Mr. L. Emanueli of Milan.

(27) International Relations.

The Council have decided that the Institution should give its official support to the following international technical organizations:—

The International Electrotechnical Commission.
The World Power Conference.
The International Commission on Illumination.

The Institution has also become an Associate Member of the "Commission Mixte Internationale pour les expériences relatives à la protection des lignes de télécommunication et des canalisations souterraines."

(28) Paris International Conference on Large E.H.T. Supply Systems.

The fifth session of the above Conference took place in Paris from the 6th to the 15th June, 1929. The number of countries represented was 29, Great Britain being represented by 46 members. The delegates appointed by the Institution were Mr. P. V. Hunter, C.B.E. (chief delegate), Mr. J. R. Beard, M.Sc., and Mr. Johnstone Wright.

The number of papers read before the Conference was 100.

(29) Anniversary Celebrations and Conferences, etc., of Other Bodies.

During the year under review, the Institution has been represented at Anniversary Celebrations and Conferences, etc., arranged by other bodies, as shown in the following table:—

Name of Body	*Nature and Date of Function*	*Names of I.E.E. Representatives*
École Centrale des Arts et Manufactures, Paris.	Centenary (26–28 May, 1929).	Mr. F. Gill (Past President). Mr. P. F. Rowell (Secretary).
Elektrotechnischer Verein, Berlin.	Jubilee (24–27 Jan., 1930).	Mr. Ll. B. Atkinson (Past President). Dr. A. H. Railing (Vice-President).
American Society of Mechanical Engineers.	Jubilee (April, 1930).	Mr. Gano Dunn (Local Hon. Secretary, United States of America). Mr. W. H. Patchell.
World Engineering Congress, Tokyo, Japan.	Oct., 1929.	Mr. F. Gill (Past President).
Royal Technical College, Copenhagen.	Centenary (30 Aug., 1929)	Mr. E. B. Petersen.
South African College, Cape Town.	Centenary (1–5 Oct., 1929).	Major F. Pickering (Local Hon. Secretary, Cape, Natal and Rhodesia).
Smoke Abatement League of Great Britain.	Exhibition, Manchester (Nov., 1929).	Mr. T. E. Herbert (Chairman, North-Western Centre).
Association of Teachers in Technical Institutions.	Annual Conference, Liverpool (18–21 Oct., 1929).	Mr. S. E. Britton [Chairman, Mersey and North Wales (Liverpool) Centre].
Royal Sanitary Institute.	Annual Congress, Sheffield (13–20 July, 1929).	Mr. S. E. Fedden (Past Chairman, North Midland Centre).

In the case of the first four bodies mentioned above, Addresses of Congratulation were presented by the delegates on behalf of the Institution. A letter of congratulation was also sent by the Institution to the Hungarian Electrotechnical Society on the occasion of the 25th Anniversary of its foundation, which was celebrated at Budapest on the 19th May, 1929.

(30) Annual Conversazione.

The Annual Conversazione was held at the Natural History Museum, South Kensington, on the 4th July, 1929. The attendance was, as usual, very large, nearly 1 850 members and guests being present.

(31) Annual Dinner.

The Annual Dinner was held at the Hotel Cecil, London, on the 6th February, 1930, when over 650 members and guests were present.

An account was published in the May number of the *Journal* (page 651).

(32) STANDARDIZATION OF VOLTAGES.

The Committee appointed by the Council to consider the above question have duly presented a Report covering their terms of reference (which were set out in full in the last Annual Report), and as a result a statement by the Council on the subject was published in the April number of the *Journal* (page 516) and also circulated to the technical Press.

The Council desire to put on record their appreciation of the assistance and co-operation rendered by the Electricity Commissioners, the British Electrical and Allied Manufacturers' Association and the Electric Lamp Manufacturers' Association in the preparation of the Committee's Report.

(33) ELECTRICAL APPOINTMENTS BOARD.

A classified register of members seeking positions, containing particulars of their training and experience, is available for inspection at the Institution offices, and the Secretary of the Board will gladly put employers in touch with highly qualified electrical engineers.

The number of applicants on the register on the 25th March, 1930, was 47, against a total of 36 last year.

The Council earnestly hope that members who are in a position to assist will not fail to make use of the register.

(34) LIBRARY.

During the year, 204 books and pamphlets were presented to the Reference Library by members and others, and 113 volumes have been purchased. The total number of readers for the year was 6 018, of whom 305 were non-members, as against 5 985 and 285 respectively in 1928–1929.

Eighty-six new volumes were added to the Lending Library and 2 462 books were issued to 949 borrowers, the corresponding numbers for the previous year being 2 257 and 1 006 respectively.

(35) GIFTS TO THE INSTITUTION.

The Council express their cordial thanks to the donors of the following gifts to the Institution:—

Donor	*Gift*
Mr. H. Cotton ..	Three wood fuse cases and an early switch.
Mr. C. W. S. Crawley	Carbon brushes used with Forbes "non-polar" dynamo, 1884.
Prof. A. E. Kennelly	Photostat copy of an autograph letter of Michael Faraday dated 19th Feb., 1858, to the late Mr. C. V. Walker, F.R.S., a former President of the Institution.

(36) FARADAY CENTENARY CELEBRATIONS.

It is proposed to celebrate in 1931, during the month of September, the centenary of Faraday's discovery of electromagnetic induction, from which have developed most of the practical applications of electricity. The Institution is closely co-operating with the Royal Institution in the matter and proposes to arrange for an Exhibition at the Albert Hall, London, on strictly scientific lines, with the object of bringing to the knowledge of the public the results of Faraday's discovery. The Institution proposes to contribute from its funds a sum not exceeding £10 000 towards the cost of the Exhibition, instead of asking its members to contribute individually towards this very important celebration, as had been at first suggested.

(37) JUBILEE OF THE INCANDESCENT LAMP.

In connection with the celebrations of the above Jubilee held in America in June 1929, the Council addressed a letter to the International Illumination Commission and other bodies with a view to placing on record Swan's pioneer work on the incandescent electric lamp.

(38) ROYAL COMMISSION ON THE CIVIL SERVICE.

As the result of a letter from the Institute of Physics drawing attention to the absence of scientists from the personnel of the above Commission, the Council appointed the President and Mr. J. M. Kennedy as representatives to attend a conference of Scientific Institutions for the purpose of discussing the matter and deciding what action, if any, should be taken.

(39) SUBSCRIPTIONS OF RETIRED MEMBERS.

In view of the fact that many members have to retire from the profession compulsorily at age 60, but, nevertheless, desire to retain their membership of the Institution, the Council have revised the Rule adopted in 1927 which applied to retired members of not less than 65 years of age, and it now reads as follows:—

> "Any Corporate Member who has reached the age of 60 and has retired from the practice of his profession or business, may apply to the Council to remit his future annual subscriptions, provided that his membership of the Institution has been continuous for at least 25 years. If he desires to have the publications of the Institution he will receive them on payment of £1 1s. per annum."

The Council are glad to note that since the adoption of the original Rule a number of members of long standing have been enabled to continue their membership.

(40) BEQUEST.

The Council desire to record a bequest of £200 to the Institution under the Will of the late Mr. H. L. Leach, Member, of which £100 is to be applied to the Benevolent Fund, and £100 "to the Research Fund of the Institution or to any other purpose which the Council for the time being of the Institution may consider desirable."

The latter amount has been handed over to the British Electrical and Allied Industries Research Association.

(41) "SCIENCE ABSTRACTS."

The Physics volume of *Science Abstracts* for 1929 contains 3 687 abstracts, as compared with 3 355 in 1928. The Electrical Engineering volume contains 2 250 abstracts, as compared with 2 110.

The very slight interest taken in *Science Abstracts* by the general body of members is a matter of considerable disappointment to the Council. The publication, which appears monthly in two sections, namely, Section " A " (Physics) and Section " B " (Electrical Engineering), and consists of full abstracts from the leading scientific and technical journals, and the proceedings of learned societies of the whole world, presents in a form convenient for immediate reference a complete and concise record of the progress of physical science and electrical engineering. It is therefore surprising that, out of a membership of some 14 000, fewer than 1 500 subscribe to *Science Abstracts*, only 779 members subscribing to both Sections and 646 to Section " B."

The Council hope that greater support will be given in future to the publication, which, if ordered in advance, is obtainable by Students of the Institution, as well as by Graduates under the age of 28, at the special rate of 7s. 6d. per annum for both Sections, or 5s. for either the Physics or the Electrical Engineering Section, and by all other members of the Institution at 20s. for both Sections, or 12s. 6d. for either Section alone, the rates charged to the general public being £1 15s. per Section, or £3 for both Sections.

(42) Model General Conditions for Contracts.

The proposed set of Model Conditions " E " for the supply and laying of cables at home have not yet been completed.

(43) Regulations for the Electrical Equipment of Ships.

A number of alterations and additions to the second edition of the above Regulations have been approved by the Council, and they are set out in a supplement, copies of which can be obtained on application to the Secretary.

(44) Regulations for the Electrical Equipment of Buildings.

There continues to be a steady demand for copies of the Ninth Edition of the above Regulations issued in May 1927, which is an indication that they are being more and more widely adopted. The drafting of the Tenth Edition is in progress.

The supplement, issued in June 1928, containing requirements in regard to radio apparatus connected to public or private supply mains has been revised and copies will shortly be available.

Towards the end of 1929 the Council addressed to a number of interested bodies the following letter urging the desirability of steps being taken in the direction of a more general adoption of the Institution's Wiring Regulations:—

" Dear Sir,

" The present policy of National Electrical Development is leading to a very extended adoption of electricity, especially in the smaller private houses, where the users are mainly non-technical people.

" The standard supply now being adopted throughout the country is alternating current at a pressure of 230 volts, and the effects of a shock from alternating current are known to be more serious than in the case of direct current.

" The use of electricity is perfectly safe provided a few simple precautions are complied with—electricity is a good servant but a bad master.

" The chances of a consumer receiving a shock are practically eliminated if the wiring installation is carried out in a correct manner and all electrical appliances are used in the right way. Such appliances and apparatus (including wireless apparatus), which are becoming more and more popular, can be purchased by any consumer and connected to an existing lampholder or plug without essential precautions, particularly as regards earthing, being taken.

" This matter has been receiving the earnest consideration of the Council of this Institution, and they would urge upon your Institution (Association) the importance of safeguarding the public if the development of electricity supply is not to be retarded by avoidable fatalities.

" In this connection the Council have instructed me to draw your attention particularly to the desirability of the 'Wiring Regulations' issued by this Institution being observed. These Regulations have been framed with a view to securing safety from fire and shock, and the Council would appreciate any steps which your Institution (Association) may see their way to take to ensure a more general compliance with such Regulations.

" The Council will be pleased to provide you with any further information or assistance that you may require to secure the desired result."

" I am, dear Sir,
Yours faithfully,
P. F. Rowell,
Secretary."

At the same time the Council also caused the following letter to be published in the technical Press, including a number of architects' and builders' journals:—

" Dear Sir,

Smethwick Fire Disaster.

" The attention of the Council of The Institution of Electrical Engineers has been drawn to newspaper reports of the proceedings at the inquest, which concluded on the 25th September last, upon eleven persons who lost their lives by reason of a fire at premises in Rolfe Street, Smethwick, on the 2nd September.

" Some of the evidence purported to show that the fire was due to a defective electrical installation in a neighbouring building, and in this connection one of the witnesses condemned the use of lead-covered rubber-insulated cables for the wiring of public buildings. This statement has caused great uneasiness in the minds of consulting engineers, architects, electrical contractors and others, inasmuch as the use of lead-covered rubber-insulated cables is permitted by, and the proper methods of installation of such cables are set out in, the 'Regulations for the Electrical Equipment of Buildings' issued by the Institution. These Regulations are recognized by consulting engineers, electrical contractors, electricity supply authorities and the Fire Offices, as representing the best standard practice, and the Fire Offices in particular recommend their use.

"The Council re-affirm, therefore, that they are of the opinion that lead-sheathed cables are both suitable and safe for electrical installations if installed and maintained in accordance with the I.E.E. Wiring Regulations.

"From the evidence given, as reported in the newspapers, there is every indication that the electrical installation which, it is suggested, caused the fire at Smethwick, did not comply with these Regulations."

"I am, dear Sir,
Yours faithfully,
P. F. Rowell,
Secretary."

(45) Electricity Regulations.

During the year under review, the Electricity (Supply) Regulations Committee received from the Electricity Commissioners a proof of the new Code of Safety and Supply Regulations proposed to be made under the provisions of the Electricity (Supply) Acts, 1882 to 1928. These proposed Regulations were largely based upon the draft which was submitted by the Committee to the Commissioners in 1926, and the Commissioners requested the Regulations Committee to let them have, at an early date, any observations which they might desire to offer on the proof. In due course the Committee submitted their observations to the Council, but the matter was referred back to the Committee for them to carry out certain suggestions made by Members of Council. A second report was subsequently made to the Council and this is still under consideration.

(46) Benevolent Fund.

The Committee of Management of the Benevolent Fund of the Institution report that on the 31st December, 1929, the total assets of the Fund amounted to £16 500 17s. 11d., of which £14 242 8s. 4d. was on Capital Account, and £2 258 9s. 7d. in respect of unexpended Income. These figures include legacies of £100 each from the late Dr. C. S. du Riche Preller and the late Mr. H. Louis Leach (Members). The donations and subscriptions to the Fund in 1929 amounted to £2 296 5s. 3d., in which amount are included the proceeds of Golf Competitions organized by the Mersey and North Wales (Liverpool) and Scottish Centres.

Year	Subscriptions and donations received	Total grants made during year	No. of cases assisted
	£	£	
1920	821	341	11
1921	616 809 (Hughman collection)	525	14
1922	632 1 768 (Hughman collection)	776	16
1923	637	1 034	21
1924	1 152	1 323	26
1925	1 241	1 199	30
1926	1 484	1 498	32
1927	1 574	1 307	29
1928	1 998	1 409	32
1929	2 296	1 539	32

In the course of 1929, 99 grants were made to 32 persons, amounting to a total of £1 538 15s. 0d. The table in the preceding column summarizes the operations of the Fund during the last 10 years.

The Council most earnestly desire to bring the Fund to the notice of all members of the Institution. Donations and promises of annual subscriptions of any amount will be gratefully received.

(47) Summary of Annual Accounts.

Excess of Income over Expenditure.—After making provision for contingencies, there is a balance to the good on the Revenue Account for 1929 of £5 242 6s. 8d. This amount, which has been carried to the credit of the General Fund, compares with £6 040 10s. 6d. in 1928.

Assets.—Taking the investments at cost and the Institution Building and lease, the library and furniture, etc., at the values standing in the books after writing off depreciation—

	£	s.	d.
the Assets amount to	186 343	4	10
against Liabilities	10 200	14	3
leaving a surplus of	176 142	10	7
which, in comparison with that of the year 1928, viz.	168 078	2	2
shows an improvement of	£8 064	8	5

The surplus of £176 142 10s. 7d., referred to above is made up as follows:—

Assets.	£	s.	d.	£	s.	d.
Institution Building and lease				73 028	6	10
Investments, cash, etc.				105 706	1	3
Stock of paper, libraries and furniture				7 608	16	9
				186 343	4	10
Less *Liabilities.*						
Trust Fund Accounts	812	5	10			
Sundry creditors ..	4 750	4	2			
Repairs Suspense Account	4 205	9	1			
Subscriptions received in advance	432	15	2			
				10 200	14	3
				£176 142	10	7

Investments.—The investments (including re-investments and conversions) made during the year were as follows:—

	£	s.	d.
£1 000 5 per cent War Stock (1929–47) cost	1 024	10	6
£2 380 4 per cent Consolidated Stock cost	2 000	0	0
£3 000 Birmingham Corporation 4½ per cent Stock (1948–68) cost	2 906	11	0
£3 000 London County 4½ per cent Stock (1945–85) cost	2 936	11	0
£1 000 Bootle Corporation 4¾ per cent Stock (1949–59) cost	967	12	0
£5 000 5 per cent Conversion Stock (1944–64), first instalment of £10 per cent	500	0	0
	£10 335	4	6

(48) THE INSTITUTION AND BODIES ON WHICH IT IS REPRESENTED.

Appendix C shows in diagrammatic form the organization of the Institution and the bodies on which it is represented.

APPENDIX A.

MEMBERSHIP OF THE INSTITUTION.

The changes in the membership since 1st April, 1929, are shown in the following table:—

	Hon. Mem.	Mem.	Assoc. Mem.	Com.	Assoc.	Grad.	Stud.	TOTAL
Totals at 1 April, 1929	13	1 959	5 356	—	287	2 633	3 313	13 561
Additions during the year:—								
Elected ..	1	1	136	4	42	142	767	1 093
Reinstated	—	1	4	—	1	6	41	53
Transferred to ..	—	50	184	132	1 624	880	33	2 903
Total ..	1	52	324	136	1 667	1 028	841	4 049
Deductions during the year:—								
Deceased ..	1	36	25	3	4	6	5	80
Resigned ..	—	9	32	9	52	45	52	199
Lapsed ..	—	7	46	—	55	18	102	228
Transferred from ..	—	—	48	1	159	1 795	900	2 903
Total ..	1	52	151	13	270	1 864	1 059	3 410
Net Increase								639
Totals at 1 April, 1930	13	1 959	5 529	123	1 684	1 797	3 095	14 200

APPENDIX B.

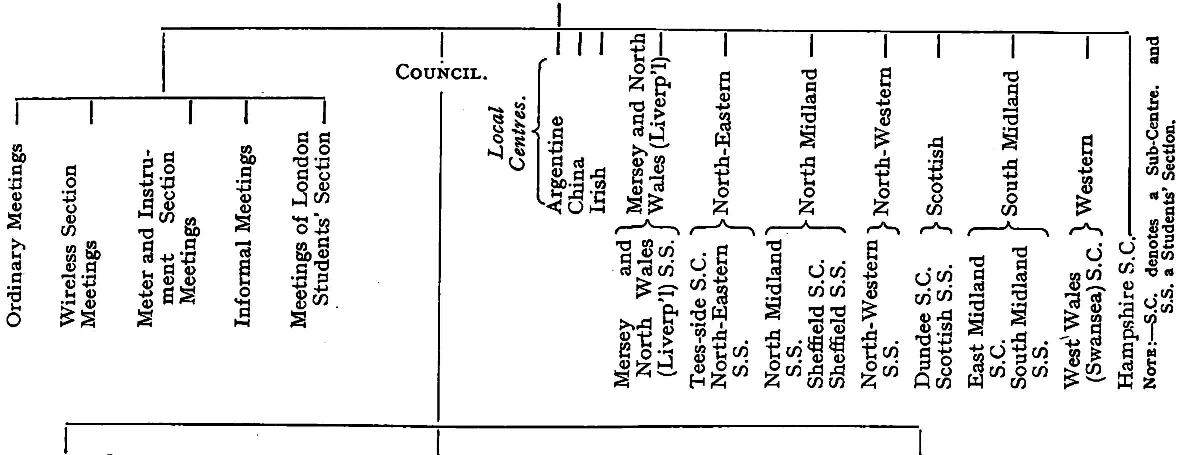
MEETINGS.

The following is a list of the meetings held during the past 12 months:—

Ordinary Meetings ..	17
Annual General Meeting	1
Special General Meeting	1
Annual General Meeting (Benevolent Fund)	1
Wireless Section ..	7
Meter and Instrument Section	7
Informal Meetings ..	13
Council Meetings ..	15
Local Centres:—	
Irish	7
Mersey and North Wales (Liverpool)	11
North-Eastern ..	15
North Midland ..	12
North-Western ..	14
Scottish	10
South Midland ..	10
Western	11
Local Sub-Centres:—	
Dundee	7
East Midland ..	8
Hampshire ..	8
Sheffield	7
Tees-side	8
West Wales (Swansea)	7
Students' Sections:—	
Liverpool	10
London	11
North-Eastern ..	10
North Midland ..	9
North-Western ..	10
Scottish	9
Sheffield	6
South Midland ..	6
Committees:—	
Benevolent Fund ..	5
Electricity (Supply) Regulations.. ..	8
Committees—*continued.*	
Examinations ..	
Faraday Celebrations (and Sub-Committee) ..	4
Finance	9
General Purposes (and Sub-Committees)	12
Informal Meetings (and Sub-Committee)	7
International Relations (and Sub-Committees) ..	7
Local Centres ..	2
Membership ..	8
Meter and Instrument Section (and Sub-Committees)	12
National Certificates (England)	4
National Certificates (Scotland) ..	1
Papers (and Sub-Committee) ..	9
Paul Scholarship ..	2
Scholarships ..	2
" Science Abstracts"	4
Ship Electrical Equipment (and Sub-Committee)	2
Voltage Standardization	1
Wireless Section (and Sub-Committee)	9
Wiring Regulations (and Sub-Committees)	23
Other Committees	25
Total ..	431

APPENDIX C.

THE INSTITUTION OF ELECTRICAL ENGINEERS.


Council.
Ordinary Meetings
Wireless Section Meetings
Meter and Instrument Section Meetings
Informal Meetings
Meetings of London Students' Section
Local Centres.
Argentine
China
Irish
Mersey and North Wales (Liverp'l)
North-Eastern
North Midland
North-Western
Scottish
South Midland
Western
Mersey and North Wales (Liverp'l) S.S.
Tees-side S.C.
North-Eastern S.S.
North Midland S.S.
Sheffield S.C.
Sheffield S.S.
North-Western S.S.
Dundee S.C.
Scottish S.S.
East Midland S.C.
South Midland S.S.
West Wales (Swansea) S.C.
Hampshire S.C.

Note:—S.C. denotes a Sub-Centre, and S.S. a Students' Section.

Committees of Council.

Examinations
Finance
General Purposes
Library and Museum
Membership
Papers

Special Committees.

Benevolent Fund
Electricity (Supply) Regulations
Faraday Celebrations
Informal Meetings
International Relations
Local Centres
Meter and Instrument Section
Model General Conditions
Patent Law
Scholarships
" Science Abstracts "
Ship Electrical Equipment Regulations
Wireless Section
Wiring Regulations

Technical Committees.
- Electrical Plant and Machinery, including Marine Applications
- Electricity in Mines
- Electro-Chemistry and Electro-Metallurgy
- Industrial, Agricultural and Domestic Applications, including Illumination and Tariffs
- Power Stations and their Equipment
- Telegraphs and Telephones
- Traction
- Transmission and Distribution

Bodies on which the Institution is Represented.

Alloys of Iron Research (Royal Society)
Bristol University
British Cast Iron Research Association
British Electrical and Allied Industries Research Association
British Electrical Development Association
British Engineering Standards Association
British National Committee of the International Electrotechnical Commission
British National Committee, World Power Conference
British National Illumination Committee of the International Illumination Commission
City and Guilds of London Institute
Council for the Preservation of Rural England
Engineering Joint Council
Imperial College of Science and Technology, Governing Body
Imperial Minerals Resources Conference, Copper Committee
Institute of Metals, Corrosion Research Committee
Institution of Civil Engineers, Engine and Boiler Testing Committee
International Association for Testing Materials
International Electrotechnical Commission
International Scientific Unions
Leeds Municipal Technical Library Committee
Loughborough Technical College Advisory Committee
Mechanical Warfare Board, War Office
Metalliferous Mining (Cornwall) School, Governing Body
Middlesbrough Technical College, Governing Body
National Certificates and Diplomas in Electrical Engineering, Joint Committees for
National Committee on Physics (Royal Society)
National Committee on Radio-Telegraphy (Royal Society)
National Physical Laboratory, General Board
National Register of Electrical Contractors
Professional Classes Aid Council
Radio Manufacturers' Association, Committee on Battery Eliminators
Royal Engineer Board
Science Museum, S. Kensington, Advisory Council
Smoke Abatement League of Great Britain
Union of Lancashire and Cheshire Institutes, Panel for Engineering
Women's Electrical Association
Women's Engineering Society

THE INSTITUTION OF ELECTRICAL ENGINEERS.

REVENUE ACCOUNT FOR THE YEAR ENDED 31ST DECEMBER, 1929.

Dr. EXPENDITURE.

Year ended 31 Dec., 1928.* £ s. d.		£ s. d.	£ s. d.
	To **MANAGEMENT** :—		
	Salaries and Wages (including Staff Provident Scheme)	13,442 18 9	
	National Insurance	66 0 11	
	Audit Fee	52 10 0	
	Printing	605 16 0	
	Stationery and Office Requisites	533 19 5	
	Addressing Machine Requisites	32 5 1	
	Postage of Correspondence and Notices	711 14 10	
	Telephone	90 16 5	
	Travelling Expenses	137 5 1	
	Bank Charges	16 8 1	
15,068 16 8			15,689 14 7
	„ **INSTITUTION BUILDING** :—		
	Ground Rent	2,201 0 0	
	Rates	2,860 9 8	
	Heating	274 6 6	
	Lighting and Power	368 12 10	
	Insurance	170 18 6	
	Reserve for Repairs	1,500 0 0	
	Redecoration and Relighting of Lecture Theatre	1,245 4 4	
	Structural Alterations	958 10 0	
	Household Requisites and Cleaning	354 0 4	
	Estate Agents' Fees	10 10 0	
		9,943 12 2	
	Less Rents from Tenants	5,665 0 0	
2,128 8 8			4,278 12 2
294 13 0	„ **FURNITURE AND FITTINGS** (Repairs and Renewals)		514 10 10
	„ **JOURNAL** :—		
	Printing	7,414 8 8	
	Postage	2,480 13 0	
	Wrappers and Envelopes	289 7 7	
		10,184 9 3	
	Less Sales and Advertisements	5,754 6 2	
4,477 3 3			4,430 3 1
56 4 0	„ **PROCEEDINGS OF THE WIRELESS SECTION** (Printing, Postage, etc. : *less* Sales)		8 18 7
108 4 6	„ **LENDING LIBRARY** (Books, Printing, Postage, etc.)		97 13 0
	„ **SCIENCE ABSTRACTS** :—		
	Abstracting, Editing, Printing, Postage, etc.	4,881 9 5	
	Less Sales and Advertisements	3,929 13 6	
877 5 11			951 15 11
	Carried Forward		£25,971 8 2

INCOME. Cr.

Year ended 31 Dec., 1928.* £ s. d.		£ s. d.	£ s. d.
34,692 19 2	By **SUBSCRIPTIONS**		35,946 7 3
1,593 1 2	„ **ENTRANCE FEES AND VELLUM DIPLOMA FEES**		1,492 16 4
726 7 0	„ **MEMBERS' SUBSCRIPTIONS TO "SCIENCE ABSTRACTS"**		701 19 0
3,362 16 11	„ **DIVIDENDS AND INTEREST**		4,183 15 10
193 7 5	„ **MODEL GENERAL CONDITIONS**		271 10 7
72 17 8	„ **WIRING REGULATIONS**		74 13 7
23 15 0	„ **SHIP WIRING REGULATIONS**		2 6 2
	„ **EXAMINATIONS** :—		
	Graduateship Examination (Candidates' Fees and Sale of Papers, *less* Examiners' Fees, Printing, etc.)	30 1 10	
	National Certificates and Diplomas (Candidates' and School Authorities' Fees, *less* Assessors' Fees, Stationery, Postage, etc.)	411 3 11	
411 10 3			441 5 9
	Carried Forward		£13,114 14 6

REVENUE ACCOUNT—*continued.*

Dr. EXPENDITURE—*continued.*

		£ s. d.	£ s. d.
	Brought Forward		25,971 8 2
	To INSTITUTION MEETINGS :—		
	Advance Proofs	245 5 10	
	Reporting	113 9 0	
	Grant to London Students' Section ...	55 2 1	
	Honorarium to Kelvin Lecturer	25 0 0	
	Refreshments, Assistance, etc.	297 12 7	
	Travelling Expenses of Authors of Papers	112 3 0	
	Faraday Lectures	395 16 6	
	Students' Lectures	27 9 0	
1,106 18 7			1,271 18 0
	„ LOCAL CENTRES :—		
	Money Grants (including Travelling Expenses of Authors of Papers) ...	2,853 1 6	
	Travelling Expenses	791 5 5	
3,443 11 3			3,644 6 11
201 7 10	„ PREMIUMS FOR PAPERS		217 11 5
	„ SPECIAL GRANTS :—		
	British Engineering Standards Association	1,000 0 0	
	Electrical Research Association... ...	1,000 0 0	
	National Illumination Committee ...	32 0 0	
	International Illumination Congress, 1931	350 0 0	
	Commission Mixte Internationale ...	47 14 4	
2,331 10 0			2,429 14 4
100 4 6	„ ANNUAL DINNER		73 13 5
592 9 8	„ CONVERSAZIONE...		594 19 6
189 13 9	„ LEGAL EXPENSES		60 2 0
90 13 7	„ MISCELLANEOUS EXPENSES		93 1 5
31,277 12 10			34,356 15 2
	„ AMOUNTS TRANSFERRED TO :—		
277 12 2	SINKING FUND (Premiums for Redemption of Cost of Building and Lease) ...	277 12 2	
3,000 0 0	RESERVE FUND	3,000 0 0	
	GENERAL FUND :—		
632 14 4	Obligatory Repayment to Economic Life Assurance Society	nil	
197 0 6	Expenditure on Books and Binding for Library	238 0 6	
6,040 10 6	**Balance carried to General Fund** ...	5,242 6 8	
10,147 17 6			8,757 19 4
41,425 10 4			£43,114 14 6

INCOME—*continued.* **Cr.**

		£ s. d.
	Brought Forward	43,114 14 6
41,425 10 4		£43,114 14 6

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* These columns do not add up to the totals of Income and Expenditure shown, as some of the items in the Accounts for 1928 did not occur in 1929.

BALANCE SHEET, 31ST DECEMBER, 1929.

Dr. LIABILITIES.

	£	s.	d.	£	s.	d.
To **Kelvin Lecture Fund**:—						
As per last Balance Sheet				648	13	0
" **Uninvested Balances of Trust Funds**				812	5	10
" **Sundry Creditors**				4,750	4	2
" **Subscriptions received in advance**				432	15	2
" **Repairs Suspense Account**:—						
Balance at 1st January, 1929	3,469	0	11			
Amount set aside in 1929	1,500	0	0			
	4,969	0	11			
Less Expenditure on Repairs in 1929... ...	763	11	10			
				4,205	9	1
" **Reserve Fund**:—						
Balance at 1st January, 1929	18,940	16	6			
Amount transferred to Reserve Fund in 1929 ...	3,000	0	0			
				21,940	16	6
Carried Forward				32,790	3	9

ASSETS. Cr.

	£	s.	d.	£	s.	d.
By **Institution Building and Lease**:—						
Cost	73,028	6	10			
Less Reserve for Depreciation, being Surrender Values of Sinking Fund Policies	6,848	4	0			
				66,180	2	10
" **Sinking Fund** (Surrender Values of Policies for Redemption of Cost of Building and Lease)				6,848	4	0
" **Kelvin Lecture Fund Investment** (at cost):—						
£694 16s. 9d. 5 % War Stock (1929–47)				648	13	0
" **Library** (exclusive of the Ronalds Library and Faraday Papers, which are held in trust):—						
As per last Balance Sheet	1,391	18	2			
Additions in 1929	238	0	6			
	1,629	18	8			
Less Depreciation (10 %)	162	19	10			
				1,466	18	10
" **Thompson Memorial Library** (Contribution towards purchase)				1,000	0	0
" **Furniture, Fittings, and Apparatus**:—						
As per last Balance Sheet	5,058	17	7			
Less Depreciation (5 %)	252	18	11			
				4,805	18	8
" **Sundry Debtors**				3,345	19	0
" **Insurance Premiums and Sundry Payments in Advance** ...				1,074	9	3
" **Stock of Paper, Etc., for Publications**				335	19	3
" **General and Reserve Funds Investments** (at cost):—						
£2.600 Natal Zululand Railways 3 % Debenture Stock	2,270	12	0			
£1,500 London, Midland and Scottish Railway 4 % Preference Stock	1,513	10	4			
£2,000 Assam Bengal Railways 3 % Stock (1931 or after)	1,548	0	6			
£750 Western Australia 4 % Stock (1942–62) ...	730	8	3			
£750 Union of South Africa 4 % Stock (1943–63) ...	742	12	0			
£750 Madras and Southern Mahratta Railway 4 % Debenture Stock (1938)	738	15	6			
Carried Forward	7,543	18	7	85,706	4	10

BALANCE SHEET—*continued.*

Dr. LIABILITIES—*continued.*

	£ s. d.	£ s. d.	£ s. d.
Brought Forward			32,790 3 9
To GENERAL FUND :—			
Balance at 1st January, 1929		148,488 12 8	
Expenditure in 1929 on—			
Books and Binding for Library		238 0 6	
Balance from Revenue Account for 1929 ...		5,242 6 8	
		153,968 19 10	
Less Depreciation :—			
Library (*per contra*)	£162 19 10		
Furniture, Fittings, and Apparatus (*per contra*)	252 18 11		
		415 18 9	
			153,553 1 1
			£186,343 4 10

P. F. ROWELL,
Secretary.

ASSETS—*continued.* **Cr.**

	£ s. d.	£ s. d.
Brought Forward		85,706 4 10
By GENERAL AND RESERVE FUNDS INVESTMENTS (at cost)—*contd.*		
Brought forward	7,543 18 7	
£35 East Indian Railway "B" Annuity (1953) ...	791 5 4	
£1,500 South Australia 4% Stock (1940–60)... ...	1,494 10 6	
£8,750 5 % War Stock (1929–47)	8,554 10 3	
£19,375 4 % Funding Loan (1960–90)	15,500 0 0	
£8,700 3½ % Conversion Stock (1961 or after) ...	6,651 3 3	
£11,970 11s. 4 % Consolidated Stock	10,291 6 0	
£1,000 London, Midland and Scottish Railway 5% Preference Stock (1955)	1,020 4 6	
£5,000 North Metropolitan Power Station 5 % Guaranteed Debenture Stock (1957)	4,988 11 0	
£2,000 London, Midland and Scottish Railway 5 % Redeemable Debenture Stock (1952)	1,982 5 9	
£2,300 East Indian Railway 4½ % Irredeemable Debenture Stock	2,019 13 0	
£5,000 Commonwealth of Australia 5 % Stock (1945–75)	4,964 17 6	
£2,000 Tynemouth Corporation 5 % Stock (1947–57)	2,025 4 0	
£2,500 Stoke-on-Trent Corporation 5 % Stock (1948–68)	2,550 6 0	
£3,500 East Indian Railway 3½ % Debenture Stock (1937)	2,475 15 6	
£5,000 Brighton Corporation 4¾ % Stock (1945–75)	5,050 8 0	
£2,000 New South Wales 5¼ % Stock (1947–57) ...	2,013 19 0	
£2,600 Kenya Government 4½ % Stock (1950) ...	2,483 4 0	
£3,000 Southern Railway 4 % Debenture Stock ...	2,520 5 0	
£2,500 India 4½ % Stock (1958–68)	2,329 17 9	
£2,500 Corporation of London 4½ % Debenture Stock (1940–85)	2,462 14 0	
£3,000 Birmingham Corporation 4½ % Stock (1948–68)	2,906 11 0	
£3,000 London County 4½ % Stock (1945–85) ...	2,936 11 0	
£1,000 Bootle Corporation 4¾ % Stock (1949–59) ...	967 12 0	
£5,000 5 % Conversion Stock (1944–64) (first instalment of £10 per cent)	500 0 0	
		97,024 13 5
„ CASH IN HANDS OF LOCAL CENTRES ON 30 SEPT., 1929		1,005 13 4
„ CASH :—		
At Bankers'	2,456 12 3	
In hands of Secretary	150 1 0	
		2,606 13 3
		£186,343 4 10

We beg to report that we have audited the Balance Sheet of The Institution of Electrical Engineers, dated 31st December, 1929, and above set forth, together with the annexed Statements of Account. We have obtained all the information and explanations we have required. In our opinion the Statements are correct, and the Balance Sheet is properly drawn up so as to exhibit a true and correct view of the state of the Institution's affairs according to the best of our information and the explanations given to us and as shown by the books of the Institution.

15th April, 1930.

ALLEN, ATTFIELD & CO., *Auditors.*
Chartered Accountants.
24, MARTIN LANE, CANNON STREET, E.C. 4.

SALOMONS SCHOLARSHIP TRUST FUND.

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount (as per last Account)	2,155	14	10	By Investments (at cost) :—			
				£1,528 5s. 1d. New South Wales 5% Stock (1935–55)	1,585	1	4
				£500 Cape of Good Hope 3½% Stock (1929–49)	570	13	6
	£2,155	14	10		£2,155	14	10

SALOMONS SCHOLARSHIP TRUST FUND (Income).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount paid to Scholars in 1929	100	0	0	By Balance (as per last Account)	41	5	1
„ Balance carried to Balance Sheet *	34	4	6	„ Dividends received in 1929	92	19	5
	£134	4	6		£134	4	6

DAVID HUGHES SCHOLARSHIP TRUST FUND.

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount (as per last Account)	2,000	0	0	By Investment (at cost) :—			
				£2,045 Metropolitan Water Board (Staines Reservoirs) 3% Guaranteed Debenture Stock (1922 or after)	1,998	15	0
				„ Balance carried to Balance Sheet *	1	5	0
	£2,000	0	0		£2,000	0	0

DAVID HUGHES SCHOLARSHIP TRUST FUND (Income).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount paid to Scholars in 1929	50	0	0	By Balance (as per last Account)	25	13	8
„ Balance carried to Balance Sheet *	36	8	11	„ Dividends received in 1929	60	14	9
				„ Interest do. do.	0	0	6
	£86	8	11		£86	8	11

PAUL SCHOLARSHIP FUND.

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount (as per last Account)	500	0	0	By Investment (at cost) :—			
„ Donation received from Mr. R. W. Paul ...	500	0	0	£625 4% Funding Loan (1960–90)	500	0	0
				„ Balance carried to Balance Sheet *	500	0	0
	£1,000	0	0		£1,000	0	0

PAUL SCHOLARSHIP FUND (Income).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount paid to Scholars in 1929	75	0	0	By Balance (as per last Account)	25	0	0
„ Balance carried to Balance Sheet *	25	0	0	„ Dividends received in 1929	25	0	0
				„ Donation received from Mr. R. W. Paul ...	50	0	0
	£100	0	0		£100	0	0

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* Included in the total of £812 5s. 10d. shown on the Liabilities side of the Balance Sheet.

WILDE BENEVOLENT TRUST FUND.

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount (as per last Account)	2,957	11	11	By Investments (at cost) :—			
„ Amount transferred from Income Account ...	92	4	3	£1,308 London and North Eastern Railway 4% First Guaranteed Stock...	1,744	3	11
				£100 London County 3½% Consolidated Stock (1929 or after)	101	8	6
				£250 New South Wales 4% Stock (1942–62) ...	251	6	0
				£500 5% War Stock (1929–47)	501	9	3
				£381 15s. 1d. 4% Funding Loan (1960–90) ...	300	0	0
				£200 3½% Conversion Stock (1961 or after) ...	151	8	6
	£3,049	16	2		£3,049	16	2

WILDE BENEVOLENT TRUST FUND (Income).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Grants made in 1929	92	0	0	By Balance (as per last Account)	156	1	6
„ Transfer to Capital in 1929	92	4	3	„ Dividends received in 1929	110	4	2
„ Balance carried to Balance Sheet*	87	17	5	„ Interest do. do.	5	16	0
	£272	1	8		£272	1	8

WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount (as per last Account)	1,700	0	0	By Investment (at cost) :—			
				£2,000 5% War Stock (1929–47)...	1,700	0	0
	£1,700	0	0		£1,700	0	0

WAR THANKSGIVING EDUCATION AND RESEARCH FUND (No. 1) (Income).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Grants made in 1929	171	5	0	By Balance (as per last Account)	146	5	0
„ Balance carried to Balance Sheet *	75	0	0	„ Dividends received in 1929	100	0	0
	£246	5	0		£246	5	0

PAGE PRIZE FUND.

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount (as per last Account)	50	19	5	By Investment (at cost) :—			
„ „ presented by Anonymous Donor ...	50	0	0	£50 5% War Stock (1929–47)	50	19	5
				„ Balance carried to Balance Sheet*	50	0	0
	£100	19	5		£100	19	5

PAGE PRIZE FUND (Income).

Dr.	£	s.	d.	Cr.	£	s.	d.
To Cost of Prize awarded in 1929	2	10	0	By Balance (as per last Account)	2	10	0
„ Balance carried to Balance Sheet *	2	10	0	„ Dividends received in 1929	2	10	0
	£5	0	0		£5	0	0

THORROWGOOD SCHOLARSHIP FUND.

Dr.	£	s.	d.	Cr.	£	s.	d.
To Amount bequeathed by the late Mr. W. J. Thorrowgood (Member)	1,000	0	0	By Investment (at cost) :—			
				£1005 Agricultural Mortgage Corporation 5% Debenture Stock	1,000	0	0
	£1,000	0	0		£1,000	0	0

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* Included in the total of £812 5s. 10d. shown on the Liabilities side of the Balance Sheet.

THE BENEVOLENT FUND OF
THE INSTITUTION OF ELECTRICAL ENGINEERS.

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR 1929.

Dr. EXPENDITURE.

	£	s.	d.
To Grants	1,538	15	0
„ Printing, Stationery, Bank Charges, Postage, etc.	17	2	9
„ Unexpended Balance carried to Balance Sheet	1,454	19	10
	£3,010	17	7

INCOME. **Cr.**

	£	s.	d.
By Dividends on Investments...	681	15	6
„ Interest	32	16	10
„ Annual Subscriptions	606	11	0
„ Donations of £5 and over...	541	0	8
„ Donations under £5	948	13	7
„ Legacy from the late Dr. C. S. du Riche Preller	100	0	0
„ Legacy from the late Mr. H. Louis Leach	100	0	0
	£3,010	17	7

BALANCE SHEET, 31ST DECEMBER, 1929.

Dr. LIABILITIES.

	£	s.	d.	£	s.	d.
To Capital Account:—						
As per last Balance Sheet	£12,068	6	10			
Amount transferred from Income in 1929	2,174	1	6			
				14,242	8	4
„ Income and Expenditure Account:—						
As per last Balance Sheet	£2,977	11	3			
Unexpended Balance in 1929	1,454	19	10			
	4,432	11	1			
Less Amount transferred to Capital in 1929	2,174	1	6			
				2,258	9	7
„ Grants authorized but not yet disbursed				93	15	0
„ **Sundry Creditors...**				63	0	2
„ Subscriptions and Donations received in advance...				5	19	6
				£16,663	12	7

ASSETS. **Cr.**

	£	s.	d.	£	s.	d.
By Investments (Capital), at cost:—						
£961 7s. 7d. Cape of Good Hope 3 % Stock (1933–43)				950	0	0
£593 1s. 7d. New South Wales 3 % Stock (1935)...				600	0	0
£420 London and North Eastern Railway 4 % First Preference Stock				503	18	3
£450 London, Midland and Scottish Railway 4 % Debenture Stock				551	0	9
£750 East Indian Railway 3½ % Debenture Stock				737	18	0
£300 London, Midland and Scottish Railway 4 % Guaranteed Stock				333	11	6
£500 New Zealand 3½ % Stock (1940)...				486	18	6
£500 Canada 3½ % Stock (1930–50)				478	16	0
£4,280 2s. 9d. 5 % War Stock (1929–47)				4,230	9	9
£350 New South Wales 4 % Stock (1942–62)...				336	18	6
£2,128 8s. 6d. 4 % Funding Stock (1960–90)...				1,624	2	0
£3,295 3½ % Conversion Stock (1961)...				2,512	11	10
£450 Commonwealth of Australia 5 % Stock (1945-75)				438	16	0
£450 Tynemouth Corporation 5 % Stock (1947-57)				457	7	3
				14,242	8	4
„ Investment (Income), at cost:—						
£1,519 17s. 3d. 5 % War Stock (1929–47)				1,552	16	4
„ Sundry Debtors				66	0	6
„ Cash:—						
At Bankers'	796	7	9			
In hand	5	19	8			
				802	7	5
				£16,663	12	7

I have audited the above Balance Sheet and Income and Expenditure Account with the Books and Vouchers and certify them to be correct, and have verified the Investments with Certificates from Bankers. The Investments, which are stated at cost, are subject to depreciation.

JAS. ATTFIELD, F.C.A.,
Honorary Auditor.

3rd April, 1930.

A THERMIONIC VALVE POTENTIOMETER FOR AUDIO FREQUENCIES.*

By W. S. STUART, M.Eng., Associate Member.

(*Paper received* 21*st November*, 1929.)

SUMMARY.

A description is given of a method of measuring audio-frequency potential vectors with the aid of thermionic valves. The arrangement used is a modification of one originally given by A. Pagès, and is adapted for tests on circuits such as artificial lines. A method of estimating the admittance existing between the input potential terminals is described.

TABLE OF CONTENTS.

Introduction.
Description of the circuit.
Admittance between the potential terminals.
General remarks on the use of the circuit.

INTRODUCTION.

The measurement of audio-frequency potential vectors is conveniently carried out by means of the well-known circuit, described by Larsen,† in which the e.m.f. derived from the secondary coil of a variable mutual inductance is added to the potential-drop across a pure resistance in series with its primary coil. The total potential provided by this arrangement, which is thus of the form $(R + j\omega M)I$, where I is the current carried by the resistance and primary coil, is balanced against the potential to be measured, the detector being usually a telephone. Balance is effected by simultaneous adjustment of the resistance and mutual inductance, the former measuring the horizontal component and the latter the vertical component of the potential vector, with reference to the phase of the current passing through the circuit.

Larsen, in the paper referred to above, has drawn attention to the care necessary to avoid the effects of stray capacities, particularly in connection with the detector. The disturbing effects of body capacity when telephones are used are well known to users of a.c. bridges, and while, in the case of the bridge, capacity effects may be annulled by taking suitable precautions, there is little doubt that in the potentiometer circuit here considered the capacity existing between the detector and earth may seriously affect the accuracy of a reading. The effect is particularly marked when the method is used to measure the potential developed in a circuit of high impedance.

The difficulty is removed if use is made of triode valves, in that, since the detector is placed in the anode circuit of a valve, its capacity is not thrown across any part of the circuit containing the measuring instruments.

A scheme involving the use of two triodes for this purpose is shown in its simplest form in Fig. 1, the triodes having identical characteristics. The potential to be measured is applied between the grid and filament of V_1, while an equal and opposite potential, derived from the combination of resistance and mutual inductance, is applied to the grid of V_2. Balance is effected by adjusting for silence in the telephone which is common to both anodes.

A practical potentiometer based on this principle has been described by A. Pagès,* in which a mutual inductance with central zero is used, the arrangement thus permitting the measurement of potential vectors lying within ± 90° of the potentiometer current vector.

In conducting experiments with an artificial telephone line, the author found it desirable to have a potentiometer with which rapid measurements of potential vectors lying in any quadrant could be made, at frequencies up to 4 000 cycles per sec. After experimenting with several circuits of the type referred to above, it was finally decided to adopt one involving three triodes. This circuit, which is described below, is particularly suited to artificial-line measurement but can, of course, be used for the determination of any potential the magnitude of which is not greater than that which the valves can handle.

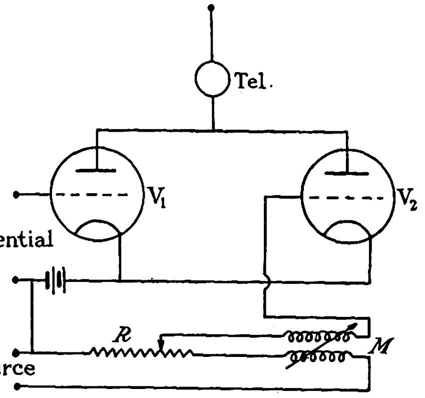

FIG. 1.

DESCRIPTION OF THE CIRCUIT.

It will be seen from the circuit diagram, Fig. 2, that the valve V_2 obtains its grid potential from the resistances R and r, the former consisting of a box with 10 sections and the latter of a slide-wire, while the grid of V_3 is connected to the secondary of the variable mutual inductance M. The primary winding of M is in series

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* The Papers Committee invite written communications, with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† *Elektrotechnische Zeitschrift*, 1910, vol. 41, p. 1039.

* *Revue Générale de l'Électricité*, 1926, vol. 19, p. 381.

with R and r, the current passing through this circuit being measured by the thermo-ammeter A. This arrangement enables one end of the secondary winding to be always at earth potential and has been found to minimize the effect of impurity due to capacity between the windings. The advantage is also secured that the switches for reversing the component potentials may be transferred to the anode circuits of their respective valves. Any errors introduced by spurious capacity effects in the grid circuits are thus made definite and may be allowed for if necessary.

The anodes of the valves are connected respectively to three identical coils, L_1, L_2, L_3, mutually coupled by being wound on a ring-shaped iron core. Provided that the mutual conductances of the valves are similar, an e.m.f. applied to the grid of V_1 (i.e. between the terminals E and E′) may be balanced by the component e.m.f.'s applied to the grids of V_2 and V_3, when the alternating m.m.f.'s due to L_2 and L_3 exactly balance that due to L_1. Under balance conditions the anode circuits are therefore non-inductive. A fourth winding L_4, connected to a telephone, serves to detect the condition of balance.

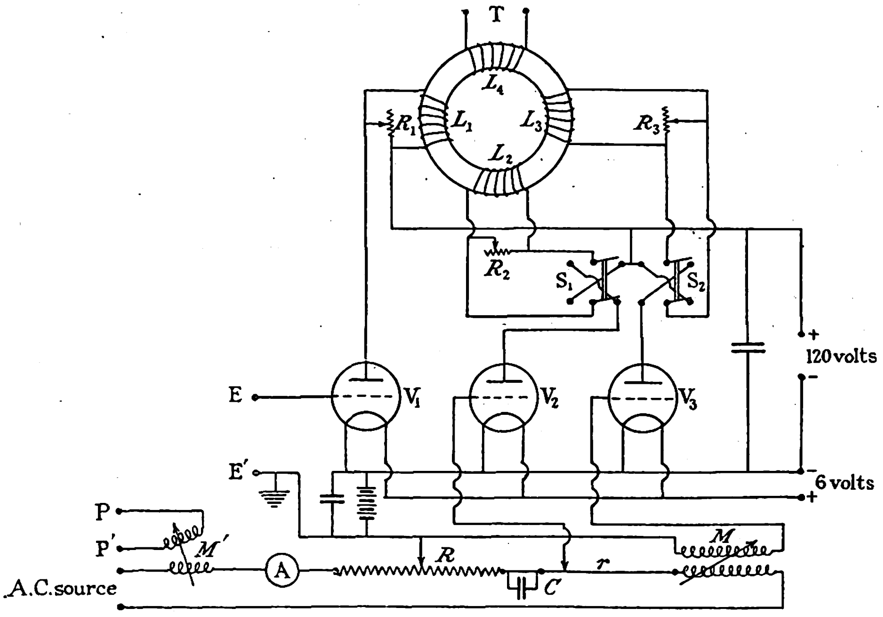

FIG. 2.

It is, of course, essential that the variations of anode current for a given grid voltage, i.e. the mutual conductance, should be the same for each of the three valves. The author attempted to adjust this, in the first place, by varying the filament currents. It was quickly discovered, however, that valves having nominally similar characteristics were actually so different in respect of their mutual conductances that the process of balancing by means of the filament current led, in the case of many valves, to a reduction of the emission below the minimum which could be tolerated. It was finally decided to balance the magnification by means of variable resistances shunting the anode coils as shown. This method was found to be quite satisfactory in practice, since, if the anode coils are tightly coupled, the resistances may be widely different from one another without introducing phase-angle errors.

A variable mutual inductance, shown at M', supplies current from its secondary winding for the circuit under test. In the apparatus as set up by the author the anode coils have 150 turns each, three wires being wound in parallel and uniformly distributed round the ring-shaped core. The latter is built up with 20 laminations of mumetal, having an outside diameter of 5·5 in. and an inside diameter of 3·75 in. The thickness of each lamination is 0·0225 in. The winding L_4 has 500 turns, wound on top of the others. The valves have an a.c. resistance of approximately 3 000 ohms, and with a grid potential of −12 volts pass a current of 12 mA. The anode potential is 120 volts. The resistances R_1, R_2, R_3 are continuously variable and have a maximum value of 5 ohms.

An oscillator of the heterodyne type is used to supply the potentiometer current, which is normally 30 mA. The resistance R consists of 10 sections of 10 ohms each, while the slide-wire r, 1 metre in length, is adjusted also to 10 ohms. The maximum potential which can be balanced by the resistance component is thus 3·3 volts. The mutual inductance M is a standard Campbell inductometer having a maximum value of 11·1 mH.

The employment of a mutual inductance makes the accuracy of the method dependent on an exact knowledge of the frequency. A stretched-wire vibrator,[*] calibrated by tuning-forks, has been used with success, it having been found possible to determine, to an accuracy of ±0·5 per cent, frequencies which are fundamental or are multiples of the fundamental. An alternative method is to make use of a condenser, shown at C in Fig. 2, inserted in the slide-wire circuit. With R and

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[*] P. K. TURNER: "A Wireless Works Laboratory," *Journal I.E.E.*, 1927, vol. 65, p. 881.

r set at zero, and the filament of V_1 extinguished, a balance can be obtained by adjustment of M. Provided that the phase angle of C is not large, there is no difficulty in arriving at an accurate setting of the inductometer. The frequency is then given by

$$\omega = \frac{1}{\sqrt{(MC)}}$$

ADMITTANCE BETWEEN THE POTENTIAL TERMINALS.

Since one of the most important properties of the 3-electrode valve is the small input admittance of the grid-filament circuit, its utility as a potential-measuring device in association with high-impedance circuits is without question. It is important, however, to know the magnitude of this admittance, so that allowance can be made for it if necessary, e.g. in the measurement of small capacities, and the amount of error introduced by neglecting it, in other cases, known. The admittance of the valve V_1 may be measured in the following way:—

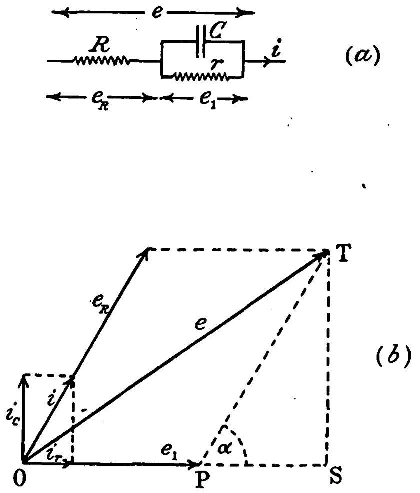

FIG. 3.

The e.m.f. obtained from the terminals P and P′ is measured by connecting these terminals respectively to E and E′. A known pure resistance of the order of 2 megohms is then inserted between P and E and a fresh balance obtained. In this way are obtained the vector voltages which are shown as e and e_1 in Fig. 3(a). In this diagram the valve admittance is represented as a capacity C shunted by a resistance r. The drop across the inserted resistance R is shown as e_R. It is, of course, assumed that the voltage e remains at the same value throughout. Then, referring to the vector diagram, Fig. 3(b),

$$\frac{e_R}{e_1} = R\sqrt{\left[(C\omega)^2 + \frac{1}{r^2}\right]} = \frac{R}{r}\sqrt{[(C\omega r)^2 + 1]}$$

or

$$\frac{(C\omega r)^2 + 1}{r^2} = \frac{1}{R^2}\left(\frac{e_R}{e_1}\right)^2$$

and, since $\tan \alpha = C\omega r$,

$$\frac{\tan^2 \alpha + 1}{r^2} = \left(\frac{e_R}{Re_1}\right)^2 = \frac{1}{r^2 \cos^2 \alpha}$$

or $$r = \frac{Re_1}{e_R \cos \alpha} \quad \text{and in the figure is } R \cdot \frac{\mathrm{OP}}{\mathrm{PS}}$$

also $$C = \frac{\tan \alpha}{\omega r} = \frac{\tan \alpha \,.\, e_R \cos \alpha}{\omega R e_1} = \frac{e_R \,.\, \sin \alpha}{\omega R e_1}$$

and in the figure is $$\frac{1}{\omega R} \cdot \frac{\mathrm{TS}}{\mathrm{OP}}$$

The values of C and r may thus be conveniently obtained by plotting on squared paper the vectors e and e_1 as given by the potentiometer readings. In performing this test on various valves in the position V_1, it was found that the holder and also the cap of the valve contributed in no small degree to the total admittance.* The following figures show the results of tests, at 2 000 cycles, on a valve having the characteristics referred to above. The resistance R used in the grid circuit was of the grid-leak type and had a value of 1·84 megohms.

	C	r	cos α
	μμF	MΩ	
Valve with cap and holder	22·7	31	0·11
Valve with cap only ..	14·6	54	0·10
Valve without cap and holder	12·2	92	0·07

These figures show the desirability of dispensing with the ordinary mounting of the valve, and the apparatus in its final form now has the valve V_1 supported by means of the bulb, so that direct connection can be made to the grid lead which comes through the glass. The valves V_2 and V_3 are held in ordinary holders.

GENERAL REMARKS ON THE USE OF THE CIRCUIT.

In the setting up of the apparatus it is important to guard against the influence of stray magnetic fields. Unless care was taken to keep these components well separated, it was found that a considerable amount of coupling took place between the inductances M and M' and the anode coils, notwithstanding the toroidal shape of the latter.

The anode shunting resistances are set in the following way:—The grid of V_1 is joined to that of V_2, and a potential is applied to both from the resistance box R. With the switch S_2 open, and S_1 closed in the "first quadrant" position, R_1 and R_2 are adjusted until silence is obtained in the telephone. The grid of V_1 is then connected to that of V_3 and a potential applied to both from M, the switch S_1 now being open and S_2 closed in its "first quadrant" position. Adjustment is now made to R_3 for silence. The adjustment is quite critical, and these rheostats should therefore be capable of continuous variation. Care should be taken to earth the common negative connection to the batteries as shown in Fig. 2.

When taking a reading of potential, the quadrant in which the vector lies may be determined from the position of the switches. It will be evident that when these switches are both in the "first quadrant" position the connection to the anode coils should be such that the magnetic effects of L_2 and L_3 are additive, while both are in opposition to L_1. As in the case of the valve voltmeter, the circuit connected to the input terminals must be a conducting one, in order that the grid-bias voltage may be applied to V_1. It will be found desirable to use a bias battery of rather less voltage than is customary when the valves are connected in an ordinary amplifying circuit, since in the present case the external anode impedance is almost zero.

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* L. HARTSHORN: *Proceedings of the Physical Society of London*, 1927, vol. 39, p. 108; also G. W. SUTTON, *ibid.*, 1927, vol. 40, p. 14.

The by-pass condensers shown in the circuit diagram are preferably of large size in order to guard against the effects of unduly high resistance in the batteries.

It has been found possible to read values of potential, over the greater part of the range of telephonic frequencies, with a possible error of 1 mV on either scale. At frequencies below 200, on account of lack of sensitivity in the telephone it will be found advisable to employ a slide-wire current of greater value than the normal, or alternatively to use an amplifier in the telephone circuit.

The author wishes to express his indebtedness to the authorities of the University of Leeds for placing at his disposal workshop and testing facilities, and for permission to describe the apparatus.

AN ACCURATE METHOD OF TESTING BENT PERMANENT MAGNETS.[*]

By C. E. Webb, B.Sc. (Eng.), Associate Member, and L. H. Ford, B.Sc. (Eng.).

[From the National Physical Laboratory.]

(*Paper first received 15th October, and in final form 11th December, 1929.*)

SUMMARY.

The application of the search-coil method of measuring H to the testing of bent magnets by the use of jointed coils is fully described. The effects of distribution of magnetizing coils, location of search coils, reluctance of the joint between magnet and armature, and radial variation of magnetizing force are examined and the conditions for the maximum accuracy of measurement are determined.

LIST OF SYMBOLS.

H_m = maximum magnetizing force applied to magnet.
B_m = maximum flux density produced.
H_{res} = magnetizing force acting after magnetizing current is switched off.
B_{res} = flux density after magnetizing current is switched off.
B_r = remanence.
H_c = coercive force.
B_c = local flux density when mean flux density = 0.
A = area of cross-section of coil.
S = number of turns in coil.

INTRODUCTION.

Commercial tests on bent magnets—particularly on magneto magnets of horseshoe shape—are usually carried out by comparison with a standard of similar pattern to the magnet to be tested. The calibration of such standards involves the use of an absolute method of measurement, and presents considerably greater difficulties than the testing of samples of simple ring or bar form owing to the non-uniformity of the magnetic circuit which the bent magnets provide.

The application to horseshoe magnets of the search-coil method for measuring H by the use of flat coils placed inside and outside the magnet at the middle of the bend was suggested by A. Campbell and D. W. Dye,[†] and a further development, by the introduction of flexible coils, was described by D. W. Dye in the *Dictionary of Applied Physics*.[‡]

The method used in the present investigation was the same, apart from slight modifications in the construction of the search coils, as that described by Dye, and the measurements recorded were made with the object of determining the conditions for the highest accuracy by this method.

DESCRIPTION OF THE METHOD.

(1) *Search Coils.*—The measurement of the magnetizing force, H, by means of search coils depends on the fact that, with uniform magnetization, H in the iron is equal to H in the air adjacent to the surface of the iron and may, therefore, be measured by a thin coil placed tangentially very close to the iron, with its axis parallel to the lines of force. The coil is connected to a ballistic galvanometer and the deflection noted when the magnetizing current is reversed or altered, exactly as in the measurement of B.

For bent magnets, therefore, a coil having the shape of the magnet is essential. The accurate determination of the product of cross-section and number of turns, AS, is impracticable, however, on a bent search coil, but may readily be carried out in a long solenoid on a straight coil. Thus for satisfactory calibration, and also to allow of the same coil being used on magnets of different curvature, the coils must be flexible. A winding on a strip of press-spahn or similar material fulfils this condition, but it is difficult to be sure that distortion of the winding does not occur when the strip is bent, with consequent change in the value of AS from that found when calibrating. To obviate this source of error, search coils made up of short, rigid sections flexibly joined together are used. Each section is wound on a glass slip approximately 1 cm long and of a width suitable for the particular magnet under test (normally about 4 cm). The glass slips are first mounted in a cradle of silk ribbons about 5 mm wide, each ribbon passing alternately above and below successive slips, and being attached at the ends to two strips of linen tape. A flexible chain of glass slips is thus formed (Fig. 1). Silk-covered wire of fine gauge (44 S.W.G. usually) is then wound on the glass to form a flexible coil of which one section is shown in the figure. The whole is impregnated with wax to prevent the wire from coming away from the ends of the glass, and each section is covered with a binding of waxed silk for protection.

Two such complete coils are used, one on the outside and one on the inside of the magnet. To make the lengths along the magnet spanned by the two coils approximately equal without affecting the equality of the product AS, small glass rods are inserted between each pair of successive glass slips in the outer coil before winding. Two pairs of these jointed coils are used in the investigation, a long pair each of ten sections, approximately 14 cm in length and having a total AS of 650, and a short pair, each of five sections, approximately 6 cm in length and having a total AS of 280.

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] "The Magnetic Testing of Bars of Straight or Curved Form," *Journal I.E.E.*, 1915, vol. 54, p. 35.

[‡] Vol. 2: article on "Magnetic Measurements and Properties of Materials," pp. 465, 492.

The *B* search-coil consists of five or six turns of fine wire wound, over a layer of waxed silk, directly on the magnet and covering a length equal to that spanned by the *H* coils, which are placed as close to the magnet as possible, outside the *B* coil.

(2) *Magnetizing Coils and Armature.*—To obviate the labour of winding a magnetizing coil on the magnet for each test, a set of coils was made which could be slipped on over the search coils and connected together to form a continuous winding. These consist normally of four specially shaped coils—two, for the bend, of sector shape, and two, for the limbs, with sloped tops to fit closely against the sector-shaped coils (Fig. 2). These coils are designed to fill the space between the limbs of the magnet as completely as possible.

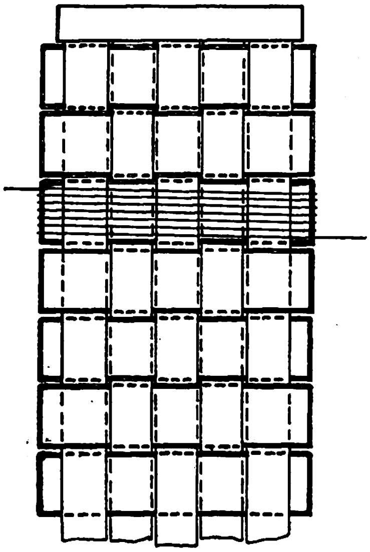

Fig. 1.—Construction of jointed search coils.

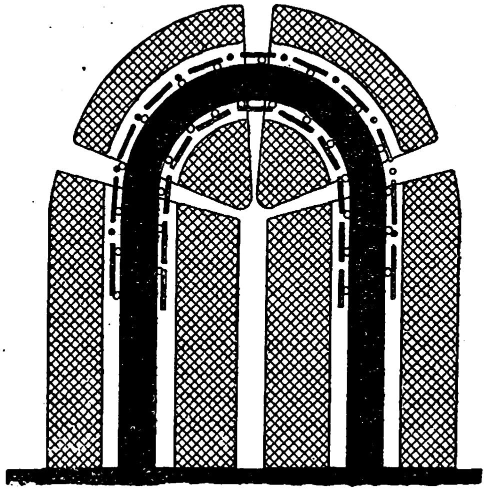

Fig. 2.—Arrangement of magnetizing coils and search coils on horseshoe magnet.

The armature for a magnet of normal length is a flat block built up of stalloy strips placed edgewise to the passage of flux and bolted together. The strips were annealed and subsequently lightly ground to give a flat surface of contact. For short magnets a U-shaped armature of soft iron annealed after cutting, and with ground faces, is used.

(3) *Method of Making Measurements.*—The value of the area-turns, *AS*, having been determined by standard methods for the *H* and *B* search coils, the ballistic galvanometer is adjusted by means of variable shunt and series resistances to be direct-reading for *H* and *B*. The magnetizing current is set to give the required maximum *H*, usually about 400 C.G.S. units, and this, together with the corresponding value of *B*, is measured by reversing the current with the *H* and *B* coils successively connected to the galvanometer. The magnetizing current is next switched off and the resultant values of demagnetizing field, H_{res}, and residual flux density, B_{res}, are measured. Further points on the hysteresis loop are then found by switching on suitable values of magnetizing current and noting corresponding changes of *H* and *B*. From the complete curves thus obtained the remanence, B_r, and coercive force, H_c, are deduced.

Description of Tests Made.

In the course of the investigation, tests were made on three horseshoe magnets having respectively no hole, one hole and two holes on each limb. Particulars of these are given in Table 1.

Table 1.

Magnet No.	Mean length	Section	No. of holes in each limb
	cm	cm^2	
1	23·4	3·55	None
2	27·1	4·4	1—approx. $\frac{3}{8}$ in. diam.
3	32·7	4·0	2—approx. $\frac{1}{4}$ in. diam.

(*a*) *Method of Magnetization.*—To check whether sufficiently uniform magnetization is provided by the made-up magnetizing coils, comparative tests were carried out with the made-up coils and with a winding of stout flexible cord wound as uniformly as possible along the length of the magnet. The results of measurements made on magnet No. 3 with short *H* coils placed first on the bend and secondly on the limb are given in Table 2, cols. (1) and (2). Agreement within 1 per cent between the two tests is shown, which is as good as can be expected on this form of test-piece after completely dismantling the magnetic and electric circuits and setting them up again.

It is not uncommon in testing horseshoe magnets to magnetize by means of coils on the limbs only. Further tests were therefore made, using only the two made-up coils which fit on the limbs. The results, recorded in Table 2, col. (3), show that, with search coils on the limbs, good agreement with the previous tests is obtained for coercive force, but appreciably lower values of B_m and B_r are found. As in this test only the limbs were subjected to the full magnetizing force ($H_m = 400$), this reduction may be due to incomplete magnetization of the bend producing non-uniform magnetization along the limb. The long *H* coils were therefore placed on the bend of the magnet and additional measurements were made both with the complete set of magnetizing coils and with coils on the limbs only. In this case the mean magnetizing force along the bend was raised to the maximum value of 400 (H_m on the limbs being considerably higher with magnetizing coils on the limbs only) and the results, given in Table 2, cols. (2) and (3), show very close agreement between the two tests. To obtain accurate measurements, therefore, it is important to subject the whole length of the magnet to a sufficiently high H_m, to ensure that the remanent flux density and the coercive force reach their maximum values at every point.

Provided that this condition is fulfilled, the location of the magnetizing coils produces a negligible effect even with such a non-uniform magnetization as is provided by coils on the limbs only. In all subsequent tests, therefore, made-up magnetizing coils were used.

TABLE 2.

Search coils	Quantity measured	(1) Uniform flexible winding	(2) Made-up coils	(3) Coils on limbs only
Short—on bend	B_m	14 930	14 910	—
	B_r	10 450	10 430	—
	H_c	63·6	63·0	—
Short—on limb	B_m	14 980	14 900	14 620
	B_r	10 140	10 120	9 640
	H_c	61·4	62·0	61·7
Long—on bend	B_m	—	15 340	15 190
	B_r	—	10 580	10 560
	H_c	—	62·0	62·3

(*b*) *Location of Search Coils.*—Comparative tests were made on each magnet with short search coils located entirely on the bend and also on the limbs, and with long search coils placed symmetrically on the magnet so as to embrace the bend and a portion of each limb. The results obtained are given in Table 3, cols. (1), (2) and (3).

TABLE 3.

Magnet	Quantity measured	(1) Short coils on limbs	(2) Short coils on bend	(3) Long coils	(4) Coils at join of limbs and bend
No. 1	B_m	16 100	16 070	16 030	—
	B_r	10 620	10 620	10 580	—
	H_c	59·1	59·1	59·6	—
No. 2	B_m	15 800	15 860	16 000	16 400
	B_r	10 370	10 920	11 000	11 120
	H_c	49·9	49·2	48·1	44·2
No. 3	B_m	14 900	14 910	15 340	15 890
	B_r	10 120	10 430	10 580	10 770
	H_c	62·0	63·0	62·0	58·0

It will be seen that on magnet No. 1 very close agreement is obtained between the tests on limbs and bend, while the test with long search coils also gives substantially the same results.

On magnets Nos. 2 and 3, however, the remanence values obtained on the limbs are considerably lower than those found on the bend. The tests with the long search coils on these two magnets also, somewhat surprisingly, give values of B_m and B_r higher than those found either on the limbs or on the bend. As there was a small gap between the portions of the magnet covered by the search coils in the separate tests on bend and limbs, a further set of measurements was made on this intervening length at the join of the bend and limb using a pair of very short H coils, about 1 cm long and approximately equivalent to one section of the jointed coils. As the AS value of these coils was small, the accuracy of this test was less than usual, but the results, recorded in Table 3, col. (4), appear to show conclusively that on magnets Nos. 2 and 3 higher values of B_m and B_r and lower values of H_c are obtained at the join of the bend and limbs than on either the bend or the limbs. Thus the material at such a point is appreciably softer than throughout the rest of the magnet. As this portion is included in the length tested by the long coils, the higher values of B_m and B_r recorded in Table 3, col. (3), are doubtless due to this difference in properties.

To show in more detail the variation of flux density along the magnet under various conditions of magnetization, a number of tests were made with localized B coils spaced 1 cm apart along half the length of the magnet. Measurements were made, with each coil, of the flux density at maximum magnetization (B_m), at switch-off (B_{res}), and when the mean B along the magnet was reduced to zero (B_c).

The results obtained on magnets Nos. 1 and 3 are plotted in Figs. 3 and 4 on a base-line having the shape of the axis of the magnet. For each curve the base-line is taken to represent the mean value along the whole magnet of the quantity in question, and the difference from this mean value is plotted normally to the base-line at each point, an excess being plotted outwards and a deficiency inwards.

The curves of B_m show that with made-up coils the bend is appreciably less highly magnetized than the limbs, owing to the limited space available for the magnetizing coils on the bend. The curves of B_{res} and B_c, however, show very constant values on the bend, with a fairly uniform decrease along the limb. A few measurements were also made of the distribution of B along the magnet when magnetized to the point on the negative part of the loop giving the maximum value of the product BH. A curve very similar in shape to those for B_{res} and B_c was obtained. As would be expected, the holes in magnet No. 3 cause considerable local variations in B_m and B_{res}, but have little effect on B_c.

All these measurements of B were referred to the mean value of H for the whole length of the magnet as given by a pair of long coils covering one limb and half the bend. The actual value of H varies to some extent along the magnet, and an attempt was made to investigate these variations, particularly at switch-off (H_{res}). For this purpose two very short H coils were placed successively over the various localized B coils, but owing to the necessity for dismantling the set-up after each test in order to move the H coils there was some uncertainty as to whether identical conditions of joint reluctance were obtained in all the tests. The results, however, indicated clearly that H_{res} had a larger negative value near the end of the limb than on the bend. Thus, although B_{res} is lower near the end of the limb than on the bend, the values of true remanence, B_r, deduced from local tests at the two points would be in much better agreement. In fact, Table 3 shows that on magnet No. 1 tests on the limbs and bend gave exact agreement for B_r. The lower values of B_r on the limbs than on the bend, shown by the same table for magnets Nos. 2 and 3, are explained by the effects of the holes in the limbs of these magnets.

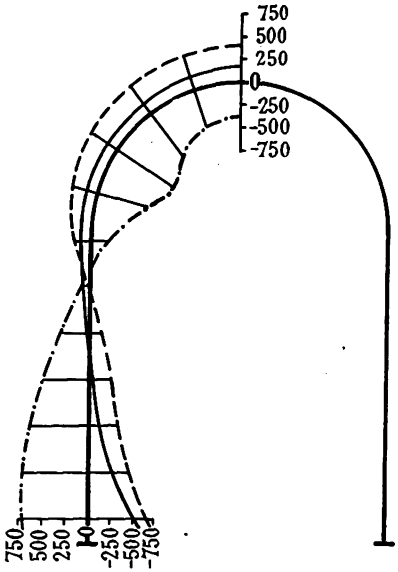

FIG. 3.—Distribution of flux along magnet without holes (No. 1).

— · — · — B_m
———— B_{res}
- - - - - - B_c

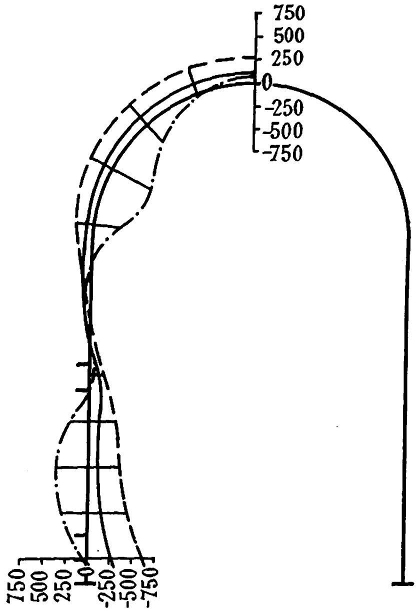

FIG. 4—Distribution of flux along magnet with two holes (No. 3).

— · — · — B_m
———— B_{res}
- - - - - - B_c

(*c*) *Variation in Reluctance of Joints.*—The reluctance of the joint between the ends of the magnet and the armature influences the demagnetizing field along the magnet when the magnetizing current is switched off, i.e. H_{res}. To determine whether an alteration in H_{res} affects the results, tests were made with the joint reluctance increased by the insertion of paper between the magnet and its armature. The results are given in Table 4 and show that while the value found for the coercive force is unaffected by the magnitude of H_{res}, at least up to $H_{res} = 20$, the apparent remanence decreases as the negative value of H_{res} increases. The decrease, however, is very small for search coils on the bend, but becomes large for search coils on the limbs.

TABLE 4.

Search coils	Quantity measured	(1) No paper inserted	(2) 0·3 mm paper inserted	(3) 0·7 mm paper inserted
Long—on bend	H_{res}	$-7{\cdot}_0$	$-13{\cdot}_0$	$-21{\cdot}_8$
	B_r	10 500	10 480	10 440
	H_c	$62{\cdot}_0$	$62{\cdot}_0$	$61{\cdot}_8$
Short—on limbs	H_{res}	$-1{\cdot}_0$	$-11{\cdot}_4$	$-25{\cdot}_4$
	B_r	9 640	9 360	9 120
	H_c	$61{\cdot}_4$	$61{\cdot}_4$	$61{\cdot}_4$

Curves showing the variation of B_m, B_{res} and B_c along magnet No. 1 were also taken with a very large joint reluctance giving a value of $H_{res} = -30$, and are shown in Fig. 5. A comparison with Fig. 3 indicates clearly the increased variation in B_{res} along the magnet and the almost complete identity of the curve of B_c in the two cases. It will be seen, however, that B_{res} remains nearly constant along the bend, thus explaining the very small change of apparent remanence with increased joint reluctance when the measurements are made on the bend.

(*d*) *Radial Variation in Field.*—The difference between the magnetizing fields inside and outside the bend of a magnet was measured by mounting two short jointed H coils on the bend and connecting them separately to the ballistic galvanometer. The difference was practically a constant percentage of H and its magnitude in the readings of coercive force is shown in Table 5.

TABLE 5.

Magnet	Inner H	Outer H	Mean H
No. 2	$59{\cdot}_1$	$39{\cdot}_3$	$49{\cdot}_2$
No. 3	$76{\cdot}_0$	$50{\cdot}_0$	$63{\cdot}_0$

Appreciable error may be caused by averaging over such a wide range of H where the curvature of the hysteresis loop is large. To indicate the magnitude of such errors, measurements were made on the negative part of the loop in the region of $(BH)_{max.}$ on the bend and limb of magnet No. 1, which give agreement for remanence and coercive force (Table 3). The results in Table 6 show a small effect, though there may, of course, be a genuine difference between the shapes of the loops for bend and limb superimposed upon the error due to averaging over a range of B and H.

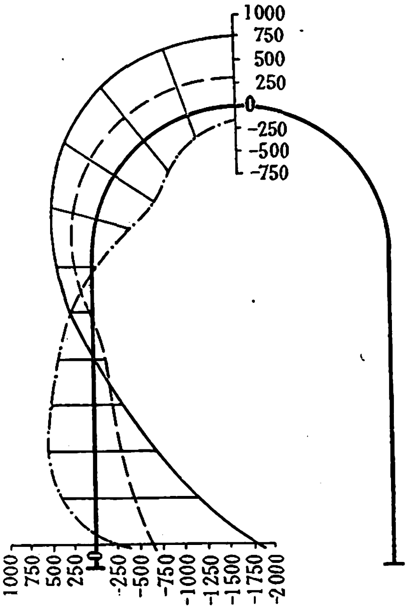

FIG. 5.—Distribution of flux along Magnet No. 1 with large joint-reluctance.

— · — · — B_m

———— B_{res}

- - - - - - B_c

TABLE 6.

Magnet	B	H on bend	H on limb
No. 1	10 620	0	0
	7 500	− 36·5	− 36·9
	5 000	− 48·1	− 48·9
	0	− 59·1	− 59·1

DISCUSSION OF RESULTS, AND CONCLUSIONS.

The use of made-up magnetizing coils is first justified by the fact that, although they provide less magnetization on the bend than on the limbs, the comparison with a uniform winding of flexible cord in Table 2 shows identical results with each winding within the limits of accuracy of the measurements. Even with the coil sections on the bend removed, satisfactory results can be obtained, provided the maximum magnetizing force at every point of the magnet is sufficiently large to ensure that the remanent flux density and the coercive force reach the values which they would attain after saturation.

The results obtained at the join of the limbs and bend [Table 3, col. (4)] indicate that some variation in magnetic properties may occur along the magnet, but comparison between the results on limbs and bend in Table 3, cols. (1) and (2), shows very good agreement except for the effect on the values of remanence of the holes in the limbs of Nos. 2 and 3. This may be minimized by plugging the holes with small pieces of magnet-steel, but the effect of this operation is somewhat indeterminate. An alternative and more satisfactory method of avoiding the effects of the holes is to use long search coils covering the bend and the upper part of the limbs but not extending as far as the holes. A comparison of Table 3, col. (3), with cols. (1), (2) and (4), shows that these give results practically unaffected by the presence of holes.

The effect of a large joint-reluctance between magnet and armature, such as might result from badly ground poles, was also shown to be almost negligible on the results obtained with this arrangement of search coils, but to be considerable on those given by search coils on the limbs. Confirmation of the uniformity of the conditions around the bend and their comparative immunity from the influence of extraneous variations is given by the curves of distribution of B_m, B_{res} and B_c along the magnet in Figs. 3, 4 and 5.

The use of long search coils on the bend and upper part of the limbs only, is further justified by the fact that pole-shoes are normally fitted to the limbs of horseshoe magnets so that only the bend and a short part of the limb are fully effective in use.

The magnitude of the radial variation of H observed on the bend (Table 5) shows the importance of obtaining a true average of the values of H at the inner and outer surfaces of the iron. For this purpose, the values of the product AS must be made as nearly as possible equal for the inner and outer H coils, and it is also desirable that they should span the same portion of the magnet, i.e. that the outer coil should be a sufficient amount longer to allow for the greater radius on the bend. The good agreement obtained for the coercive force between the bend and the limb (where the radial variation does not occur) suggests that a satisfactory average of the inner and outer values has been obtained. Moreover, the influence of the radial variation would be less with the long search coils than that shown in Table 5, since the effect on the bend would be diluted by the parts of the coils on the limbs.

The conclusions reached are, therefore:—

(i) The use of made-up magnetizing coils is satisfactory, provided sufficient magnetization is applied along the whole magnet.

(ii) The most reliable results are obtained using search coils covering the bend and a short length of each limb, and avoiding any holes in the magnet. A length of 12 to 15 cm is suitable for the normal size of magnet.

(iii) High joint-reluctance of a magnitude likely to occur in practice produces only a negligible effect on the results if the above arrangement of search coils is used.

(iv) The inner and outer H coils must have as nearly as possible equal area-turns and should be adjusted in length to span the same portion of the magnet.

(v) The results recorded suggest that, when attention has been paid to the previous conclusions, the values obtained are accurate within 2 per cent.

In conclusion, the authors desire to express their hearty thanks to Dr. D. W. Dye, F.R.S., for helpful suggestions and criticisms in the course of the investigation.

DISCUSSION ON

"IMPEDANCE AND POWER LOSSES OF 3-PHASE OVERHEAD LINES." *

Mr. C. G. Carrothers (*communicated*): I notice that the authors confine their calculations to the reactance of the lines to symmetrical 3-phase currents and to the special case of one conductor of a line carrying a single-phase current with earth return. For short-circuit calculations it is more useful to know the reactance of the three conductors of the line carrying a single-phase current in equal parts with earth return, i.e. the reactance of the line to a symmetrical leakage current. In making short-circuit calculations a great deal of complication is avoided if it is possible to ignore the asymmetry of the lines and the difference in direction of the impedance vectors of the various parts of the circuits concerned. Several types of short-circuit calculating table depend for their accuracy on the admissibility of such assumptions. It would therefore be a very useful extension to the report if the authors would examine the errors involved by the approximations commonly made in the calculations of short-circuit currents.

Mr. E. Parry (*communicated*): There appears to be a conflict of evidence as to whether or not the inductance per unit length of a conductor with an earth return varies with the length of the line. I have some records of experiments by Nishi and Mori in Japan, according to which the inductance per unit length, and hence the depth of the virtual earth plane, varied with the length, and thus established the validity of Prof. H. Ho's equations.† On the other hand, the experiments of Mayr ‡ and Rüdenberg § afford evidence to the contrary, and point to the fact that the inductance per unit length is independent of the length of the line. Possibly the authors may be able to account for these discrepancies. Personally I have a suspicion that the cause of the conflict is to be found in the peculiarities of the terminal earth contacts. According to Heaviside || the d.c. resistance between two hemispherical electrodes of radius a placed on the surface of a homogeneous solid is $\rho/(\pi a)$, or $\rho/(2\pi a)$ per electrode, where ρ is the specific resistance of the material. It follows that one-half of the resistance lies between the electrode and the surface at a radius of $2a$, three-fourths at a radius of $4a$ and nine-tenths at a radius of $10a$, and consequently the resistance for a given radius depends materially upon the specific resistance of the soil in the vicinity of the electrode. Also the smaller the electrode the greater the variation in the resistance, for if we compare two electrodes of radii 1 in. and 12 in. respectively, 90 per cent of the resistance lies within a radius of 10 in. in one case, and within 120 in. in the other, but the variation in specific resistance is much greater in a depth of 10 in. than it is in a depth of 120 in. I do not think that the specific resistance of the general mass of earth near the earth's surface varies very much, but if account is not taken of the peculiarities mentioned above it may appear to do so, and different experiments will obtain values for the apparent specific resistance which will show a wide range of variation. The conditions favourable to a good earth connection are rare and are often a matter of considerable difficulty and expense, and for this reason the use of multiple earthing as advocated by the authors is to be commended. Has the earth resistance between pairs of towers on the grid system been measured, and, if so, what are the values? The results of such measurements are often surprising.

Messrs. P. D. Morgan and **S. Whitehead** (*in reply*): Replying to Mr. Parry, an earth current will have a theoretically uniform flow only when the earth plates are infinitely large or infinitely distant. In practice, however, substantially uniform flow, at any rate as far as impedance measurements are concerned, is attained under much less rigorous conditions depending upon the nature of the earth plates and upon the specific resistance of the soil. Tests made in Germany at Doberitz, Oldenburg and Munsingen, which gave a wide variation of local soil conditions, confirmed that, subject to an initial "earth plate resistance" the impedance and mutual inductance of the earth current were proportional to the length of line for lengths of the order of a few km.* On the other hand, it is not surprising if non-uniformity were to be observed when short distances in soil of high resistivity are considered or where local variations in geological structure occur. Our experiments gave agreement with theories based on the assumption of uniform flow, together with terminal earth-plate resistances. In the case of the Runcorn line the earth-plate resistances could not be measured directly, since the earth wire could not be disconnected. The resistances were, however, of the order of a fraction of an ohm by deduction from test-results and from the experience of the Mersey Power Co. Such low values were to be expected since the foundations of many of the towers were submerged in salt water at high tide. A number of measurements

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* Paper by Messrs. P. D. Morgan and S. Whitehead (see page 367).

† See Bibliography, (20).

‡ *Ibid.*, (23).

§ *Ibid.*, (24).

|| "Electrical Papers," vol. 1, p. 194.

* See Report to the 8th Sub-Committee of the C.C.I., 1928, and Report 32 to Paris High Tension Conference, 1929, by Dr. Klewe.

were made on the Bedford–Little Barford line. The resistance from tower to tower was not measured but the subsidiary electrodes were distant 50 and 100 ft. respectively from the tower. Accordingly, the specimen figures given in Table A may be of interest. The impedances in Table A are at 50 periods per sec. As stated in the paper, the average value of the resistance of the earth plate and foundation in parallel was 2·5 ohms. It is to be noted that when the earth resistance was so connected that all the towers (about 50 in this case) were earthed in parallel, the resistance to earth at any given tower showed little variation, the figures of 0·76 and 0·38 ohm representing extreme values observed. It thus appears that the variation mentioned by Mr. Parry is to a large extent removed by multiple earthing and also by the use of earth grillage and Malone anchor foundations as on the "grid" system, several cases occurring where the earth plate was less efficient than the tower foundations. It may also interest Mr. Parry to know that with alternating current the earth-plate impedance is often partly reactive. In the theory developed by us for the effect of an earth wire the error due to this cause was negligible for the cases examined experimentally.

TABLE A.

Type of foundations	Earth-plate resistance	Foundation resistance	Resistance of earth plate and foundations	Resistance to earth with earth wire attached
	ohms	ohms	ohms	ohms
Concrete ..	2·58	1·65	1·25	0·76
Earth grillage ..	No earth plate	4·7	—	—
Malone anchor..	18·8	5·2	4·8	—
Malone anchor..	0·80	0·80	0·80	0·38

Mr. Carrothers raises a matter which it is desirable to include in a discussion of the line constants of overhead lines. The impedance of an overhead line to a symmetrical leakage current, that is, the "zero-phase impedance" in the method of symmetrical co-ordinates for short-circuit calculations, may be deduced from equation (31) of Appendix III in the paper by making $I_1 = I_2 = I_3$ and evaluating $\Delta e_1/I$. This gives the impedance of phase I. In practice, however, the asymmetry of the separate lines is ignored owing to the excessive complication introduced if this is taken into consideration. The error involved is small. For example, on the grid system, assuming an earth resistivity of 10 000 ohms per cm the difference between the zero-phase impedance of the lowest phase of an untransposed line and the impedance of a transposed line which is the mean of the phase impedances in the untransposed case is as follows:—

Single-circuit Towers:—

Impedance per phase (transposed)
$= 0{\cdot}625 + 1{\cdot}61j$ ohms per mile
Modulus $= 1{\cdot}73$ ohms per mile
Impedance of lowest phase
$= 0{\cdot}634 + 1{\cdot}56j$ ohms per mile
Modulus $= 1{\cdot}68$ ohms per mile

Double-circuit Towers:—

Impedance per phase (transposed)
$= 0{\cdot}613 + 1{\cdot}63j$ ohms per mile
Modulus $= 1{\cdot}77$ ohms per mile
Impedance of lowest phase
$= 0{\cdot}595 + 1{\cdot}62j$ ohms per mile
Modulus $= 1{\cdot}74$ ohms per mile

Accordingly we shall merely give here the formula for the zero-phase impedance of a transposed line:—

$$\begin{aligned} Z_0 = R_E &+ \left\{3ww_4/(w + w_4)\right\} + j\omega\Big[A + 2 \times 10^{-9} \operatorname{logh} \\ &\left\{h_1h_2h_3/b(s_{12}s_{23}s_{31})^{\frac{2}{3}}\right\} \\ &- 2 \times 10^{-9}\Big\{w \operatorname{logh}\left(h_4^3h_1h_2h_3/s_{14}^2s_{24}^2s_{34}^2\right) \\ &+ 2j\omega\mu_4 \operatorname{logh}\left(h_4^3/s_{14}s_{24}s_{34}\right)^{\frac{1}{3}}\Big\}/(w + w_4)\Big] \text{ ohms per cm} \end{aligned}$$

The symbols employed are those of Appendix I of the paper, with the addition of the following:—

$$w = \tfrac{1}{2}\pi\omega + 2j\omega \operatorname{logh}(2/\gamma K h)10^{-9} \text{ ohms per cm}$$
$$w_4 = R_4 + j\omega\left\{A_4 + 2\operatorname{logh}(h_4/r_4)\right\}10^{-9} \text{ ohms per cm}$$
$$r_4 = \operatorname{logh}(h_1h_2h_3/s_{14}s_{24}s_{34})10^{-9} \text{ ohms per cm}$$

This formula does not take into account the inductive action of other circuits or of balanced currents flowing in the same circuit. The effect of the latter may usually be neglected in short-circuit calculations. It may be noted that a single-phase short-circuit (the case worked out in detail in the paper) may be represented as the sum of equal positive, negative and zero-phase currents, the components being in phase in the fault phase. The overall impedance is therefore $\frac{1}{3}(Z_0 + 2Z)$, if Z is the balanced 3-phase impedance. If the values already given in the paper for Z and the value for Z_0 given above are substituted, then for single-circuit towers the single-phase impedance should be 1·05 ohms per mile, which is the same as the value for the middle phase directly deduced in the paper. The question as to whether the phase rotation may be neglected and the impedance treated as pure reactances * for short-circuit calculation depends upon the type of system concerned. Calculations have been made for a specimen interconnected system using lines of the single-circuit type, and the conclusion has been reached that the complex nature of the line impedances may usually be neglected except with long lines and complicated systems, if errors of 10 per cent in the absolute values of the short-circuit currents are admissible. It may also be remarked that the zero-phase impedance is two to three times greater than the balanced-current impedance in modern high-voltage lines.

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* Suggested by Mr. Carrothers (*Electrical Review*, 1929, vol. 105, p. 309).

DISCUSSION ON

"THE ANALYSIS AND MEASUREMENT OF THE NOISE EMITTED BY MACHINERY."*

Western Centre, at Bristol, 11th November, 1929.

Mr. J. M. Bowman: It seems to me that it might have been advantageous if the authors had given some suggestions as to how to prevent noise in various types of machinery. It would have added interest to the paper and would have been useful to engineers in general. I sincerely hope, however, that the authors will continue their research work and ultimately prevent noises in our streets, and so receive the blessings of the Ministry of Transport.

Mr. S. B. Haslam: I was rather disappointed at not getting from the paper more information in regard to the steps which are being taken for the prevention of noise, but I can quite appreciate that this does not come within the scope of the paper and that there are good reasons for its exclusion. Not long ago I installed a 50-kW turbine set in a hospital and the noise effect was rather strange. The occupants of none of the wards near the generating station heard the hum at all, but the wards on the two top stories of an extension at right angles to the main block in which the station was situated were definitely affected by it. The experts who were consulted said that the noise must be due to air vibration, as ground sounds would affect the lower wards. They recommended that the station be insulated from the rest of the building by means of matchboarding with a distinct air space. This method was quite useless, so we tried filling the space with sawdust, but this again did no good. Someone then suggested trying the foundations and, after some trials and worry, a thin layer of a material called "Korfund" was placed under and around the foundations, with entire success. The only place where the hum could be heard was just outside the station. To everyone concerned it appeared to be very extraordinary that what was obviously a ground vibration should miss the two lower stories of the building, and be heard on the two upper stories. So far I have not found or heard of any reasonable explanation, and even the experts admit that little is known about it as yet.

Mr. F. O. Hunt: The paper is of great interest to one who was concerned with somewhat similar problems in anti-submarine work during the War, and I should like to congratulate the authors upon the precision attained in a difficult class of measurement and on the useful attempt to correlate the energy measurements to their effectiveness upon the ear. The investigation was complicated because extraneous noise might have opposite effects. In general, the amount of background noise makes a great difference to the lower limit of audibility, but on the other hand there are cases, especially in some classes of deafness, where a person can hear words spoken in a noisy tramcar but is unable to hear in a quiet room. The matter of total effective noise is closely akin to that of total effective light, for difference of pitch and difference of colour are exactly parallel difficulties. Similar methods should be applicable to both problems, but probably the ear is even more selective than the eye with regard to its most effective range and it also varies considerably in different individuals. I should like to support the authors' plea that extreme silence in motors should not be specified where it is not absolutely necessary. Otherwise, there would be a repetition of the unsatisfactory condition which obtained when 10-ampere and even 5-ampere increment limits were specified for d.c. starting switches. The orders always went to the firms who ignored the specification, because no check was applied to see that the specification was fulfilled.

Mr. J. McK. Knowlson: Most of us are practically concerned with the reduction in the noise of machines already in use, which probably remain as a legacy of our predecessors. Some solution is usually attempted by altering the foundations of a machine. I should like to ask whether the authors could expand their investigations so as to include the subject of the mechanical transmission of noise with various forms of mounting, particularly in consideration of the growth of ferro-concrete buildings, for which it is peculiarly difficult to find a solution. In the case of these buildings, mere height and distance are practically of no assistance in reducing the noise effects of a machine. I hope that the authors will give us, in a few years' time, further information on the subject of machine mountings as well as of machines themselves.

Mr. J. E. Macfarlane: I do not know whether in the course of their work the authors have dealt with clients who have specified freedom from audio-frequency noise, or whether they have any scale whereby a machine can be judged to be free from such noise. On page 122 of the paper mention is made of the "800-cycle standard mile." What does this mean? I should like to know whether this apparatus has been used by any inspecting department for checking audio-frequency noise. Some of the machines with which I have had to deal have passed the "freedom from audio-frequency noise" test. One day a machine was passed as satisfactory and the next day a similar machine, which to my insensitive ear appeared to be equally good, was rejected by the inspector, thus bearing out the authors' contention that individual judgment of sound values varies.

Prof. D. Robertson: The following calculation gives an interesting confirmation of the data of Fig. 1. The hammer of the great bell of the University of Bristol weighs 4 cwt. and falls 4 ft. at each stroke. The energy of each blow is thus about 150 joules, of which part is lost in the recoil of the hammer, and part is wasted in hammering out the metal and in the shock given to the building when the hammer falls. The loud sound dies away in less than 5 seconds, but the initial intensity of the sound is much greater than the average value. If that initial value is estimated as something approaching 100 watts, it is probable that about the right order of magnitude will be obtained. Neglecting reflection and other irregularities this would give 3×10^{-12} watt per cm^2 at a distance of 10 miles, corresponding to a sound pressure of, say, 0·05 R.M.S. dyne per cm^2 (see data on page 99). This is about the value given by Fig. 1 for a sound to be just audible when the frequency is 150 cycles per sec. (that of the bell), and actually the greatest distance at which the bell has been reported as audible is just over 10 miles. The authors' apparatus would be most useful for investigating some of the curious phenomena in the transmission of sound, of which one is the large effect on the range of audibility produced by winds whose velocity is less than 1 per cent of that of sound.

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* Paper by Messrs. B. A. G. Churcher and A. J. King (see page 97).

Mr. A. M. Willis: It appears to me that in investigations such as those in which the authors have been engaged considerable differences arise, owing to the fact that they have been working without a general standard. Noise, as far as I can understand, affects us individually, each of us having his own idea as to the intensity or volume of any particular sound. An oculist can say, for instance, whether a person's sight is plus or minus normal, as he has a standard of vision. Without a similar standard, I fail to see how the subject of noise can be definitely attacked. I have had some experience of variations in the hearing powers of individuals, and have noticed many remarkable features. For instance, my wife who, unfortunately, is deaf, on certain occasions is able to hear the slightest whisper where I, who am credited with good hearing, cannot hear anything at all. I remember raising this point a few years ago with one of the greatest ear specialists then living. He informed me that he himself was deaf but that he could distinctly hear a partridge rising, where others were unable to do so. In dealing with machinery such as motors, where noise is a matter of some concern, it would be a great advantage to be able to speak in terms of definite units. To-day it is found that two people often have separate ideas on the sound emitted. Many years ago, I gave evidence in an action at Bristol in connection with an alleged public nuisance arising from a noisy motor (the motor in my opinion certainly was noisy). The action seemed to be going against the defendants but the counsel prevailed upon the judge to inspect the motor in order to satisfy himself. After so doing, the decision was given in favour of the defendants and I think that this would not have happened if the judge could have been given some definite figures in sound units. The work which the authors and the Metropolitan-Vickers Co. have done in this connection is, in reality, a public service.

Messrs. B. A. G. Churcher and **A. J. King** (*in reply*): In reply to Mr. Bowman, the reasons for our not giving information on methods of preventing noise in various types of machinery ought, we think, to be fairly obvious. We heartily agree that the reduction of street noise is a most urgent and important matter, but nearly all the noise arises from motor vehicles. Our object has not been to tackle every noise problem that has arisen, but only those that arise in the products of the company with which we are associated. Even the prospect of receiving the blessings of the Ministry of Transport will not deflect us from that course.

We are much interested in Mr. Haslam's description of noise arising from a turbo-set in a hospital building. Vibration is much more likely to be transmitted through the foundations than through the surrounding air, as events showed, but why the sound should appear at the upper stories and not at the two lowest stories is difficult to explain.

Mr. Hunt's point about the practically deaf person who can hear more easily in noisy than in quiet surroundings is interesting. We have come across a few such cases.

In reply to Mr. Knowlson, we intend to go into the question of the transmission of noise with different forms of mounting when we have an opportunity. We quite agree that the use of ferro-concrete enhances the difficulty of sound isolation and constitutes a serious problem.

In reply to Mr. Macfarlane, the requirement that a machine shall have "freedom from audio-frequency noise" is quite new to us. Just what does that phrase mean? All noise is of audio frequency. Is it seriously meant that the machine shall emit no noise whatever, even when run in perfectly quiet surroundings? No manufacturer would be prepared to guarantee that. On the other hand, if the test were made in a noisy machine shop and the observer did not stand too near, many machines of standard design could be deemed "free from noise" for those conditions, as the motor noise might easily be masked by the background of noise. This brings us to the question of standards, a point raised by Mr. Willis, who suggests that we have been working without a standard. We hoped that in the paper and in our remarks we had made the present position clear. The physical measurements, viz. the measurement of the frequency and pressure amplitude of the air-pressure waves that cause the sound, are on a perfectly definite and absolute basis. We have related these to the sensitivity of the average ear and have so obtained the scale of loudness for pure tones given in the paper. What we have not yet developed is a scale of loudness for complex sounds. This is a matter of some difficulty and must necessarily precede the setting up of standards of permissible noise for machines. Furthermore, it is necessary to correlate a large number of observations on machines of various types and sizes before standards of permissible noise can be formulated, since, while complete "freedom from noise" is no doubt the ideal standard, any commercial standard must be capable of being realized without undue difficulty. In other words, a practical standard must be a compromise.

After having taken us to task for working without a standard, Mr. Willis seems to doubt the possibility of a standard, since "each has his own idea of intensity." He then alludes to the oculist's standard for sight. Now sight and hearing obey very similar laws and we do not think that a definite standard for complex sounds is inherently more difficult of attainment than one for polychromatic light. Apart from persons who have undoubtedly defective hearing, the maximum and minimum audible intensities are fairly definite quantities, as shown in Fig. 1 of the paper, which gives not only the average values but the range of variation among persons with normal hearing. Compared with the total range of intensity which the ear can perceive as sound, it is seen that the range of variation is not large. The considerable differences which arise in considering sound intensities are due, we feel sure, much more to lack of judgment than to variations in acuity of hearing. The judge alluded to by Mr. Willis may have been highly competent in legal matters but was not necessarily competent to judge sound intensities. Acuteness of vision does not necessarily make a person a good judge of distances. The persons who are good judges of sound intensities are not necessarily those who have acute hearing but those who are used to listening to sounds of known intensity, which is an experience denied to most people. Apart from all this, there remains the question of the nuisance which a given complex sound creates for different individuals. While standards of permissible noise will have to be settled with reference to the average person, there should undoubtedly be a bias in favour of the temperamentally sensitive individual for situations where a noise has to be endured for long periods.

Prof. Robertson's calculation in regard to the propagation of sound from the great bell of the University of Bristol is of great interest. We have not yet seen any satisfactory explanation of the large effect produced by winds on the range of audibility.

NORTH-EASTERN CENTRE, AT NEWCASTLE, 9TH DECEMBER, 1929.

Mr. F. H. Williams: A method of measuring quantitatively and qualitatively the noise emitted by machinery is long overdue. The authors' solution of the problem is ingenious and it would be interesting, after they have collected and analysed a large amount of data, to have a further paper from them giving the results of their work. It appears from the paper that their measurements have scarcely emerged from the laboratory stage and they have still to decide how to translate these measurements into terms of ordinary acoustical effect. Their system of measurements appears to be based merely upon sound transference by air. The noise emitted by any given machine is transmitted to a given person not only by sound waves through the air, but also through solid objects such as foundations, walls and the human body, as well as by reflection. I should like to ask the authors whether they propose to take any steps to measure the sound transmitted in this way. Up to the present, the decision as to whether a machine is noisy or otherwise has been extremely difficult as, apart from extraneous noises such as are invariably obtained on a test bed, and the difficulty of deciding whether a machine will appear more noisy or less when finally erected, the human ear seems to concentrate subconsciously on certain sounds to the exclusion of others. I have noted, for instance, in connection with rotary convertors, that whereas when standing close to a machine the predominant noise appears to be due to the brushgear, a little further away it is possible to lose this noise and for its place to be taken by one of much lower note due to windage, etc. It would be interesting to know whether the authors in their investigations have taken cognisance of this by plotting polar curves at varying distances from the machine under examination. What is really wanted is some form of apparatus which, while being reasonably portable, would also enable one to analyse fairly easily the effect upon the individual of noises produced by any machine, i.e. to integrate all the sound effects, giving them the relative values which they would appear to have to the human being.

Mr. J. L. Jefferson: Referring to section (2) of the paper and equation (1), viz. $P = \frac{A\rho f}{2r\sqrt{[1 + k^2r_0^2]}}$, the assumption is made that r_0, the radius of the pulsating sphere, is small compared with λ and thus $P = A\rho f/(2r)$ dynes (max.) per cm^2. I consider this to be rather a wide assumption, when one considers the radius of the source of sound in, say, an induction motor compared with that of a sound wave of length equal to 2 ft. or 3 ft. Apparently, this approximate formula for P was used to reduce the intensity measurements to a standard distance of 1 m, and I should have expected this assumption to have effected the reduction to a standard distance of 1 m in the case of larger apparatus. I am interested in one point in the account of the experiments on the measurement of radiation pressure by means of an aluminium disc. On page 106 it is stated that the control produced by the earth's field acting on iron impurities in the aluminium did not disappear when a mica disc and glass framework were used. This statement does not appear to be clear, and perhaps the authors could give us some further information. I should like to call attention to what appears to be a printer's error in connection with Fig. 26. "The readings at A and B are almost identical" should read, I think, "The readings at A and C are almost identical."

Mr. J. C. Read (*communicated*): About 5 years ago I made some tests on the causes of noise in squirrel-cage motors, and though quite simple apparatus was used and the tests were made with a large background of shop noise, enough information was obtained to clear up the problem at that time. The noise was merely picked up on an ordinary carbon-granule microphone placed close to the machine, amplified in a simple single-stage amplifier consisting at that time of 6 valves in parallel, and then recorded by an oscillograph. Fig. B shows a typical oscillogram obtained in this way, from which it will be clear that in spite of considerable distortion the frequency of the principal note can be readily determined, with ample accuracy. Due to the characteristics of the microphone, the amplified current obtained varied slowly and continually between a condition of irregular "mush" and one of a fairly smooth regular wave; by watching for the latter condition on the oscillograph screen it was easy to take the oscillogram at the most favourable moment. Several other types of frequency-measuring apparatus, including one rather similar to that described by the authors, were tried, but on grounds of simplicity the oscillograph scheme was found preferable in practically all cases. I think there is usually one predominating note contributing nearly all the noise, the remaining notes being of little importance; for example, the twice-supply-frequency hum is usually slight, difficult to cure, and not annoying even when of fairly large amplitude. Having then suitably placed the microphone close to the source of the particular predominating note, so that the effect of the latter is large compared with that of extraneous noises, one can find the frequency of this note by taking an oscillogram. In testing squirrel-cage motors in this way, as soon as it had been found how the noise frequency varied with slip and with supply frequency in some typical cases, the right explanations of the causes of the noise could be picked out. When the investigation was shelved in favour of other work, 4 years ago, the effects of different constructions, slot combinations, etc., on both windage noise and noise due to magnetic causes had become clear, and it was thus possible to design to reduce these noises to a minimum with reasonable certainty.

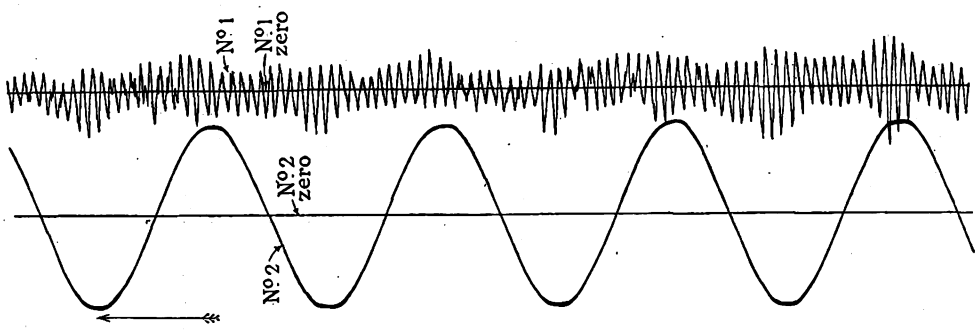

FIG. B.—Sound oscillogram taken on a 10-h.p., 4-pole, 1 460-r.p.m. machine.

Curve No. 1.—Sound wave.
Curve No. 2.—50·7 cycle timing wave.

Messrs. B. A. G. Churcher and **A. J. King** (*in reply*): Mr. Williams raises the question of vibration transmitted by solid substances as contrasted with air-borne vibrations. As far as the consideration of sound intensities at a given point near a machine is concerned, which is the subject of the paper, the only question that arises in regard to solid transmission is transmission through the body of an observer listening at that point. As far as the observer is concerned, all the rest of the sound reaches him by the air, whether it has come wholly by air or partly by solid transmission from the foundations of the machine and along the walls. Experience does not indicate that the body is a good transmitter of vibration. An engineer wishing to listen attentively to a machine puts one end of a pencil between his teeth and presses the other end against the machine to obtain adequate solid transmission to the bones of the head. Or he may take a stick and press one end against the side of the head near the ear. To demonstrate this point further, one of the authors stood on the cast-iron bedplate of a fairly noisy motor-generator set. On stopping the ears, an enormous decrease in noise sensation took place. On stepping off the bedplate on to the concrete foundation with the ears stopped and the head in practically the same position, no change in noise sensation could be detected. Similarly, when stepping on to some wooden flooring close to the machine with the ears stopped, no appreciable change took place. This, we think, disposes of the contention that sound transmission from the floor through the body to the head is an appreciable factor in listening and that our system of measurement ignores a factor of importance. As to the subject of sound transmission through foundations and walls in general, we agree that it is a matter of importance but is not one that primarily concerns the manufacturer of electrical machinery and, furthermore, it is not possible to deal with every aspect of acoustics in one paper. We have taken polar curves on certain machines. The results are very striking in some cases, especially in regard to the directional effects associated with some components. There are many possible reasons for the effects mentioned by Mr. Williams. It is possible that, in noticing the appearance and disappearance of different components on walking away from the machine, he has moved out of the sound shadow cast by the yoke of the machine. Or it may be that on reaching a certain distance the limit of audibility for certain components is reached, the limit being artificially raised owing to the background of noise in the shop. In attempting to point out what is "really wanted" in the way of apparatus, the phrase "to analyse fairly easily the effect upon the individual of noises," etc., prompts us to remind Mr. Williams that for the manufacturer there are two distinct problems in sound measurement. One is the analysis of complex sounds for the purpose of tracing the cause. This has been described in the paper and it chiefly concerns the manufacturer of electrical machinery. The assessment of the sensation produced by the total noise is the other problem and concerns both user and manufacturer. As has been pointed out in the paper, this problem has not yet been satisfactorily solved, the essential difficulty being the establishing of a scale of loudness for complex sounds. The establishing of such a scale must necessarily precede the development of apparatus to measure the sensation produced by complex sounds.

In reply to Mr. Jefferson, we are quite aware of the limitations of the assumption that r_0 is small compared with λ, but the practical consequences are not serious. With small motors the assumption is not far from the truth, and with large ones a plot of the sound field is made if conditions permit. In any case, if the distance at which observations are made is stated, the intensities recorded by the microphone are those which would act on the ears of a person standing there.

Mr. Read's remarks seem to indicate that the whole problem of producing quietly-running motors is much simpler than we have imagined. The oscillogram shown relating to an induction motor has a simplicity we have not found in our work. One wonders whether all the relevant components have been recorded, when it is stated that nearly all the noise is contributed by one predominating note. That is not our experience. Bearing in mind the large variation in loudness with frequency for a given pressure, it is possible to have small-amplitude high-frequency components that contribute largely to the noise but would not be detected in the oscillogram. That is why we avoid the use of oscillograms where possible. We think that if Mr. Read had used apparatus of more suitable characteristics and had interpreted his results in terms of loudness rather than of pressure amplitude, his conclusions would have been considerably modified.

North-Western Centre, at Manchester, 21st January, 1930.

Mr. D. B. Hoseason: With reference to Fig. 26, we are told that the readings at A and B in the vicinity of a motor are almost identical, as also are those at B and D. Therefore those at A and D should correspond. In the column lower down I find that with 225 cycles per sec. a pressure of $0 \cdot 625$ dyne per cm^2 is shown at A, whereas at D the value is $0 \cdot 235$ dyne per cm^2. Presumably there is a misprint in the text. My second point relates to the comparison of the noise from a large piece of apparatus, such as a transformer or a turbo-alternator, with the noise from a small machine, such as a motor. In the case of the small machine, it is stated in the paper that the distance of the microphone is measured from the centre of the machine and that this distance is made large compared with the size of the motor. If it is proposed to measure the noise emitted by a turbo-generator or even a rotary convertor, presumably the distance of the microphone will be made correspondingly large as compared with the measurement for a small motor. Even so, it seems to me that the physical shape of the apparatus emitting the noise will have an appreciable effect upon the distribution of the sound field. The case I have cited is an extreme one, but the same problem is met with on a smaller scale when we endeavour to compare the noise emitted by, say, a 2-h.p. with that from a 20-h.p. motor. It would be interesting to have the authors' views on the comparison of the figures in dynes per cm^2 for the noise emitted from two machines of appreciably different size and shape, when considered as a standard of nuisance.

Mr. D. A. Trickett: If there are any who doubt the value of pure science applied to practical engineering, I think this paper definitely disposes of their doubts. It reflects great credit on the authors that they have been able to measure quantities which we have hitherto believed could not be measured. I have been concerned with my colleagues in years gone by in evolving a technique for the production of silent-running direct- and alternating-current motors. When we had a difficulty with a customer who thought our motor to be noisier than it really was, we longed for an absolute standard which would enable us to say to him, " That is really a first-class silent machine." But now that the authors have placed the means of measuring absolutely the amplitude of each component frequency in my hands, I am a little in doubt as to whether I really welcome the method for use by the arbitrator in such a dispute. I am not at all sure that the method is really as absolute as I at any rate thought it would prove to be when I first read the paper. Considering the results published by the authors in regard to the 10-h.p. 3-phase motor and the turbo-alternator from the point of view of the figure of loudness, the average figure for the 10-h.p. motor is about 30, whereas for the turbo-alternator it is roughly 50. The 3-phase motor would, I consider, be a fairly passable machine but the turbo-alternator would be intolerable. The relation between 30 and 50 did not seem to me to be a true expression of the relative noise or silence qualities of the two machines. In Fig. 1, which is used as the basis for the estimation of the figure of loudness, I see that there can be, for instance, between the pressures of $0 \cdot 1$ and 10 dynes per cm^2, a variation in the figure of loudness which is relatively very much smaller than the corresponding range of pressure of 100 to 1 would appear to indicate. It seems to me that it is a question of what the ear considers to be normal. I have measured these quantities in the past by my ear with the assistance of a simple form of a stethoscope, and by what one would expect to find in the way of noise emitted by a given machine. After all, the question of noise is not an absolute question like that of temperature; it is a question of nuisance. The point then arises as to what is a nuisance and what is not. This is a matter to be decided by the ear, and so in an analysis the ear is the instrument which has to be satisfied. I feel that I would rather trust my judgment in dealing with given conditions than trust to an estimate of what the pressure ought to be under those conditions. If I were dealing with a motor for a library I should want to do everything possible in order to make it absolutely quiet, but if I were sending a motor into a boiler shop the noise emitted by a normal motor would not matter at all. All the conditions ranging between these two extremes are really matters of judgment. At times one's judgment fails and it is necessary to make a second attempt, but I believe that this would still apply if the standards described by the authors were utilized instead of the human ear. I do not wish to disparage the work which they have done, because I think their paper may help us immensely by forming some sort of a standard to which we can refer when we have learned to assess the results for p.

Mr. J. Frith: The measurement of noise is difficult for three reasons. In the first place it is necessary to study the physical aspect, which is perhaps comparatively simple. The rapid advance of wireless has placed in the hands of the authors apparatus which they might not otherwise have had. Then there is the physiological side, for, as another speaker has said, sound has ultimately to be judged by the ear and in that sense it resembles the science of light and illumination, where the peculiarities of the eye have to be studied. And it has also to do with psychology—the effect of noise upon the individual—and this is perhaps the most difficult of the three. We want ultimately to be able to measure the irritation produced in the hearer. I should like to ask whether the authors have studied the noises emitted by fans. They mentioned the ventilating motor, but in our experience it is more often the fan that is at fault. We have found that the main note emitted by a fan is twice the blade-tip frequency, and that a good deal of the noise of a motor comes from ball bearings. One would naturally expect a ball bearing to be quieter, but actually it is noisier than the other type. A standard of noise is much needed. It is impossible to specify absolute silence, because nothing is absolutely silent; one can stipulate that a motor say shall be "reasonably silent," but this stipulation depends so much upon the standard of "reasonableness" by which the machine has to be judged.

Mr. J. M. Jackson: In section (3), on page 99, the authors state, referring to Fig. 1, that the lower full-line curve represents the average minimum audibility for 72 normal ears. Should this read "72 pairs of ears," i.e. were 72 individuals tested? Similarly, the maximum audibility curve was based on 48 normal ears and the same question arises. I am chiefly interested in the practical outcome of the methods which the authors describe. It is hoped that some method will soon be developed sufficiently to be put to regular commercial use. Hints have been given as to possible applications, e.g. the measurement of noises emanating from loud-speakers. The qualities of such instruments in connection with speech are usually sufficiently good for all practical purposes, but when we pass to the realm of art the reproduction is lamentably lacking in quality. Possibly the fact that time, rhythm and form in music are correctly rendered tends to mask the actual absence of tonal qualities. There is certainly plenty of scope here for actual measurements of sound. Referring to section (11) on the assessment of total noise, it is stated on page 122 of the paper that: "It is generally accepted by psychologists that the ear adapts its sensitivity to the strength of the sound which acts on it." Is it not a fact, however, that the will of the individual has something to do with the reception of noise? I am thinking of people who, listening to an orchestra at full blast, strongly object to whispering going on a short distance away. The problem of assessing noise is further complicated by the fact that workers in an office who have always been accustomed to machinery which is running, say, in the same building, are unlikely to object to its noise, whereas in another case the introduction of a comparatively quiet machine will at once cause objection. The questions as to whether a noise is justifiably objectionable and as to the amount of expenditure which can be justified in silencing or reducing it are not easily answerable on a quantitative basis.

Mr. G. A. Juhlin: The interesting feature of the apparatus designed by the authors is, I think, that it enables us to diagnose the trouble in a noisy machine. Our difficulties in the past have been that it was impossible to determine which particular feature in design was responsible for noise, and the difficulties in the way of effecting an improvement were, therefore, very great. The authors have provided a means for analysing the various noises emitted from any apparatus, and the source of the trouble can therefore be determined; in general it is a simple matter to cure a trouble when its cause has been diagnosed. The question of absolute measurement of sound is undoubtedly an important matter, and it is to be hoped that the authors will, by further experimental work, succeed in obtaining an absolute standard of comparison.

Mr. F. Roberts: I have been concerned with the inverse of the case presented by the authors. They have been dealing with the noise received by the microphone and I have been concerned with the noise emitted by a loud-speaker. I have not gone into the subject to the same extent that they have in determining the absolute sound produced by my instruments, but I have found in their work a valuable means of investigating my problems. They have been dealing with rotating electrical machinery, finding the cause of the noises emitted and rectifying them, and this seems to me to be a comparatively simple thing to do. With few exceptions, all the main notes are at frequencies which are multiples of the number of revolutions per minute, and the exceptions may be easily traced, apparently, by going round and tapping with a screwdriver. If for a loud-speaker such as that described on page 121 an attempt is made to relate the peaks found in the response curve to the physical characteristics of the instrument itself, great difficulty is experienced. I should like to ask a question with reference to these curves. The theoretical treatment of loud-speaker operation has been given by Kennelly and his associates, and, as investigated from the electrical side, it leads to certain expectations with regard to a response curve such as that of Fig. 27. On the other hand, the actual response curve obtained seems to be unrelated to this expectation, with the exception, possibly, that the two ends of some response curves show marked peaks. I should be grateful if the authors could indicate how loud-speaker performance may be reconciled with expectation, or show what physical factors are responsible for the numerous peaks they have obtained.

Mr. R. W. Fryer: I am interested in the subject of noise, not as regards large machines, but in connection with meters. It is well known that many people whose homes are connected to an electrical supply are troubled at nights by noises which, it is supposed, are emitted from the meters. A well-known firm of meter manufacturers has been concerned with this problem during the past few years and I can safely say that, as the result of their researches, their meters are now practically noiseless. The apparatus used was not quite so elaborate as that described to us to-night, as it was not their intention to go so deeply into the subject. The object was to find out what was the cause of the noise. After much trouble and toil it was ascertained that it was caused by the vibration of the meter spindle. I should like to ask the authors whether they can give us any information as to their experience of noises emitted from such equipment.

Mr. A. G. Ellis: The paper records a splendid piece of research work, and I should like to pay my tribute in public to the assistance which the results have afforded to those who have had the opportunity of taking advantage of them in matters of design. From the discussion the fact has emerged that what we are really seeking is some unit of measurement. There are two aspects of the case, one being the method of diagnosing the trouble in the case of excessive noise, and the other the provision of some absolute comparative basis of measurement, or commercial standard. The provision of a standard is a practical problem and such a standard would have to be applicable to a commercially acceptable article. It is the purchaser and user of the machine who will have the final say, but unfortunately everyone has different views in this respect. In the long run, I do not think that the authors will find the provision of a standard quite so difficult a matter as it now appears. When scientists first attempted the measurement of light they turned to the homely candle and decided to measure light by "candle power." Can we not conceive of noise being measured by "tin whistle power," or by some similar simple unit? At any rate, I look forward to the time when the authors will have evolved some form of commercial standard by which we shall be able to compare the apparatus we are building. They have shown apparatus which covers tests over a very wide field, from large turbo-alternators down to meters. I am interested in the measurement of noise from transformers, and the problem in that connection is much more difficult than with rotating machines. The table on page 121 indicates how easy it is to diagnose in the case of noise from a rotating machine. The authors separate the various harmonics and then look for a part of the machine (e.g. armature teeth) the frequency of vibration of which corresponds to a particular harmonic. By this means they can relatively easily trace the source of the troublesome harmonic. In a transformer there are no moving parts and it is difficult to isolate the cause of the trouble in the same way. However, very valuable results have up to the present been obtained on transformers, and we look forward to the time when the authors will be able to give us something more absolute in the way of measurement. I anticipate with interest the introduction by the authors of a portable sound meter or noise meter which could be taken to a noisy substation and used on the spot.

Messrs. B. A. G. Churcher and **A. J. King** (*in reply*): Mr. Hoseason's first point has arisen owing to a printer's error. The pressures observed on opposite sides of the motor correspond. The question of defining conditions for testing large machines requires careful consideration and experimental investigation. We have not so far had an opportunity of going into this matter in detail. With rotary convertors, the composition of the sound heard near the machine varies according to whether one stands at the front or the rear of the machine. At the rear the yoke casts a sound shadow for the sound coming from the commutator and brushgear. Only at large distances would this effect become small. One has also to consider whether large distances are relevant, when it is borne in mind that the machine is intended to run in a substation building of limited dimensions. Although we do not wish to minimize the importance of the question in any way, the difficulties are to some extent mitigated by two considerations. One is that the microphone measures the true sound intensity at the point at which it is placed, so that by specifying the point or points at which the measurements are to be made a considerable amount of indefiniteness is removed. The other is that a given error in the observed sound pressure involves a much smaller error in the deduced loudness value. Thus at moderate frequencies an error of 15 per cent in the pressure would cause an error of only 1 in the loudness value. It is altogether doubtful whether a change of loudness from, say, 30 to 31 would be noticeable unless the change was made deliberately and suddenly. This, we think partly answers Mr. Hoseason's question regarding the 2-h.p. and 20-h.p. motors, but he must remember that we do not yet claim to have assessed the loudness of a complex sound but only that of the components.

Mr. Trickett's remarks deal wholly with the question of the assessment of the total noise emitted by a machine and he doubts whether we have succeeded in dealing with this. We would point out, however, that we have not suggested that the work described enables total noise to be assessed and, therefore, disputes as to the relative noisiness of different machines to be settled. In our remarks at the meetings and in the paper (page 123) we have repeatedly called attention to the fact that no satisfactory basis for assessing the loudness of complex sounds has yet been established, and that we hope to give attention to the subject in the near future. It is just such easy assumptions as that taking the average of the loudness values for the different components gives a measure of the total noise that we wish to deprecate. What has been done in the present work is to analyse the complex sound emitted by a motor on a physical basis, to assess the relative importance of each component on a loudness basis and to trace the source of the components. Mr. Trickett raises the question of the permissible limits of noise in a motor for different situations. This is a matter of the background of noise in those situations. When it is possible to assess the total noise made by a motor, it will be equally possible to evaluate the intensity of a background of noise. By considering one in relation to the other, it will be possible to choose a suitable limit of permissible noise.

Mr. Frith calls attention to the second-harmonic frequency emitted by fans. We have found this harmonic in certain types of fan. We have not studied the noise characteristics of fans in general but only those fitted to a motor for ventilation purposes. We have appreciated the misapprehension that may arise as to the relative amounts of noise contributed by the motor and the fan in a motor-driven ventilating fan. We fully agree with Mr. Frith's remarks regarding the need for a standard of noise and the absurdity of specifying "absolute silence" or even "silence."

With regard to the question of the prediction of the performance of loud-speakers, raised by Mr. Roberts, we put the characteristic curve of the loud-speaker into the paper as an example of one of the uses to which our apparatus could be put and not as an indication that we have made a serious study of loud-speaker design. From the way in which commercial loud-speakers are made, both in regard to materials and construction, we should imagine that many factors enter into their operation which could not be taken account of in any reasonably simple theoretical treatment of the subject.

Mr. Juhlin has summed up the situation very well when he points out that once the cause of excessive noise in electrical machines is found, it is, in general, a simple matter to remove it, and further, that the absolute measurement of sound, or, as we prefer to call it, the measurement of total noise, is an important matter.

Mr. Ellis also calls attention to the need for total-noise measurement in connection with transformers. As a matter of fact, the method with which we are experimenting, namely the "reference tone" method, is closely analogous to the photometric example he quotes. The adjustable pure reference tone would correspond to an adjustable standard of monochromatic light, the standard being adjusted in intensity until it appears equal, by ear in the one case and by eye in the other, to the complex quantity under observation. With regard to measurements on site, a portable sound analyser is now being developed and it is hoped that it will be capable of rapid operation. The combining of portability with sufficient range and sensitivity to deal with transformers as well as rotating machines is a matter that requires a good deal of thought and experiment.

DISCUSSION ON

"VOLTAGE CONTROL OF LARGE ALTERNATORS."*

NORTH-EASTERN CENTRE, AT NEWCASTLE, 13TH JANUARY, 1930.

Mr. W. D. Horsley: The paper gives the impression that the ordinary shunt-wound exciter is inherently unstable at low voltages and that separate excitation in some form is essential. As the author himself states, some attention to design details is necessary to guard against instability at light loads, and he also mentions that the shunt-wound exciter is not so inherently unstable as is indicated by the characteristic curve shown in Fig. 1. The ordinary shunt-wound exciter if carefully designed is stable and reliable at all loads. There is no difficulty in designing an exciter and exciter shunt-field regulator for the range of voltage given on page 325 of the paper. It seems to be advisable to retain, wherever possible, the single self-contained exciter. The advantages are that it is simple and reliable and that it conforms to the principle of making the alternator a self-contained unit. These views were expressed by Mr. C. H. Merz in the discussion on a recent paper.† In some circumstances it may be necessary to adopt separate excitation, and for this purpose the double exciter appears to be sound practice, the only disadvantages being that additional sources of breakdown are introduced and the reliability of the excitation system is lowered. A compounding winding on the main poles of an exciter does not improve the inherent stability, but numerous experiments have shown that it does prevent permanent reversal of the exciter voltage when a surge occurs on the alternator. The exciter voltage may be momentarily reversed, but the fact that the current through the compounding winding is maintained in the same direction ensures that the exciter voltage finally builds up to the correct polarity. Even if the exciter is separately excited, the polarity across the rotor slip-rings may reverse when a surge takes place on the alternator. An exciter may also be reversed if resistance is too rapidly inserted in the shunt field-circuit. This is due to the same cause and is also avoided by fitting a light compounding winding. The phenomenon is described in detail in a paper by Mr. J. Rosen.† Compensated windings have been fitted to prevent load instability of exciters, but it is difficult to see how an improvement could be effected by this means, and experience has shown that a compensated exciter may reverse when a surge in the load occurs on the alternator. Instability of alternators when carrying light loads at leading power factor has been experienced and is due to the alternators operating under conditions for which they were not designed. The difficulty is overcome by the use of automatic regulators. Alternators which are designed to run at unity or a leading power factor are quite stable, even without the use of automatic voltage regulators. Alternators having a higher synchronous reactance than that given on page 324 of the paper have operated satisfactorily on a large system for many years, and they are quite stable without the use of automatic voltage regulators. It would be of interest to have the author's views on the limiting value of synchronous reactance. The combined response of the exciter and the alternator at the higher loads is not very much greater for the separately-excited exciter than for the self-excited exciter. At low loads on the alternator the time-constant is much greater and it seems that for general purposes the self-excited exciter gives an adequate response, more particularly as the delay in action of even the vibrating-contact type of voltage regulator is of the order of 1 second.

Mr. J. W. Jackson: Referring to the remarks made in the paper at the foot of page 317, I would confirm the opinion that "a shunt exciter may lose its voltage altogether and then build up with reversed polarity." If this takes place on service load it is clear that during

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[*] Paper by Mr. H. W. TAYLOR (see page 317).

[†] F. H. CLOUGH: "Stability of Large Power Systems," *Journal I.E.E.*, 1927, vol. 65, p. 660.

[†] "Some Problems in High-Speed Alternators and their Solution," *Journal I.E.E.*, 1923, vol. 61, p. 452.

the period of reversal the generator goes out of service and, in addition to throwing all of its load on to the other generators, calls upon them for a synchronizing current to pull itself into service again. On page 325 the author states that " full load is never thrown on or off," but it is found to be necessary under many conditions of service practice to throw full load off the machine occasionally in order to find out whether the main controlling governor is in order, and this is in many cases the only satisfactory way of dealing with the governor on test. The author's suggestion of providing super-exciters appears to me to be a sound one, and it should permit of the installation of turbo-generators of great stability. Some critics would undoubtedly question the advisability of apparently adding to the complication of the electrical side of the alternator. Before arriving at any conclusion on a matter of this sort, it must, however, be realized that in order to secure equal reliability a storage battery, together with its charging device, is necessary on the other scheme. Those who have used storage batteries for any length of time know that their capital cost is high, that maintenance charges are heavy and that a large sum must be allowed for depreciation.

Mr. F. C. Winfield : In his introductory remarks the author acknowledged that he was an apostle of the stabilized exciter, but on reading through the paper one gathers the impression that he places greatest stress on the need for quick response and a low time-constant in the excitation system to ensure maintenance of voltage in fault conditions. It will be readily agreed that in the larger power stations now in prospect the greatest load unit will be a relatively small proportion of the station capacity and that normal load variations will affect voltage-regulation little, so that there is no need for a particularly small time-constant on this score, even with the very large generators under consideration. The author suggests, however, that quick excitation response is of considerable importance in fault conditions, and that special steps are very necessary in designing the excitation system of the larger generators now building or in prospect. I am not sure that I have quite appreciated the necessity of this from the author's paper, and feel that one should be well assured on the point before agreeing to complicate the exciter system and, presumably, to reduce its reliability. The duration of the low-voltage period which follows a fault may be a function of the time-constant of the generating sets, but it is surely also a function of the speed of switching. Large generating sets imply large stations as well as large and important feeders, and in modern British practice important feeders are usually provided with high-speed pilot wire protection, enabling faults to be cleared in $\frac{1}{2}$ second or less. Assuming this, the duration of low voltage would appear to be half a second plus the time of recovery of the generator voltage after the fault has been cleared. The recovery time will depend on the time-constant of the set but, in any case, I assume this will be a few cycles only, so that it would appear that the time of switching constitutes the major part of the low-voltage period and that the time-constant of the set is of little importance. Going a step further, the paper discusses the voltage response between no load and full load, but in fault conditions the response which really appears to be in question is that between, say, 75 per cent of full load-current and 2, 3, 4 or more times full load. Since the exciter definitely cannot maintain voltage in these conditions, the advantage of a small decrease in the time-constant would appear to be very small. The author's views on this point would be appreciated. The author states that when a severe fault occurs close to the generating machinery in one section of a busbar system sectionalized by reactors it is unlikely that any practical design or mode of operation could maintain full voltage; I would suggest that feeder reactors are a direct solution of this problem. Mainly due to cost, difficulty of accommodation and the additional voltage-drop introduced, the use of feeder reactors has not made great headway in this country. One of our most serious troubles in large station practice to-day is the spreading of the disturbance from a fault on one feeder due to the falling out of step of synchronous plant on other feeders. Busbar reactors limit the magnitude of fault current satisfactorily from a switchgear point of view, but with a fault close to the busbars of a large station loss of synchronous load on the busbar section directly connected to the fault appears to be almost inevitable and frequently occurs on adjacent sections. It would be interesting to know whether the author has ever considered as an alternative to the combination of a main and an auxiliary exciter, a combination of a main exciter and an auxiliary booster, that is to say, a main exciter capable of supplying maximum generator field-current at, say, 75 per cent normal voltage together with a reversible booster, such as is sometimes used for d.c. feeder regulation. The main exciter would operate at approximately constant voltage and would also supply the booster excitation, which would be automatically controlled in the usual way. At a cursory glance, it would appear that such a combination would give even a smaller time-constant than the arrangement using an auxiliary exciter, since only the time-constant of the booster would enter into consideration.

[The author's reply to this discussion will be found on page 792].

NORTH-WESTERN CENTRE, AT MANCHESTER, 18TH FEBRUARY, 1930.

Mr. G. A. Juhlin : Most engineers operating turbo-alternator plant will agree that separate excitation of the exciter is the system which gives the most satisfactory operating conditions. The requirements regarding the excitation of modern machines have increased in difficulty with the increase in size, not only of the alternator but also of the system generally. The author describes a system whereby a double exciter set is used, a small machine being provided for excitation of the main exciter. We have adopted a slightly different system; a small exciter is driven from the turbine at 750 r.p.m. This small exciter is of the permanent-magnet type. I am in agreement with most of the points brought forward by the author. The question as to what should be termed "super-excitation" is somewhat debatable. It is our general practice to be conservative as regards the margin on the exciter, and I would suggest that 15 per cent is on the small side. Possibly the author has taken this value merely to illustrate the point. We recently put into operation a large frequency changer, and as this machine connects to an extensive power system the maximum voltage used on the exciters is $2\frac{1}{2}$ times the normal value, in order to obtain a very rapid response in case of heavy overloads. The rate of building-up of the exciter voltage (i.e. the response of the exciters) was 630 volts per sec. up to about 90 per cent of the full voltage. Considerably higher figures than this can be obtained by increasing the ceiling voltage of the exciters, and by specially constructing the exciters themselves so as to minimize the time required to build up the exciter voltage. The author has clearly indicated the difference in type between machines designed 15 years ago and those designed to-day. The machine with a high armature reaction and poorer regulation than that of the older type of machine is necessary if large high-speed units are to be produced. It would be uneconomical, and in some cases impossible, to produce a large high-speed machine with the characteristics of those built 15 or 20 years ago, nor would these machines be desirable from an operating point of view on account of the large short-circuit currents which would be obtained, and which would unduly stress not only the machines themselves but the switchgear on the system. It is of interest to note that the tendency in America seems to be towards machines with heavy armature reaction. Some investigations have recently been made on a system of paralleling machines at the load end with a view to obtaining better stability.

Mr. W. Jackson: In explaining the oscillogram of alternator field-current shown in Fig. 19, the author states that the fall in exciting current, at the instant of breaking the short-circuit, is not so sharp as the rise in stator voltage, because of the presence of mutual circuits. While I can appreciate the importance of these mutual circuits in helping to determine the rate at which the exciting current rises following the commencement of the transient period, I have difficulty in appreciating their effect during the fall of current, unless the author intends that the small interval of time represented by the fall is to be accounted for as the time during which the electromagnetic energy stored in the short-circuited stator is dissipated in the mutual circuits. Even then I should have difficulty because of the time-constant of from 2 to 4 sec. mentioned in connection with these circuits. I should be glad if the author would help me on this point as I should have expected the stored electromagnetic energy to be dissipated in the arc occurring at the switch contacts when the short-circuit was broken, and the small interval of time elapsing during the fall in exciting current at this instant to correspond to the duration of the arc. On page 330 of the paper it is stated that in calculating the combined response of alternator and exciter following a sudden increase in load from 40 to 80 per cent of full load, it is sufficiently accurate to use the alternator time-constant for the new load. As, however, there is a difference of at least 1 sec. between the time-constants at 40 per cent and at 80 per cent of full load, and as 1 sec. is an appreciable percentage of the total time-constant at the latter load, I should have considered it to be more accurate and equally simple to take the average value over the period of change, especially in view of the detailed and accurate nature of the investigation which leads to the derivation of the time-constant variation curve.

Mr. H. Topley: I should like the author's opinion on a question of operation of a plant with which I think he is familiar. The conditions are a 32 000-kW, 11 000-volt, 50-periods per sec., 1 500-r.p.m. alternator stepping up to 33 000 volts, and a 1 000-kW 400-volt auxiliary alternator provided on the same shaft. The arrangement of main and service exciters is as shown in Fig. 4, but in addition to supplying the field of the main exciter the service exciter supplies the field of the auxiliary alternator. The question is what would be the effect upon the main alternator voltage of a sustained short-circuit on the stator of the auxiliary generator, with or without a voltage regulator. The effect of the variation of the ordinary load on the auxiliary generator is another point which demands consideration. I have examined the service exciter and find that there is a mutual winding which is used in connection with the voltage regulator. I should like some explanation of its use.

Mr. A. L. Lunn: When reading the paper I gained the impression that it would be of more interest to the designer than to the user, but the manner in which the author has presented his paper has reminded me of one or two experiences which may be of interest. It has been stated that as the alternator load is increased or decreased the voltage can be controlled and maintained within reasonable limits when separately-excited exciters are used. To some extent I agree with the author that under normal operating conditions it is possible to maintain a fairly constant pressure when a small extra load is thrown either on or off the alternator, but I should like to have his opinion on the advisability or otherwise of maintaining normal voltage on an alternator which is suddenly called upon to carry an abnormal overload with the frequency below normal. Under such conditions most automatic voltage regulators will clear themselves, and in power station operation it is usually considered that the best policy is to allow the alternator voltage to fall with the frequency. With alternators running in parallel it is obviously the best practice to operate the most efficient plant at the highest power factor. This applies particularly to systems where a modern and a much older station are linked together. The wattless current passing between the two stations should be reduced to a minimum and, if possible, be carried on the least efficient set. The following occurrence would seem almost incredible had one not actually witnessed it. A 2 000-kW 1 500-r.p.m. turbo-generator with a shunt-wound exciter and a voltage regulator applying a positive or negative boost (as required) into the exciter field, was running in parallel with two high-speed reciprocating engines each driving an 800-kW alternator when, owing to a defect in the voltage regulator, the polarity of the exciter was reversed and built up in the opposite direction. The supply was maintained and the voltage was restored to normal in seconds, the alternator apparently having slipped a pole. The remarkable feature of this incident was that outside the power station no one reported or appeared to have noticed any irregularity on the supply—not even the attendants in charge of the rotary substations. Another experience occurred in connection with a turbo-alternator of 6 000 kW and 3 000 r.p.m. with a shunt-wound exciter. When passing along the switchboard it was noticed that the machine had lost its field, and a dynamo attendant was observed wiping the exciter commutator with a rag which was afterwards found to be oily. Fortunately, at this time other sets were operating in parallel and by regulating the field rheostats the exciter built up again, in this case in the right direction.

Mr. S. Garbutt: It is stated on page 317 of the paper "that there is a difference of opinion among operating engineers as to whether the excitation of machines should be allowed to increase when a fault occurs close to the generating machinery." If an automatic voltage regulator without any compensating windings on the main control coil is in operation it will increase the excitation, when a fault occurs, in endeavouring to maintain the busbar voltage at the particular value for which the automatic voltage regulator has been set. In view of the above remarks it might be interesting to know whether it is possible to meet the requirements of the operating engineers who do not desire increased excitation in the event of a fault close to the generators and yet require automatic voltage regulation during normal conditions. It might also be of interest to know whether the voltage regulation of generators of, say, 50 000 kVA capacity is generally automatic. I have noticed that some firms manufacture turbo-alternators which have control both on the exciter field and also on the alternator field, that is to say, rheostats are connected in both field circuits. Is the manufacturers' object to obtain greater stability of excitation? With regard to the new exciter mentioned by the author, is it necessary to insert as much resistance in the exciter field-circuit for the main contacts of the automatic regulator to operate on as in the ordinary type of exciter? In the ordinary type of exciter it is necessary to insert sufficient resistance in the exciter field to bring the no-load voltage down to 60 per cent of normal busbar voltage, in order that the automatic regulator may take care of all voltage variations from no load to full load. What is the voltage range at the exciter terminals from no load to full load of this new type of exciter? A considerable amount of difficulty was at one time experienced in manufacturing the main relay coil of a certain type of vibrating-contact automatic regulator if the ratio exceeded 1 to 3.

Mr. O. Howarth: Does the author advocate attempting to maintain the voltage when phase-to-phase faults occur on the system, and when such faults persist for 1 or 2 seconds? The voltage regulator is connected across a pair of phases which may not be appreciably affected by a particular fault. There appears to have been no development in the method of connecting voltage regulators. Is it not time some arrangement was made whereby the voltage of at least two pairs of phases would be included, so that wherever the fault might occur the voltage would be maintained? With regard to machines in parallel on a set of busbars in a station without reaction between them, would the author suggest the use of a regulator on each machine with the usual power-factor compensating device? Here again it seems to me that trouble will arise if the voltage across any pair of phases is to be maintained. How is the power-factor compensation on the regulators to be arranged?

Mr. T. B. Somerville (*communicated*): Many operating engineers have experienced, at some time in their career, some unusual phenomenon for which no altogether convincing explanation has been forthcoming, and others, I think, do not realize how precarious are the conditions under which their machines are working. All will be reassured, after reading the paper, by the knowledge that the "hit and miss" stage in machine design has now been passed, at all events as far as the excitation system is concerned. The paper is chiefly of interest to me in so far as it brings into prominence the requirements and responsibility of the automatic regulator. Regarding speed of response, the automatic regulator may in many cases be as important a source of sluggishness as the exciter and the alternator field. Indeed, I will go so far as to assert that operating engineers wishing to improve their generating plant by increasing the rapidity with which necessary changes to the excitation are effected, can often obtain considerably greater improvement by installing a quicker-acting regulator than they could by changing the method of exciting the exciter field. To illustrate this assertion, I propose to make a comparison between the results obtained with the imaginary regulator of Fig. 24 and the results which would be possible on the same machine, using a regulator of a type with which I have had some experience. I know that the author had no particular regulator in mind when preparing Fig. 24, and that he has introduced the delay of 1 sec. merely to illustrate the manner in which the curves in Fig. 21 must be modified to allow for the time required by any automatic regulator to operate. The comparison should be no less interesting on this account, however, as I have seen in this country many automatic regulators which would give a much less satisfactory performance than that of Fig. 24. From Fig. F, which indicates the time taken by the contacts of the quick-acting regulator to cease beating after the imposition of a reduction in the voltage across the regulator control coil (the regulator having first been floated in the light-load position), it will be noted that the voltage disturbance illustrated in Figs. 21 and 24 would cause a complete

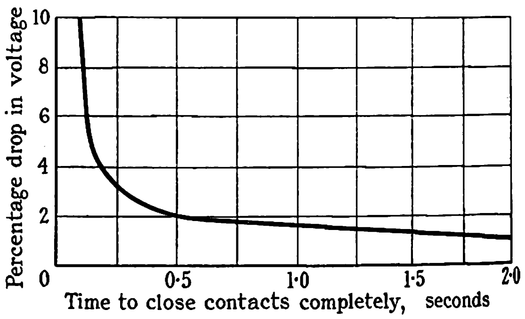


FIG. F.

closure of the contacts in 0·2 sec. If we now draw the curves to show the actual alternator-voltage variations as in Fig. 24, but commencing to rise only 0·2 sec. after the initial voltage-drop, we find that the voltage disturbance using this regulator and separate excitation is actually less, both in magnitude and duration, than when using the imaginary regulator and what the author describes as " super-separate " excitation. Furthermore, there is not a great deal to choose between the effect obtained when using the imaginary regulator with separate excitation and that obtained with the quicker-acting regulator and shunt excitation. The actual regulator used in the preparation of this response curve had been in use on a 500-kW turbo-alternator with direct-coupled shunt-connected exciter, but it is interesting to note that, in this particular, it does not differ very much from the regulators recently installed on a 30 000-kW frequency changer having separately-excited exciters. In practice, the regulator is required to commence re-opening its contacts shortly before the exact normal voltage is resumed, so that the return to normal is asymptotic rather than abrupt as illustrated. No one is concerned, however, at the slight delay in restoring the last 1 or 2 per cent. It may interest some to know by what means the regulator is enabled to short-circuit the rheostat in so brief a space of time, and then re-insert sufficient resistance for the new load condition immediately normal voltage is restored, at the same time avoiding what is known as " hunting." Taking the no-load position of the regulator control lever as zero and the lower position at which the regulator contacts are completely closed as 100 per cent down, we find that as the alternator load increases slowly from no load to full load, the regulator control lever moves slowly downward from zero position to perhaps 80 per cent down, at which point the contacts are opening and closing sufficiently to give full-load excitation. In order to prevent hunting, the movement of the regulator control lever is necessarily damped. Without such damping, a fraction of 1 per cent rise or fall in voltage would result in completely opening or completely closing the regulator contacts immediately, and the alternator voltage would swing rather rapidly up and down above and below normal. Accordingly, the piston of an oil-filled dashpot is connected to the regulator control lever, and the amount of damping adjusted to prevent hunting. This dashpot is connected to the regulator control lever by means of a flexible leaf spring, so that it does not prevent a rapid movement of the lever in the event of a sudden disturbance to the voltage. Let us suppose that the alternator is on no load, so that the regulator control lever is in the zero position. Half of full load is now suddenly switched on. The resultant drop in voltage causes the regulator control lever to move rapidly to 100 per cent down, or lower, thus closing the regulator contacts completely. The dashpot piston moves more slowly downward, and by the time the voltage is restored almost to normal it has reached the 40 per cent down position. Under the action of the leaf spring connecting the dashpot piston to the regulator control lever the latter now moves up to the 40 per cent down position, which it reaches when the alternator voltage is back to normal. In the 40 per cent down position the regulator contacts open and close sufficiently to give correct excitation for half load. In this way the actual voltage variations of the alternator after a sudden increment in load can be made to approximate very closely to the curves in Fig. 21. With regard to reliability, no doubt some operators will be filled with remorse after reading this paper, when they realize that they may have suspected their automatic regulator on account of peculiar behaviour which was possibly due to some inherent weakness or peculiarity in their machine. In a recent instance this proved to be the correct explanation. The automatic regulator was observed and reported to have varied the beat of its contacts in a manner which was not considered to be justified by any simultaneous fluctuations in the load. This so-called erratic behaviour of the automatic regulator, although not producing noticeable disturbances in the alternator voltage, eventually resulted in the automatic regulator being left out of commission until such time as it could be attended to. In the following few days the machine completely lost its excitation on two occasions. Nevertheless, automatic regulators, however reliable they have proved to be, cannot be truthfully described as infallible. Indeed, in my opinion, as the automatic regulator is sometimes the weakest link in the chain of voltage control of an alternator from the point of view of speed of response, so it may be also from the point of view of reliability. If, in order to obtain quicker response from the machine, we make available to the automatic regulator a wider margin of excitation in excess of actual full-load requirements, the results of incorrect operation may be correspondingly more serious, and, if the operating engineer is to enjoy any peace of mind at all, these results must be guarded against. In the past it has been common practice to install with each automatic regulator a cut-out arranged to operate in the event of excessively high or low voltage, cutting the automatic regulator out of action and leaving the machine on (usually) half-load excitation. Such cut-outs usually operate in the event of a system fault, thus cutting the regulator out of action at a time when it is most desirable to keep it working, and in order to make such unwanted operation less frequent it is usual to arrange the cut-out with a very coarse setting. With this necessarily coarse setting, the protection afforded against the results of faulty operation of the automatic regulator is, in my opinion, inadequate for present-day conditions. Consider, for example, the case of two machines in parallel each under the control of a separate automatic regulator, one of which becomes faulty. The healthy regulator operates in such a way as to maintain approximately normal voltage and thus prevents operation of the regulator cut-out. One of these machines may easily have its excitation reduced to a value which is not sufficient to hold it in synchronism. To take another example, suppose that a system fault occurs and that this is followed by a large loss of load. The regulator cut-outs operate due to low voltage, leaving the machines on half-load excitation. At the abnormally light load, particularly if a long unloaded feeder remains connected to the machines, the voltage may quite easily rise to a disconcerting value, which would have been prevented if the automatic regulators had remained in operation. I have recently been responsible for the introduction of a new form of protective cut-out, which does not operate unless the voltage disturbance is actually caused or maintained by faulty operation of the automatic regulator. This cut-out can therefore be set sufficiently fine to give adequate protection without running the risk of unwanted operation. In the case of parallel-running machines each under the control of a separate regulator, a faulty regulator would be cut out of operation immediately, leaving the others in service and the voltage normal. I entirely agree with the author that separate excitation of the exciter field is well worth while, not only on account of the increased speed of response, but also for the vast improvement in stability which is obtained. A difficulty which I have experienced with some exciters is that it is not possible to choose a point on the rheostat corresponding to a definite value of excitation. The excitation obtained at a given point depends not only on whether the rheostat has been brought up or down to the point, but also very largely on how far the rheostat has been moved up or down before being brought back to the given point. This effect, which is referred to on page 319 of the paper, is presumably due for the most part to hysteresis, and is exaggerated by the use of steel in the magnetic circuit. I assume that no advantage is to be gained by the use of hard magnetic steel when the exciter is to be separately excited, but I should like the author's confirmation on this point. From the point of view of the automatic regulating equipment, I consider it a distinct advantage to be able to rely on obtaining always the same value of excitation for any given point on the rheostat, at normal speed.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT NEWCASTLE AND MANCHESTER.

Mr. H. W. Taylor (*in reply*): Mr. Horsley stresses simplicity, reliability and the desirability of making a self-contained unit, and it was to meet these requirements that the stabilized exciter described in the paper was introduced, as the only alternative where quick response is desired is separate excitation from a battery. In particular, the reliability of the arrangement has been proved by the service it has given since it was introduced a few years ago. The question of using a compound winding with the exciter has already been reviewed on page 338 in reply to a previous discussion. In reply to the question as to what is the limiting value of synchronous reactance, I would say that one of the obstacles to further increase in synchronous reactance has been the extra losses which take place in machines with short air-gaps. These losses have been studied during the last two or three years and have been much reduced. With this advance in the art of design, together with improvements in regulators, values of synchronous reactance 25 per cent higher than those indicated in Fig. 15 of the paper are now possible. The delay in the action of the vibrating-contact regulator is of an order less than 1 sec., as shown by Mr. Somerville later in the discussion.

Mr. J. W. Jackson's remarks are interesting in that he indicates the inherent disadvantages of using a battery as an alternative to the service portion of the stabilized exciter.

In reply to Mr. Winfield, the double machine discussed in the early part of the paper was introduced to improve both stability and response, but in order to give it a name which was not too verbose it was decided to call it a "stabilized exciter," although it fulfils both the functions mentioned. I agree with the suggestion that quick response is not so necessary when protective devices function properly, but line faults are sometimes sustained owing to the defects in protective devices, and in such cases a quickly responding exciter and a quick-acting regulator are valuable in holding together the various parts of the system. The recovery of line voltage after a heavy fault which requires excitation beyond the capacity of the exciter can be determined from the curves in Fig. 20, using the time-constant corresponding to the load left on the system when the fault is cleared. The time for recovery will be more than a few cycles. The advantage of super-excitation and quick response upon the occasion of a prolonged fault is that while voltage may not be maintained there is a large amount of leakage flux built up in the machine, and this, upon removal of the fault, appears as a larger percentage of line voltage. The booster excitation scheme suggested by Mr. Winfield might be more responsive under ordinary load conditions, but it does not admit of such a degree of super-excitation as the usual arrangement. The possibility of super-excitation depends upon the voltage range which can be obtained from the exciter, and the machine which in this scheme is varied in voltage seems to have only one-quarter of the range of the exciter described in the paper.

In reply to Mr. Juhlin, the 15 per cent margin between maximum excitation requirements and maximum excitation voltage was taken as the minimum which would be considered reasonable, having regard to the stable range of voltage which can be obtained from a shunt machine. One of the aims of the paper was to establish a method of reference for exciter voltage response, and it might be more satisfactory to give this as a percentage per second of the excitation voltage required by the alternator for full-load operation, rather than with reference to a voltage which includes a further 15 per cent margin, as do the curves plotted in Fig. 7. In this connection it would have been interesting if the response of the exciter for the frequency-changer, given as 630 volts per second, had been given as a percentage of the exciter voltage for maximum normal operation. Towards the end of his remarks Mr. Juhlin has done well to emphasize the technical reasons which have contributed towards the design of modern machines, as it is sometimes suggested that, inasmuch as a lower short-circuit ratio produces a machine of somewhat small mechanical dimensions, this type of design is adopted for purely commercial reasons.

In reply to Mr. W. Jackson, the oscillogram from which Fig. 19 was taken contained a record of stator current, and this showed that no arcing took place at the switch.

In further explanation of the statement that the initial shape of the record of field current is due to the presence of mutual circuits, I would say that, when the short-circuit is removed, the rotor excitation circuit and the mutual circuit, formed by the solid mass of the rotor, both carry transient currents which, at the instant of breaking the short-circuit, have in combination a value which reduces the magnetizing effect of the previous steady current to a value corresponding to the voltage which appears at the open-circuited terminals. The shape of the field-current record will therefore be different from that of the alternator voltage record, and this difference can be made more pronounced during the first few cycles if, for the purpose of experiment, the alternator field current is given a long time-constant. I think that Mr. Jackson has misread the paragraph on page 330 regarding the calculation of combined response of alternator and exciter, but in further explanation I would say that as regards the alternator it is correct to use the time-constant from Fig. 20 for the new load conditions when once they are established, because, although we are calculating the alternator voltage variation, the variations are not large. In the case of exciter response the exciter voltage varies over a wide range and, due to saturation, the exciter response varies appreciably. For the sake of simplicity in calculation, however, an average value of the exciter response is taken over the range involved in adjusting the alternator excitation for the new load.

In reply to Mr. Topley, the service exciter which, in the case he cites, also excites the auxiliary alternator at constant voltage is liberally rated for the extra duty and is made with a saturated field and a long gap so that variations in the exciting current of the auxiliary alternator do not produce any appreciable variation in the main alternator voltage, even though there is no regulator in service. No provision is made for excessive excitation of the auxiliary generator in case of faults, so that no abnormal demands come upon the service exciter if that alternator be short-circuited. With regard to the mutual windings which Mr. Topley has noticed on the main exciter, I would refer to Fig. 6 and point out how sudden is the drop in voltage compared with the rise in voltage on a separately-excited exciter. The use of an additional circuit on the field spools, short-circuited on itself, adds a small but similar delay on both the rising and falling curves and, lessening the disparity between them, increases the range of a given design of voltage regulator.

In reply to Mr. Lunn, I think that the regulator and exciter should be allowed to continue to operate as long as the voltage is available from the exciter to maintain normal voltage, even though the speed or frequency has fallen. The experience of Mr. Lunn and other operating engineers who have contributed to the discussion seems to indicate that exciter instability is frequently met with.

The requirements mentioned by Mr. Garbutt to eliminate the increased excitation in the event of a fault near the station are met by the use of a stabilized exciter without provision for super-excitation. I consider it to be good practice to install a small turbo-alternator rheostat in addition to an exciter rheostat wherever a stabilized exciter is not employed. With regard to regulator operation with a stabilized exciter, resistance should be inserted to reduce the alternator voltage on open-circuit down to about 75 per cent instead of the lower value usually adopted when a shunt exciter is used. The exciter voltage range depends, of course, upon the alternator and, as stated in the paper, for the typical turbo-alternator (see Fig. 15) and, allowing for hot and cold conditions of the alternator field, the approximate exciter voltage range would be at least 4 : 1. The operation of the regulator relays is improved when a stabilized exciter is used, by exciting the relay coils from the constant voltage of the service exciter.

In reply to Mr. Howarth, arrangements are available whereby a regulator can be made to maintain constant the average voltage on all three phases. This can be extended so that the regulator compensates or compounds for the average current of the three phases. With regard to single-phase fault conditions, however, it is a mistake to suppose that the three phase windings of an alternator act like three separate reactions and that voltage is maintained on the healthy phases. A single-phase fault will depress the voltage on all three phases, and a regulator connected to any of them will give satisfactory operation under these circumstances.

In reply to Mr. Somerville, we like to think that the " hit or miss " epoch in electrical machine design was passed many years ago. His comparison between the response, on the one hand, of a separately excited exciter when the action of the regulator is delayed to illustrate a method of calculation, and, on the other hand, of a shunt machine with the regulator operating normally, seems without meaning. I agree that the response curve given in his Fig. F is typical of the vibrating-contact type of regulator, but this curve does not warrant his suggestion that, in plant already installed, improvement can be obtained by changing the regulator rather than by changing the method of excitation. With regard to cut-outs, it is not, in my experience, necessary to install these to take care of faults in the regulator, as failure of the regulator is rare when it is given regular attention, and the suggestion that it is a weak link (there must, of course, always be a weakest link) in the chain of generation is not justified. Cut-outs, however, are installed to put the regulator out of action when the busbar voltage has been considerably depressed for a lengthy period and when, to all intents and purposes, the station is out of action and generators have fallen out of step, and large increases in the excitation of the coupled machine would only lead to further difficulties. Mr. Somerville's confirmation of hysteresis effects with shunt-wound exciters is welcome, and I think that these effects will be more pronounced if hard magnetic steel be used for the pole cores.

PROCEEDINGS OF THE INSTITUTION.

794TH ORDINARY MEETING, 5TH DECEMBER, 1929.

Colonel Sir Thomas F. Purves, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 28th November, 1929, were taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

The President announced that during the month of November, 1929, 22 donations and subscriptions to the Benevolent Fund had been received, amounting in the aggregate to £19. A vote of thanks was accorded to the donors.

A Lecture was delivered by Dr. H. Norinder entitled "Surges and Over-Voltage Phenomena on Transmission Lines, due to Lightning" (see page 525).

After the delivery of the Lecture and some remarks by Dr. G. C. Simpson, C.B., F.R.S., Mr. B. L. Goodlet said that he had frequently heard it stated that we in England are not paying much attention to the problems of lightning and transient phenomena generally, and that we have no impulse generator and cathode-ray oscillograph suitable for such work. He showed three slides to prove that we are not ignoring the problem. These slides illustrated (1) an impulse generator to give a voltage to earth of 1½ million volts, (2) an impulse spark-over of more than 1 million volts on an insulator chain, and (3) a cathode-ray oscillogram of an impulse spark-over.

A vote of thanks to Dr. Norinder, proposed by the President, was carried with acclamation, and the meeting terminated at 7.15 p.m.

795TH ORDINARY MEETING, 12TH DECEMBER, 1929.

(Joint Meeting with the British Section of the Société des Ingénieurs Civils de France.)

Colonel Sir Thomas F. Purves, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 5th December, 1929, were taken as read and were confirmed and signed.

A paper by Messrs. L. A. E. Sékutowicz and A. Evain, Members of the French Institution of Civil Engineers, entitled "The Electrical Plant and Network of the Société Electrique de la Sidérurgie Lorraine" (see page 413), was read on behalf of the authors by Mr. Roger T. Smith and discussed.

The meeting terminated at 7.5 p.m. with votes of thanks to the authors and to Mr. Roger T. Smith for presenting the paper, which were moved by the President and carried with acclamation.

796TH ORDINARY MEETING, 19TH DECEMBER, 1929.

Colonel Sir Thomas F. Purves, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 12th December, 1929, were taken as read and were confirmed and signed.

A paper by Lieut.-Col. S. E. Monkhouse, R.E.(T.R.), and Mr. L. C. Grant, Members, entitled "The Heating of Buildings Electrically by means of Thermal Storage" (see page 657), and a paper by Mr. T. G. N. Haldane, M.A., Associate Member, entitled "The Heat Pump—An Economical Method of Producing Low-Grade Heat from Electricity" (see page 666), were read and discussed.

The meeting terminated at 7.55 p.m. with a vote of thanks to the authors, which was moved by the President and carried with acclamation.

INSTITUTION NOTES.

Revised Supplement to the Wiring Regulations.

The Council have approved the issue of a revised Supplement to the Ninth Edition of the I.E.E. Regulations for the Electrical Equipment of Buildings. This Supplement relates to radio receiving and valve amplifying apparatus connected to the supply mains, and is in substitution for the corresponding supplement issued in June 1928, which is now withdrawn. Copies can be obtained, free of charge, from the Secretary of the Institution, for insertion in existing copies of the Ninth Edition of the Regulations.

The Benevolent Fund.

On the last page of the cover of this issue of the *Journal* will be found particulars of certain publications, etc., which are on sale on behalf of the Benevolent Fund.

Council's Nominations for Election to the Council.

The following have been nominated by the Council for the vacancies which will occur in the offices of President, Vice-President, Honorary Treasurer, and Ordinary Members of Council on the 30th September, 1930:—

President. (*One Vacancy.*)

C. C. Paterson, O.B.E.

Vice-President. (*One Vacancy.*)

R. K. Morcom, C.B.E., M.A.

Honorary Treasurer. (*One Vacancy.*)

E. Leete.

Ordinary Members of Council.

MEMBERS. (*Five Vacancies.*)

F. W. Crawter.
A. Ellis.
E. W. Hill.
W. Riggs.
R. P. Sloan, C.B.E.

ASSOCIATE MEMBER. (*One Vacancy.*)

R. Grierson.

ASSOCIATE. (*One Vacancy.*)

J. F. W. Hooper.

Premiums.

The following Premiums for papers have been awarded by the Council:—

The Institution Premium (*value* £25).

H. H. HARRISON.	"Developments in Machine Telegraph Systems and Methods of Operation."

The Ayrton Premium (*value* £10).

B. A. G. CHURCHER and A. J. KING.	"The Analysis and Measurement of the Noise Emitted by Machinery."

The John Hopkinson Premium (*value* £10).

L. C. GRANT.	"The Breaking Performance of High-Power Switchgear and of a New Form of Quenched-Arc Switch."

The Kelvin Premium (*value* £10).

T. G. N. HALDANE, M.A.	"The Heat Pump—An Economical Method of Producing Low-Grade Heat from Electricity."

The Paris Premium (*value* £10).

H. A. HUMPHREY, D. M. BUIST and J. W. BANSALL.	"The Steam and Electric Power Plant of Imperial Chemical Industries, Ltd., at Billingham."

A Premium (*value* £10).

S. W. MELSOM, A. N. ARMAN, B.Sc.(Eng.), and W. BIBBY, B.Sc.(Eng.).	"Surge Investigations on Overhead Lines and Cable Systems."

A Premium (*value* £10).

T. W. ROSS and H. G. BELL.	"Recent Developments in the Protection of Three-Phase Transmission Lines and Feeders."

A Premium (*value* £10).

E. H. SMYTHE and E. G. WEEKS.	"Low-Temperature Carbonization of Fuel, with special reference to its combination with the production of electricity (English Practice)."

A Premium (*value* £5).

BERNARD LEGGETT, M.R.C.S., L.R.C.P.	"The Medical and Surgical Applications of Electricity."

A Premium (*value* £5).

J. C. PRESCOTT.	"The Capacity Effect and Natural Free Period of a D.C. Armature."

A Premium (*value* £5).

H. W. TAYLOR.	"Voltage Control of Large Alternators."

A Premium (*value* £5).

W. WEST, B.A.	"A Measurement of the Sound Pressures on an Obstacle." "The Pressures on the Diaphragm of a Condenser Transmitter in a Simple Sound Field."

WIRELESS SECTION PREMIUMS.

The Duddell Premium (*value* £20).

J. E. P. VIGOUREUX, M.Sc.	"The Valve-Maintained Quartz Oscillator."

A Premium (*value* £10).

Captain P. P. ECKERSLEY and N. ASHBRIDGE, B.Sc.	"A Wireless Broadcasting Transmitting Station for Dual Programme Service."

A Premium (*value* £10).

G. SHEARING, B.Sc., and Captain J. W. S. DORLING, R.N.	"Naval Wireless Telegraph Communications."

The awards for papers read before the Meter and Instrument Section and also for Students' papers will be announced later.

Institution Scholarships.

As mentioned in the Annual Report, the Council have established two Institution Scholarships, to be known as the Duddell and the Ferranti Scholarship respectively. It is proposed to make the first award of each Scholarship this year. The conditions of award are as follows:—

THE DUDDELL SCHOLARSHIP.

(Founded as a memorial to the late William Duddell, C.B.E., F.R.S., a former President of the Institution.)

Conditions of Award.

(1) The Duddell Scholarship in Electrical Engineering is tenable for three years and will be awarded only to British subjects who are the sons of parents of limited means, and who fulfil the required conditions. Preference will be given to candidates whose fathers or a near relative are, or have been, members of The Institution of Electrical Engineers.

(2) Candidates must be under 19 years of age on the 1st July in the year in which the award is made. Each candidate must be nominated by a Corporate Member of the Institution and have passed the Matriculation Examination of a British University or an examination exempting from the Matriculation Examination.

(3) The successful candidate will be required to take up a whole-time day course in Electrical Engineering which would normally be taken at a University, College, etc., in The British Empire, and

(*a*) he must be, or forthwith become, a Student of The Institution of Electrical Engineers, and

(*b*) he must not concurrently be the holder of any other Scholarship.

(4) In making the award consideration will be given to the candidate's school record, Matriculation or exempting examination results, and general personality.

(5) The annual value of the Scholarship is £150, payable in equal quarterly instalments, and subject in each case to the Professor or Teacher under whom the holder of the Scholarship is studying certifying that he is working satisfactorily.

(6) Instalments may be withheld or forfeited in the event of an unsatisfactory report being received from the Professor or Teacher concerned. A Scholarship will be cancelled and any unpaid instalments forfeited if the holder should relinquish his electrical engineering studies.

(7) An award of the Scholarship will be made annually.

(8) Nominations must reach the Secretary of The Institution of Electrical Engineers not later than the 15th June on forms, copies of which are obtainable from the Institution.

(9) The Scholar will be required to commence his studies at the beginning of the Session next following the award.

THE FERRANTI SCHOLARSHIP.

(Founded as a memorial to the late Dr. S. Z. de Ferranti, F.R.S., a former President of the Institution.)

Conditions of Award.

(1) The Ferranti Scholarship in Electrical Engineering is tenable for two years and will be awarded only to British subjects who fulfil the conditions set out below. Preference will be given to candidates whose fathers are, or have been, members of The Institution of Electrical Engineers.

(2) Each candidate must be nominated by the Professor or Teacher under whom he is working, or has worked, and satisfy the following conditions:—

(*a*) He must be a Student or Graduate of The Institution of Electrical Engineers and have been such for not less than two years.

(*b*) He must have undergone a whole-time day course in electrical engineering of at least three years, and have graduated or obtained a final certificate or diploma appertaining to such course approved by the Institution.

NOTE.—Consideration will also be given to candidates who have, for any reason, been unable to take a whole-time day course of study, but who have obtained the degree of B.Sc. with 1st or 2nd Class Honours, and who have satisfied the Examiners in electrical engineering subjects.

(*c*) He must be under 26 years of age on the 1st July in the year in which the award is made.

(*d*) He must undertake to carry out whole-time research or post-graduate work of a nature and at an establishment approved by the Council of the Institution.

(3) The Scholarship may at the discretion of the Council be awarded as a Travelling Scholarship, with a view to study abroad at some approved institution, laboratory, or works.

(4) Except in the case of a Travelling Scholarship the recipient of the Scholarship must not concurrently be the holder of any other scholarship.

(5) The annual value of the Scholarship is £250, payable in equal quarterly instalments, and subject in each case to the Professor or responsible authority under whom the holder of the Scholarship is studying certifying that he is working satisfactorily.

(6) Instalments may be withheld or forfeited in the event of an unsatisfactory report being received from the Professor or responsible authority concerned. A Scholarship will be cancelled and any unpaid instalments forfeited if the holder should relinquish his electrical engineering research or other post-graduate work.

(7) An award of the Scholarship will be made annually.

(8) Nominations must reach the Secretary of The Institution of Electrical Engineers not later than the 15th August on forms, copies of which are obtainable from the Institution.

(9) The Scholar will be required to commence his research or other post-graduate work at the beginning of the Session next following the award.

Letter from Kelvin to the late Dr. Kapp.

The Institution has acquired from Mr. Kilburn Scott a very interesting letter, reproduced in facsimile on pages 798 and 799, written by the late Lord Kelvin (then Sir William Thomson) to the late Dr. Gisbert Kapp, which is evidently in reply to an inquiry as to whether there was a rational theoretical method of calculating the ampere-turns on the field magnets of a dynamo to produce a given excitation. In reference to this letter Mr. Llewelyn B. Atkinson contributes the following note:—

"In November 1885 Mr. Kapp read a paper before the Institution of Civil Engineers dealing with the design of dynamos as they were then being made, in which he gave a formula for the magnet winding in terms of the ampere-turns on the magnet and of what he, for the first time, called the magnetic resistance of the iron of the magnet, the air of the air-gap, and the iron of the armature.

"In a footnote he states that although he had used this formula for some time it was an empirical formula, and that only recently Sir William Thomson had given him explanations which showed that the formula was a rational one. I surmise that the letter now reproduced is the explanation referred to. Colonel R. E. Crompton in his "Reminiscences" states that in 1881–2, in working on the subject of dynamo-design improvement, and after consultation with Sir William Thomson, Fleeming Jenkin and others, a formula was arrived at showing that the variation in e.m.f. of a dynamo as affected by the magnetization was dependent on the quantity

$$\frac{4\pi \times \text{ampere-turns}}{\text{Air-gap} \times 2}.$$

This formula is similar in form to that given at the end of Thomson's letter, but was not, as far as I know, published. The formula therefore is a confirmation of the one communicated to Colonel Crompton's firm several years earlier and on which a large number of the machines of that date were being manufactured by him.

"An analogy will explain the idea underlying this letter, which idea certainly was not generally appreciated until Kapp's paper was read. If a magnet be pushed into a circular closed conducting circuit of uniform material and section, an e.m.f. will be set up. This will be of the same value in every element of length and there will be no difference of potential between the individual lengths. If, however, the conductor is of different sections or of different materials in selected parts, then, the current being the same at every part of the circuit, each element of length will not use up (so to speak) its own e.m.f. and differences of potential will exist between parts of the circuit. In the case of a solenoid of infinite length, considered by Maxwell and referred to by Thomson (page 284, vol. 2, 2nd edition of Maxwell's treatise), or its equivalent, a toroid magnetic ring, the magnetic force is treated as being in air and the windings uniformly distributed, and, corresponding to the uniform wire above mentioned, there is no magnetic difference of potential inside the winding. Thomson's letter explains how, if the solenoid surrounds in part a material of infinite permeability and in part there is an air space of small permeability, the whole magnetic force produced by the solenoid concentrates on this air space. In the actual case the material, iron, is not of infinite permeability, but of a permeability much greater than air, and this gives rise to the modified form of the equations which Kapp had reached empirically. In May 1886, a paper was read before the Royal Society by the brothers John and Edward Hopkinson, which completed the subject and which treated the magnetic circuit in the manner suggested by Thomson in this unpublished letter, and placed dynamo design, so far as the magnetic circuit was concerned, on a perfectly sound scientific basis."

Elections and Transfers of Members.

At the Ordinary Meeting held on the 13th March, 1930, the following elections and transfers were effected:—

ELECTIONS.

Associate Members.

Baldwin, Percy Noel St. J., Lieut.-Commdr.R.N.,B.A.
Bearcroft, Ernest Charles L., Captain R.M.
Booth, John Arthur.
Brown,John Hugh H.,M.A.
Cameron, Gregor Stuart.
Dale, William Bourne.
Edgley, George Wilfred.
Fleming, Elliott.
McKenna, John Joseph.
Mackenzie, John Peacock, Captain R.S.
Nutt, Alfred.
Padmore, Bertram Read.
Rawlinson, William Ferdinando, D.Sc.
Semenza, Marco.
Shaw, Sydney.
Wager, Albert James.
Welman, Herbert Loftus, Lieut.-Commdr. R.N.
White, Arthur Edwin.
Winstanley,HenryMurray.
Wood, Percy Thornton.

Associates.

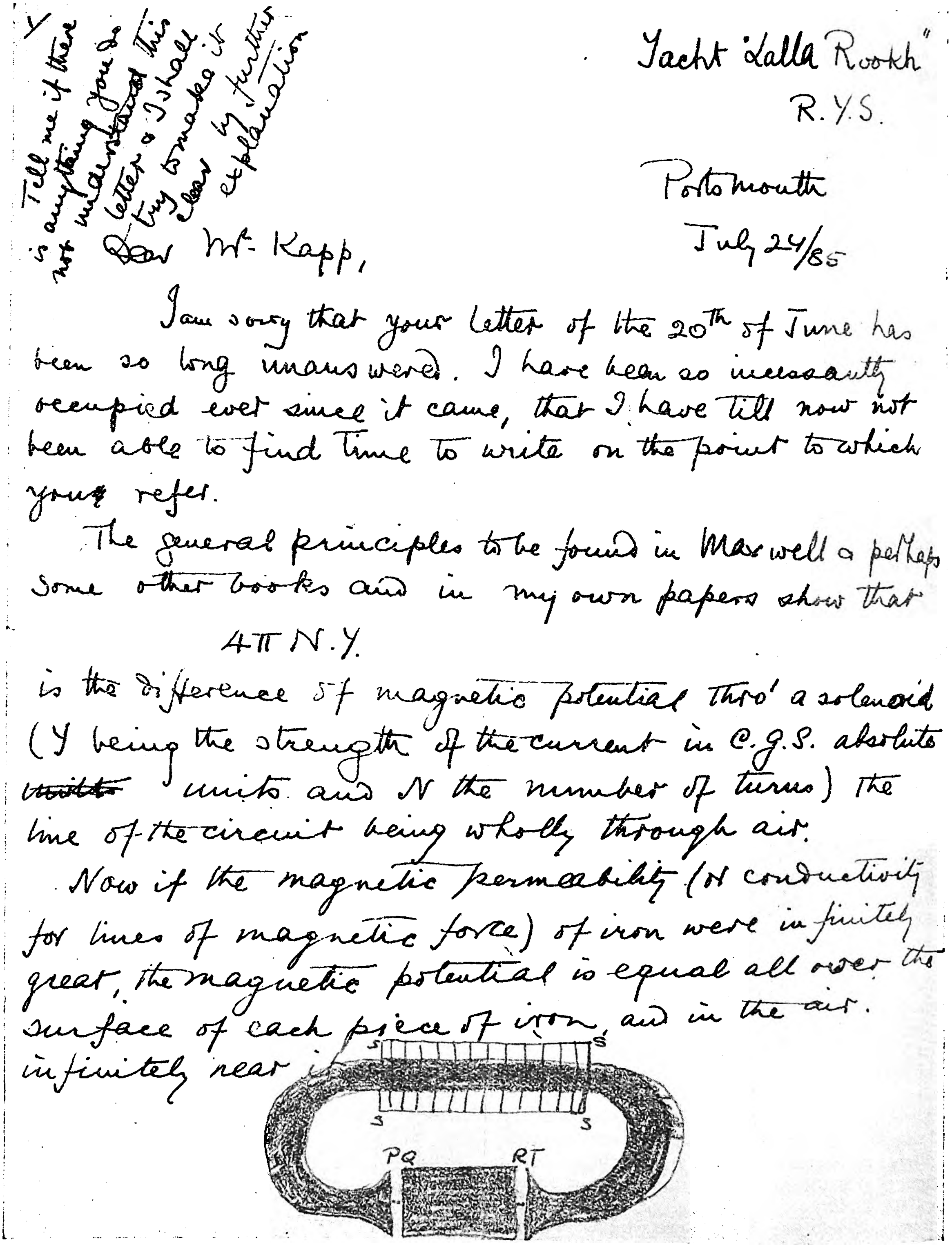
Fawcett, John William.
Gallop, Charles Clayton.
Hanlon, Edwin Marcus G.
Holmes, Walter.
Mitchell, John Albert.
Parry, Thomas Richard.
Paton, Thomas Chalmers.
Row, Leslie Franklin.
Wilson, James Haynes.

Graduates.

Batley, Henry.
Bradley, John James.
Britton,Geoffrey Alan C.R.
Clift, Reginald Charles.
Eastwood, Donald Rex.
Hegan, Alec.
Hesketh, Bernard William.
Hirst, Henry.
Johnston, ChristopherMaxwell, B.Sc.
Langley, Percy Albert.
Mason, William John.
Mathur,Raj Narain,B.Eng.
Small, Frank.
Squire, Major.
Taylor, John Alfred.
Thomas, David Stanley O.
Webb, Norman Arthur, B.Sc. (Eng.).
Whittaker, Stanhope Clarence.
Wilkinson,AlfredBentham.
Wyborn, Edward John, B.Sc. (Eng.).

Students.

Abraham, Thomas.
Adamson,Oliver Hardman.
Alderton, Edwin Arthur.
Ankerson, William Albert.
Aspinall, Wilfred.
Baber, Frederick James.
Bailey, Colin.
Bailey, James.
Baird, David.
Barnett,HenryCameron L.
Bell, Harry.
Ballamy, Alan Arthur.
Belsey, Frederick Harold.
Bhatia, Hans Raj.
Bhavnani, Krishna Jhamatmal.
Birch, Bryan.
Birkett, George William.
Boulter, Leonard John.
Bowron, Walter du Cane.
Branczik, Eric Anthony C.
Brown, James Kinghorn.
Bull, Arthur Harry.
Bunn, Sidney John.
Campbell, Allan.
Carruthers, James Pirrie.
Chantrill,Guy,B.Sc.(Eng.).
Christie, Ralph Fawcett, B.A.
Clarke, Walter.
Clewley, John Thomas.
Clifford, Frank.
Cock, Charles Edward.
Cockburn, Keith.
Cole, Ian Harry.
Coleman, John Peden.
Coleman, Thomas William.
Cowie, Ernest Thomas F.
Crampton, Raymond.
Cretchley,Kenneth Hinton.
Cronshaw, Frederick William.
Davies, John Ogilvie.
Dey, Alastair Paterson.
Dharni, Megh Raj.
Dickins, Denzil Vivian R.



Tell me if there is anything you do not understand this letter & I shall try to make it clear by further explanation

Yacht "Lalla Rookh"
R.Y.S.

Portsmouth
July 24/85

Dear Mr. Kapp,

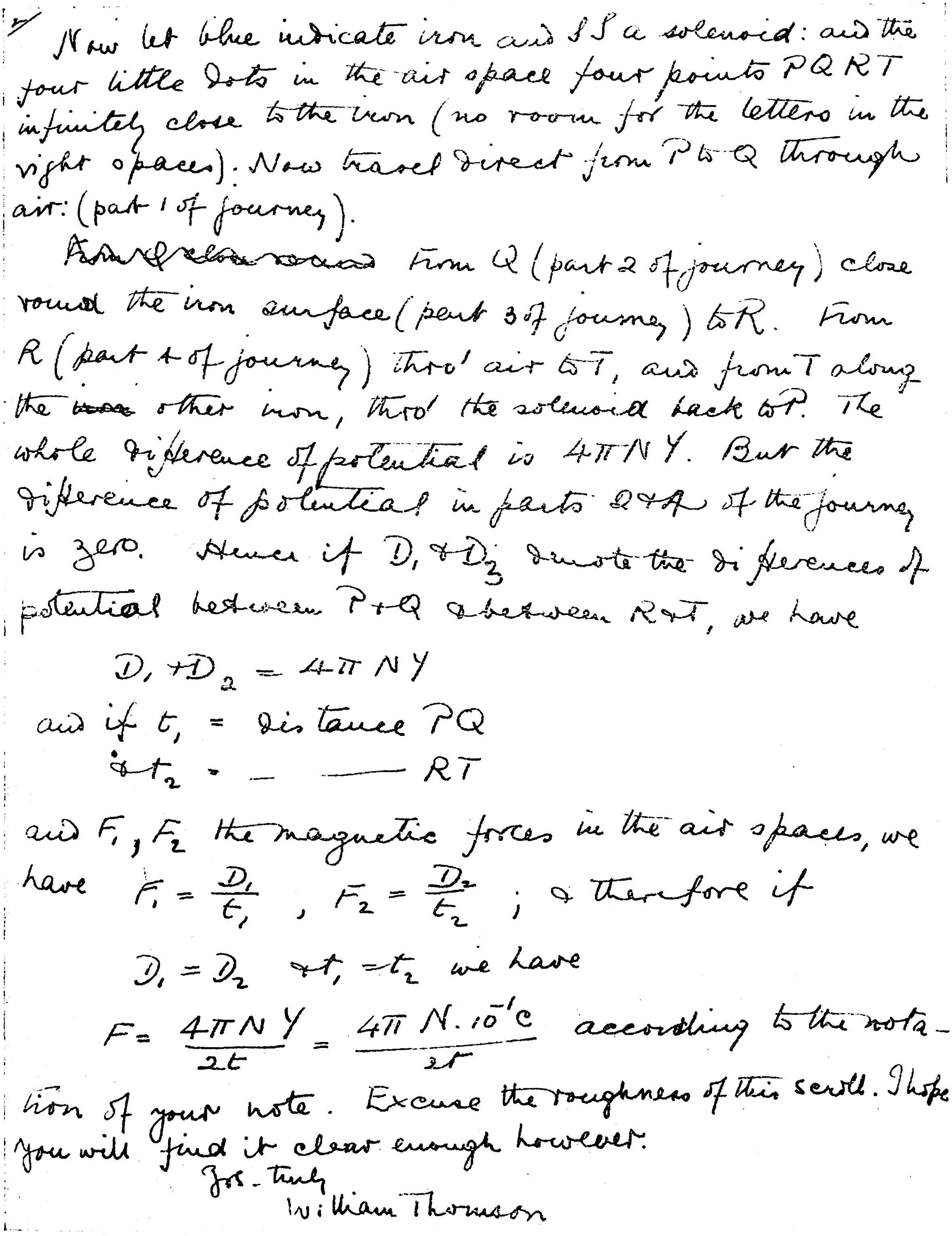
I am sorry that your letter of the 20th of June has been so long unanswered. I have been so incessantly occupied ever since it came, that I have till now not been able to find time to write on the point to which you refer.

The general principles to be found in Maxwell & perhaps some other books and in my own papers show that

$$4\pi N.\gamma$$

is the difference of magnetic potential thro' a solenoid (γ being the strength of the current in C.G.S. absolute ~~units~~ units and N the number of turns) the line of the circuit being wholly through air.

Now if the magnetic permeability (or conductivity for lines of magnetic force) of iron were infinitely great, the magnetic potential is equal all over the surface of each piece of iron, and in the air infinitely near it



Now let blue indicate iron and S S a solenoid: and the four little dots in the air space four points P Q R T infinitely close to the iron (no room for the letters in the right spaces). Now travel direct from P to Q through air: (part 1 of journey).

~~And close round~~ From Q (part 2 of journey) close round the iron surface (part 3 of journey) to R. From R (part 4 of journey) thro' air to T, and from T along the ~~[illegible]~~ other iron, thro' the solenoid back to P. The whole difference of potential is $4\pi NY$. But the difference of potential in parts 2 & 4 of the journey is zero. Hence if D_1 & D_2 denote the differences of potential between P & Q & between R & T, we have

$$D_1 + D_2 = 4\pi NY$$

and if t_1 = distance PQ

& t_2 = — —— RT

and F_1, F_2 the magnetic forces in the air spaces, we have $F_1 = \frac{D_1}{t_1}$, $F_2 = \frac{D_2}{t_2}$; & therefore if

$D_1 = D_2$ & $t_1 = t_2$ we have

$$F = \frac{4\pi NY}{2t} = \frac{4\pi N . 10^{-1}c}{2t}$$

according to the notation of your note. Excuse the roughness of this scroll. I hope you will find it clear enough however.

Yrs. truly

William Thomson

Students—continued.

Dogra, Hem Raj.
Dubovich, Jacob.
Dunkel, Christian Peter.
Dyer, Clement Stanley.
Elders, Donovan Pickton.
Ellis, Jack.
Ferguson, Andrew, B.Sc.
Fleming, Frederick George.
Gardner, Harry St.George.
Gidden, John Henry.
Gillett, Edward Arthur.
Goatcher, John.
Goodhew, Eric Geoffrey.
Gooud, William Robert.
Graham, Arthur George.
Graham, James Wilson.
Hackett, Stanley Gordon.
Havart, Ralph Travah.
Hawkes, Richard Christian.
Haythorne, William Outram.
Hearfield, Norman.
Helliwell, Kenneth.
Hewett, Henry Kensit.
Hibberd, Percy Albert.
Hickman, Terence Ernest.
Hill, Francis Glynn.
Hind, Douglas McGechan.
Hinks, Geoffrey Ditom.
Horridge, Arthur.
Imlach, Douglas Forbes.
Irens, Alfred Norman.
Jackson, Donald.
Jackson, John Benedict.
Johns, Rowland Harvey.
Johnson, Alec Owen, B.Sc. Tech.
Jones, William George.
Karim, Fazal.
Katrak, Minoo Ardeshir.
Keay, Andrew Leslie.
Kerr, Edward Stephen.
Kettlewell, John Robert W.
Khan, Ghulam Sadiq, B.A.
King, George Alfred T.
Krishna, Mylapore Bala C.
Krishnamachar, D. A.
Latif, C. M.
Lavington, Edgar.
Lawes, Reginald John.
Lloyd, Charles Noel.
McGill, John Stirling.
McLaren, Ronald Wroughton.
McNeal, George Allan.
Maddock, Roger Raymond.
Marsh, Nevill Francis, B.A.
Master, Navnitlal Hiralal, B.Sc.
Masters, William England.
Meggeson, George Richard.
Messenger, Albert Roy.
Mew, Gordon Merrifield, B.Sc. (Eng.).
Moore, Arthur Charles C.
Murison, Rae.
Norgrove, Edward Henry.
Orgill, Frank.
Oxley, John Harrison.
Palmer, Cyril Walter.
Paterson-Jones, Edward Alexander.
Pearce, Arthur James.
Pearson, Joseph Benjamin.
Phillips, Philip Carthew.
Pilkington, Garnier David.
Powell, Geoffrey Charles T.
Powditch, Raymond Vernon.
Pratt, Frederick Martin.
Ratnam, Chelasani Venkata.
Renfree, Harold Rolls.
Rennels, Cyril Hender.
Rhodes, Bernard, B.Sc.
Richardson, Claude Morris.
Riddell, Alexander.
Rippon, Edward Collingwood.
Rogers, Bernard Henry G.
Rogers, Francis Gordon.
Rowan, Vernon Harley.
Rowbotham, Hugh Rigby.
Sadleir, Cedric William M.
Sadleir, Keith Arthur.
Sarup, Shanti.
Scott, William Carlisle.
Seaman, Matthew.
Shelley, Frederick William.
Simmonds, Philip Ellis.
Singh, Hardial.
Singh, Manohar.
Sirry, Mostafa.
Smith, Charles Eric.
Stebbing, Geoffrey Charles.
Stewart, David Hopkins.
Suffield, Hilary Robert H.
Tait, William Ashton.
Taylor, Harold Frederick R.
Taylor, Paul Harvard.
Terry, George Albert.
Thomson, Hubert Archer.
Thorneycroft, William Henry.
Todd, William Russell.
Tribe, Henry Thomas.
Wallace, Samuel Archibald.
Walsh, William Ronald.
Walton, Stanley Morgan.
Warbrick, Cecil.
Warwick, George Alan.
Wassell, Harold Joseph H.
Watkins, Frederick Charles.
Wesley, Alec Charles.
Wicks, Stanley Thomas.
Wilcock, Albert.
Wragge, Colin Gordon.
Wynn, Cyril Frank.

TRANSFERS.

Associate Member to Member.

Johnson, Arthur Carrol.
Johnson, Herbert Henry.
McDermott, John.
Peebles, Arthur Charlesworth, O.B.E.
Watkins, Stanley Sylvester A., B.Sc. (Eng.).

Associate to Associate Member.

McLeod, Henry Francis.

Graduate to Associate Member.

Bryan, Ernest Alfred J.
Chase, John Joseph.
Fox, Cecil Percy, B.Sc. (Eng.).
Graham, Reginald Christopher M.
Howse, Henry Arthur G.
Lucas, George Sail C.
MacQueen, Alexander Cameron.
O'Connor, Charles Patrick, B.Sc. (Eng.).
Orme, John Leonard.
Reading, John, B.Sc. (Eng.).
Spence, Samuel, B.Sc.
Stewart, John McCulloch.
Swensen, Erling.

Student to Associate Member.

Durand, Philippe Henri R., B.Sc. (Eng.).
Lyall, James Soutar, B.Sc. (Eng.).
Tagg, George Frank, B.Sc. (Eng.).

The following transfers have also been effected by the Council under the provisions of Bye-Laws 14 and 18:—

TRANSFERS.

Associate to Graduate.

Bull, Walter John H.
Damp, John William.

Student to Graduate.

Beara, Harry Wilmot.
Belliss, William Howard A., B.Eng.
Bhatia, Shamdas Dandumal, B.Sc.Tech.
Broadhurst, Jack.
Brown, Ronald Stewart.
Connelly, Thomas Maurice, B.Sc. (Eng.).
Cunliffe, Edward Neil, B.Sc.Tech.
Douglas, Thomas Kenneth A., B.Sc.
Farrant, Dover Pearce.
Farries, Herman Ramsay, B.Sc.
Greaves, John Milne.
Hackett, Winifred (Miss), B.Sc.
Halford, Richard.
Harvey, Leonard.
Hedley, Isaac Herdman, B.Sc. (Eng.).
Hewlett, Edward William.
Jordan, Edwin Horace.
Kelly, Gerald Emil, B.Eng.
Kippen, Maxwell Duncan, B.Sc.
Lister, Clement Marshall.
McLean, George Edwin.
Morton, James Dickie, B.Sc.
Nuttall, Alexander Kirkpatrick, B.A.
Purden, Robert Hesketh.
Ratcliffe, Augustus David J., B.Sc.
Rudd, Charles Henry.
Singh, Kartar.
Wallace, Douglas Stewart, B.Sc. (Eng.).
West, Harry.
White, Henry Lachlan.

RECENT DEVELOPMENTS IN THE PROTECTION OF THREE-PHASE TRANSMISSION LINES AND FEEDERS.

By T. W. Ross and H. G. Bell, M.Sc. Tech., Associate Members.

Paper first received 10*th June*, 1929, *and in final form* 6*th June*, 1930; *read before* The Institution 9*th January*, *before the* South Midland Centre 20*th January*, *before the* North-Eastern Centre 10*th February*, *and before the* Western Centre 17*th February*, 1930.)

Summary.

The problems associated with the protection of transmission lines and feeders have in recent years become of great moment, and much development of the art has resulted. Some of the difficulties which have arisen in practice are emphasized and some of the methods of overcoming them are described. The design and lay-out of distribution systems, the earthing of the neutral point and the application of arc-suppression coils are briefly discussed, more particularly in their relation to problems of protection. Factors which influence the choice of protective systems are considered and the requirements of schemes to meet the exacting conditions of modern transmission systems are surveyed.

The several methods of obtaining discriminative protection are then reviewed. Commencing with modern designs of time-discriminative overcurrent relays, emphasis is laid upon the importance of a definite minimum time characteristic and upon correct methods of obtaining directional features. The special requirements of such relays when applied to give sensitive earth-fault protection are indicated, and means of obtaining a suitable polarizing voltage are explained; a description of sensitive earth-fault relays of the wattmeter type is also given.

The theory and application of impedance relays is discussed, with reference to definite-impedance and impedance-time relays. A method of compensation for voltage-drop across the arc resistance of a fault is indicated. The field of application of low-voltage release relays is defined and the method of their use illustrated.

Attention is then directed to the advantages of pilot-wire feeder protection, and the limiting features of older forms are mentioned. Typical modern opposed-voltage and circulating-current methods which are giving satisfactory service on modern systems are described in some detail. The new field of direct-current pilot-wire protection is discussed; the main classifications of this type of gear are defined and examples are given. The paper concludes with a description of a novel and flexible method of protection for duplicate and multiple parallel feeders.

Introduction.

Electrical energy has become such an essential factor in the life and well-being of the community that a very heavy responsibility rests upon supply authorities to maintain the supply under all conditions. This becomes ever more difficult with the growth in size of supply undertakings because of the larger short-circuit currents possible and the continual extension of systems. A failure of insulation at any point on such large systems may cause widespread disturbance and dislocation of supply unless the faulty unit is rapidly isolated. This can only be achieved by a carefully considered lay-out of the network and the correct choice and application of protective gear.

There is perhaps no other branch of electrical engineering in which so much ingenuity has been displayed as in the design of protective systems and devices, a considerable number of which have been tested under practical conditions. In many cases, however, theoretically promising schemes have proved to be unsatisfactory in practice owing, as a rule, to incorrect operation resulting in the cutting out of healthy feeders in addition to or instead of the faulty ones, rather than to failure of the gear to clear a fault. Such unwanted operation is in some cases the result of the abnormal conditions which exist during short-circuits, and the lack of appreciation of such conditions at the time the gear was designed. In other cases the heavier disturbances consequent upon the growth of the supply system have resulted in the incorrect operation of protective gear which under less onerous conditions gave entire satisfaction.

During the last 15 years the science of correctly protecting machines, transformers and feeders, so as to combine the necessary sensitiveness with stability, has been gradually developed, and the methods successfully applied to smaller machines and transformers have been found to apply, with slight modifications, to the larger units used to-day. The extension of high-voltage networks has, however, introduced entirely new factors into the question of feeder protection and it has been found that the methods hitherto used are no longer suitable for many e.h.t. feeders.

Modern Conditions.—Of the many causes which have combined to increase the difficulties of feeder protection, the exceedingly heavy faults which occur in the large networks of to-day constitute perhaps the chief. The fault currents are carried not only by the faulty sections but also by healthy sections, so that it becomes necessary to provide either balanced gear which will remain stable, or other discriminative gear which will retain its correct discrimination with much heavier through-currents. At the same time these heavy fault currents demand protective gear which will provide for rapid clearance, not only on account of the damage that may be caused in the neighbourhood of the fault but also to diminish the liability of synchronous plant falling out of step, with the consequent risk of extensive dislocation.

The extension of feeder networks, combined with the higher voltages at which they are operated, has resulted in larger charging currents in the lines and cables, and when balanced protective gear is in use these currents are of importance as they represent, under healthy conditions, an out-of-balance similar to that which exists during a fault. These currents also assume higher values in healthy feeders during fault conditions on other parts of the system, owing to the rapid voltage-change which sets up transient disturbances of frequencies much higher than the normal. Quite independently of this, other currents are induced in or find their way into the pilot cables. For satisfactory stability, balanced systems of protection must be compensated for all such conditions.

In many cases feeder networks, instead of receiving, as formerly, a supply from a single point, have now a number of feeding points, and as a result the direction in which fault currents may flow in certain of the feeders depends upon the position of the fault on the network. A similar consequence arises from the increasing use of ring mains, and although this introduces no additional difficulty where balanced protection is used, yet where other types of protective gear are employed directional relays must be installed. The increasing complexity of feeder networks also introduces new difficulties into the forecasting of the distribution of fault currents in the various feeders under all conditions, and very careful computations are necessary in many cases. When it is remembered that the opening of a switch at one end of a faulty feeder may cause a complete redistribution of fault currents in the entire network, the care necessary in the correct relaying of a complicated system will be appreciated. In certain cases where the capacity of connected generators may be varied considerably, fault currents at times of light load can actually be less than normal load current under maximum load conditions. Special schemes must be developed to provide for such requirements.

In this country balanced protective gear has been practically standard for the short feeders which have been in service. The greater distances which have now to be covered by feeders render the use of pilot wires and special cables prohibitive in many instances, and consequently non-pilot methods not requiring special cables must be used in many installations. It is desirable that such methods should give protection comparable with that obtainable with shorter feeders.

SYSTEM ARRANGEMENTS.

There are many factors in the design and lay-out of distribution systems and switchgear which materially influence the effectiveness of the protective measures, and these should be given due consideration when a system is planned. Such a course will in many cases result in more satisfactory protection with less complicated gear. The introduction of reactances, for instance, between different parts of a system is often helpful in limiting the short-circuit current which would otherwise be heavy enough to cause disturbance to the whole system, and the use of reactors is becoming more common, particularly at tie points, where the effect upon the voltage regulation of the system is less pronounced than if reactors were used in series with individual feeders. Special switching arrangements are often responsible for introducing difficulties and, although such arrangements are usually designed with a view to meeting possible emergency conditions, it is desirable to give due consideration to the question of protection before finally deciding upon them.

Neutral Points of Systems.—It will be agreed that the adoption of an insulated neutral or, if earthed, the method of earthing used, will have considerable effect upon the nature of the disturbances which may arise under fault conditions. There is, however, some difference of opinion as to the relative merits of an insulated versus an earthed neutral, and whilst in America the practice is to earth solidly, Continental engineers favour the insulated neutral. The practice in this country is to earth the neutral point, and current-limiting resistances are largely used for this purpose on e.h.t. systems up to 33 kV. This is done on the assumption that most faults start as faults to earth and that, by reducing the current which can flow to earth, less disturbance will arise. There is, however, a danger in applying this method to the higher-voltage systems, since the resistance, by maintaining the voltage on the faulty phase, will cause a rise in pressure between the healthy phases and earth. This may result in the development of an earth fault on one of these phases at any point on the system. It is also possible that transient voltages may be present which can add to the fundamental voltage and thus increase the strain on the insulation of the sound phases. Again, at the higher voltages earth faults very quickly develop into short-circuits between phases, when, of course, the earthing resistance cannot limit the magnitude of the current. The short-circuit between phases may, in many cases, be prevented by quick clearance of the earth fault, but this can often be more easily accomplished by allowing a greater current to flow and so help in the operation of the relays. It would appear that it is preferable to have a solid earth connection for voltages above 20 kV, but an expression of opinion from operating engineers on this important point would be welcome.

If an earthed neutral is decided upon, the question of earthing at more than one point very often arises. From the protection engineer's point of view, the earthing of the neutrals of the transformers at several points on the system has much to commend it, not only because it limits transient excess voltages but also because it facilitates the application of some relay schemes described later. The opposition of telephone authorities may, however, have to be overcome before multiple earthing can be employed. In this connection it is of interest to recall a statement by Messrs. Johnstone Wright and C. W. Marshall in their recent paper * to the effect that "After examining the subject from every standpoint, it has been definitely decided that the earthed neutral system is better than the insulated neutral system as regards non-interference with communication circuits."

Arc Suppression.—The practice of operating with an insulated neutral which is common on the Continent has not proved entirely satisfactory, and with the object of obtaining an improvement in the operation of such systems a number of arc-suppression or Petersen coils have been installed since 1920. The device consists of an iron-cored reactance having a number of tappings connected to a suitable tapping switch. The coil is connected between a neutral point and earth and its inductance is adjusted by means of the tapping switch so that at the fundamental frequency it resonates with the electrostatic capacity to earth of two phases of the network. When an earth fault takes place, therefore, there will be no current flowing to earth through the fault and an arc cannot be maintained. The result is that in the case of a flash-over on an insulator the probability is that the fault will clear itself without the necessity of tripping the circuit breakers. There will also be little or no danger of an abnormal rise in voltage between the healthy phases and earth, such as results from the repeated formation and extinction of an arc. Even where the fault is caused by a breakdown of an insulator, the arc is extinguished and the possibility of excessive strain on the insulation of healthy phases is less than would be the case if the system had an insulated neutral and no arc-suppression coil. This method has perhaps greater possibilities when applied to overhead lines than to cable networks, because earth faults on the former are usually caused by the flash-over of an insulator, in which case the suppressor would prevent the arc doing damage and the fault would probably clear itself.

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* "The Construction of the 'Grid' Transmission System in Great Britain," *Journal I.E.E.*, 1929, vol. 67, p. 685.

Where arc suppressors are used, no single-phase failure of a permanent character can be cleared by selective relays since no earth-fault current flows in the faulty phase, and the system must be operated with one phase at earth potential until the fault can be located and the faulty section isolated.

A further development of this method of earthing permits the use of selective relays for the isolation of faulty sections whilst retaining the advantages resulting from the use of the arc suppressor. A relay having a suitable time-delay is energized from the suppression coil and operates to connect the system to earth either directly or through a resistance, should an earth fault persist on any line. The system then becomes temporarily an earthed system and the faulty section can be isolated by suitable protective gear. Fig. 1 shows such an arrangement and also the distribution of the fault current flowing before the system is earthed through the resistance. It should be noted that the arc-suppression coil is so adjusted that resonance is obtained between the inductance of the coil and the electrostatic capacity of the healthy phases. This is indicated in the diagram by the distribution of the current and the fact that no current flows into the fault. Theoretically, this arrangement is very attractive and it is at present being installed or operated by several supply companies operating abroad. The operating experience now being accumulated will show whether these advantages are obtained in practice.

The greatest difficulty in applying arc-suppression coils is the necessity of adjusting the inductance when an alteration is made in the number of feeders in service. This can be overcome if each section of the network is provided with an arc-suppression coil of sufficient inductance to compensate for the capacity of that section. The coil can then be switched at the same time as the network section is switched, without affecting the remainder of the system.

Experience has proved that satisfactory operation can be obtained on a system of overhead lines with a dissonance of as much as 30 per cent. If, therefore, there are several arc-suppression coils on such a system, very little adjustment of the turns is necessary to meet ordinary operating conditions.

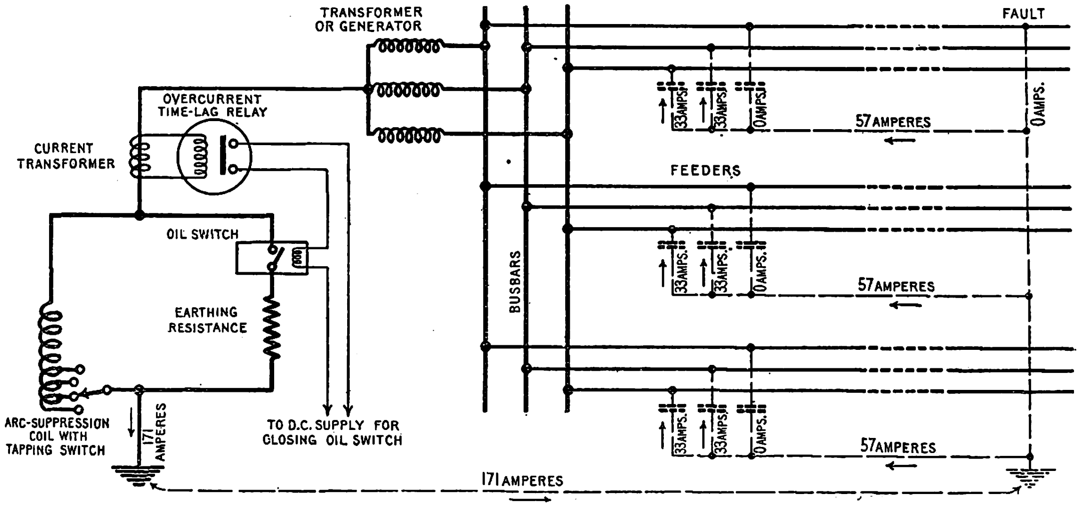


Fig. 1.—Arc-suppression coil with automatic auxiliary earthing device.

The Choice of Protective Systems.

The supply engineer called upon to choose protective gear for his special requirements finds himself faced with a bewildering array of relays and different types of gear. In a paper such as this it is impossible to describe all in detail, but an attempt is made to indicate the lines along which modern protective methods are developing, and to set out as clearly as possible the relative merits of each. This, of course, can only be carried out in a very general sense, since, before the correct choice can be made for any particular case, full consideration of all the special circumstances must be made.

The capital cost and maintenance charges on protective gear are generally regarded as a type of insurance premium, and the amount of money allocated for this purpose will largely be determined by the value placed upon the continuity of the supply at all points. For instance, the additional expense of pilot wires for certain protective schemes, which undoubtedly possess many advantages, cannot in many cases be justified, and other discriminative methods may have to be substituted. It may be necessary to take into consideration the liability of a feeder to breakdown, the existence of alternative routes of supply, the importance of the load, the liability of a fault to cause extensive disturbance and any other special conditions.

Discriminative Time and Directional Protection.—One of the first attempts to obtain the selective or sequential tripping of circuit-interrupting devices was the grading of ordinary circuit fuses, the heaviest fuse being used nearest the source of supply. This method failed because at heavy overloads the different fuses ruptured simultaneously and their discriminating features disappeared. This lack of discrimination is even more pronounced in the case of the so-called " time-limit fuses " often used for shunting the trip coils of circuit breakers. This is because the additional time for the operation of the circuit-breaker mechanism allows more time for the rupturing of the heavier fuses. Time-lag trip coils having mechanical time-lag mechanisms have also been tried and found to be unsatisfactory, but in this case the failure has been due more to defective design than to any fundamental weakness.

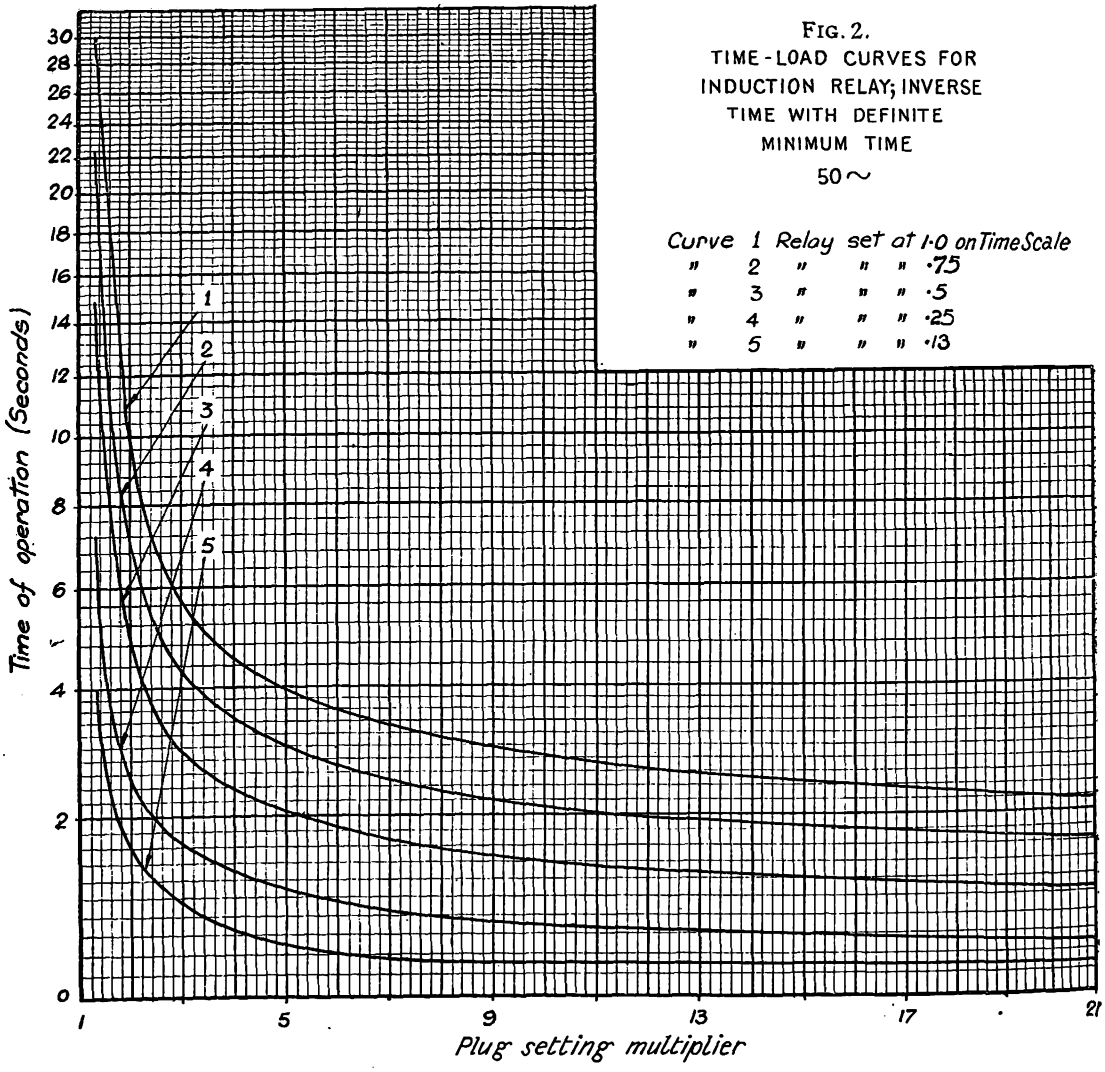


FIG. 2.
TIME-LOAD CURVES FOR
INDUCTION RELAY; INVERSE
TIME WITH DEFINITE
MINIMUM TIME
50 ~

FIG. 2.

The earlier time-limit relays were much more satisfactory but they were not, as a general rule, sufficiently accurate to allow of short time-intervals between successive circuit breakers. Time-limit relays are of two types, (*a*) " definite time," and (*b*) " inverse time," the former having a time-limit entirely independent of the value of the current and the latter having a time-limit which varies inversely as the current.

The necessity of disconnecting faulty feeders with the shortest possible delay, so that the disturbance to the system shall be minimized, demands that the time-interval between successive circuit breakers shall be as small as possible. Time-delay relays must therefore be sufficiently accurate to allow of close time-settings. The maximum time that can elapse between the short-circuit occurring and the operation of the circuit breaker without affecting the synchronous plant, is usually assumed to be of the order of 2 seconds. It is, however, difficult to estimate the effect which every short-circuit will have upon the stability of a system, and this figure is quite arbitrary. Allowing that the circuit breaker takes 0·25 sec. to clear the fault after its trip coil is energized, the successive relays must have a time-interval of at least 0·5 sec. between them. If the maximum time is not to be more than 2 seconds, it will then be possible to get discrimination with 5 circuit breakers in series, and there are relays available which are sufficiently accurate for such settings.

Definite Minimum Time-Limit Relays.—Probably the simplest and best relay for this purpose is the induction overcurrent relay which is generally of the inverse time-limit type but must be designed with definite minimum time features. The latter feature is necessary to assure that sufficient time is allowed for discrimination with the largest short-circuit current. Characteristic curves for this relay are shown in Fig. 2, and it will be seen that while for the smaller overloads the time varies inversely as the current, at the heavier overloads it becomes approximately constant and independent of the value of the current. An accuracy of plus or minus 5 per cent in the operating time of the relay is usually obtainable with an instrument of good design, and this is ample for correct discrimination. Moreover, the extreme simplicity of design achieved in some relays assures the retention of this accuracy over long periods. A further important consideration is that the accuracy is obtainable with an operating coil which has a comparatively low impedance. This is of great importance when relays have to operate from current transformers of the bushing type, which are generally suitable for only a small secondary output. Standard induction relays can now be obtained the operating coils of which require only 2 to 3 volt-amperes, and in special cases the burden on the current transformer can be reduced to less than 1 volt-ampere.

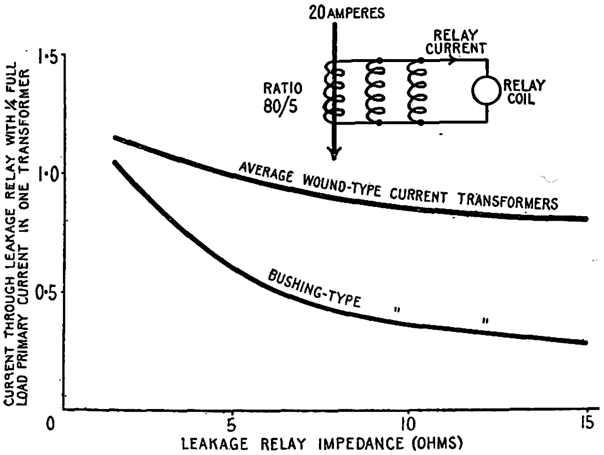


FIG. 3.—Distribution of current between relay and idle current transformers.

Low-impedance relays are also desirable if they are to be used as earth-fault relays on the residual-current principle, because when connected in this way part of the residual current will be shunted by the secondary windings of the two current transformers connected in the healthy phases and hence is not available for operating the relay. It will be apparent that the distribution of the secondary current between the relay coil and the two current-transformer windings will depend upon the relative impedance of the two paths, and if the relay has a comparatively low impedance its effective sensitivity will be increased. The curves in Fig. 3 show how the relation between the earth-fault current and relay current varies with the impedance of the current transformers and relays. It will also be seen that when bushing current transformers are used, a relay having a very low impedance is essential, if reasonable settings are to be obtained. The impedance of current-transformer secondary windings may be greatly increased if the cores are made from any of the recently developed high-permeability iron alloys, but these materials are as yet comparatively expensive and their application is in consequence limited. In many cases, however, they offer sufficient advantages to justify the extra cost involved.

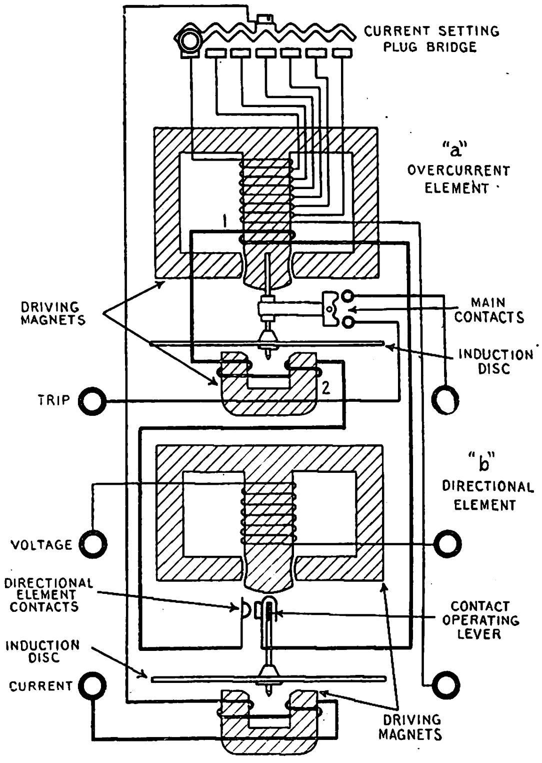


FIG. 4.—Directional overcurrent relay.

Directional Overcurrent Relays.—When graded time-limit protection is applied to ring mains or interconnected networks, in which fault current can flow in both directions, it is, of course, necessary for the relays to have directional features, in addition to the usual overcurrent and definite minimum time characteristics. Ordinary wattmeter-type relays are unsatisfactory for the purpose as the operating torque of such relays is proportional to the power factor and the voltage, both of which may be low during fault conditions. A sensitive instantaneous wattmeter element is, however, necessary in a directional overcurrent relay to indicate the direction of power flow, with an additional overcurrent time-limit element for time discrimination. Sometimes the contacts of the directional relay are connected in series with the contacts of the overcurrent time-limit relay, so that both sets of contacts must close before the circuit breaker can be tripped, but this practice is not recommended as it may cause incorrect tripping. This is due to the possibility of the overcurrent relay having its contacts closed when the fault power is flowing in the direction to open the directional contacts and after the fault has been removed by some other circuit breaker, the direction of power flow suddenly reversing before the overcurrent relay has reset. This can be overcome by arranging that the overcurrent relay cannot commence to operate until the power flow is in the required direction. A diagram of a directional overcurrent relay embodying the latter feature is shown in Fig. 4.

It will be seen from the illustration that the relay consists of two separate elements mounted in a single case, "a" being the overcurrent inverse-cum-definite minimum time relay, having characteristic curves as shown in Fig. 2, whilst "b" is a sensitive wattmeter element which operates instantaneously. The contacts of the latter element are so connected that they complete the circuit between the secondary winding of the top electromagnet (1) and the bottom electromagnet (2) of the overcurrent element "a." The latter cannot start to operate until the directional element contacts are closed, thereby allowing current to circulate through the secondary winding and so set up the moving field necessary to produce a torque in the relay movement. The secondary winding (1) is designed to give sufficient induced voltage at the lowest current setting to ensure satisfactory operation through the directional contacts.

The directional or wattmeter element has very little bias or spring control and therefore is entirely free to operate in either direction when the power flowing is as low as 4 per cent of normal, even if the voltage has fallen to 1 per cent of normal. It will thus be seen that under the most severe short-circuit conditions the directional element will correctly indicate the direction of power flow and will only allow the overcurrent element to operate when the flow is in the desired direction. The relay is therefore virtually a directional current relay as distinct from a directional power relay, and its time characteristic is a function of the current only. Fig. 5 is a single-line diagram of a ring main with overcurrent directional relay protection, with graded time-limits.

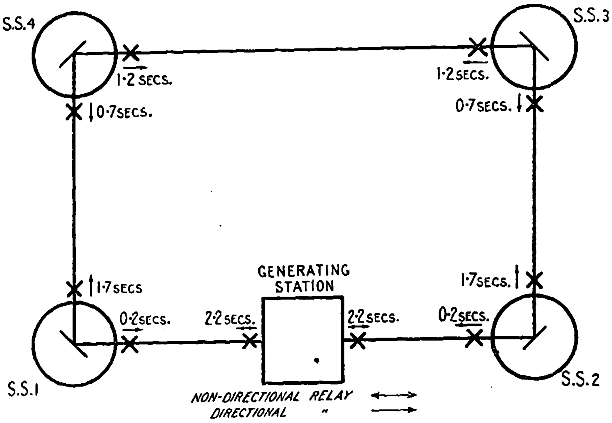

S.S.4
S.S.3
1·2 SECS.
1·2 SECS.
0·7 SECS.
0·7 SECS.
GENERATING STATION
1·7 SECS
1·7 SECS.
0·2 SECS.
2·2 SECS.
2·2 SECS.
0·2 SECS.
S.S.1
S.S.2
NON-DIRECTIONAL RELAY
DIRECTIONAL "

FIG. 5.—Discriminative time protection of ring main.

Directional Earth-Fault Protection.—When applying the directional overcurrent relay to earth-fault protection on the "residual-current" principle, the question arises of energizing the leakage relay potential element from a voltage corresponding to that of the faulty phase. The method sometimes employed of using a directional relay in each phase and connecting the contacts in parallel,

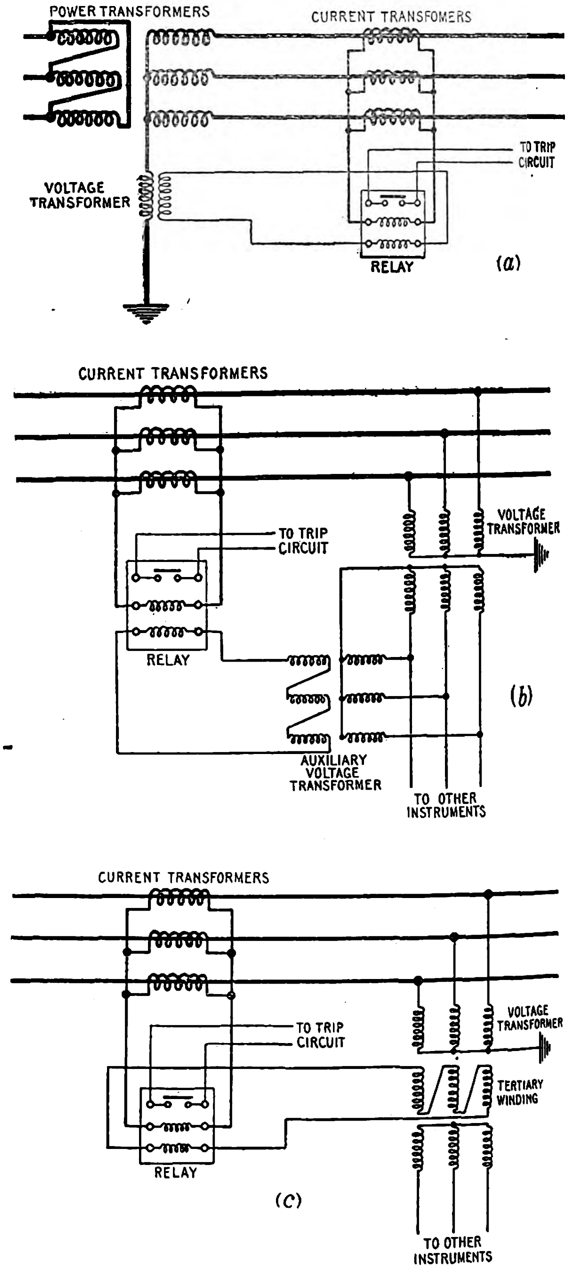

POWER TRANSFORMERS
CURRENT TRANSFOMERS
TO TRIP CIRCUIT
VOLTAGE TRANSFORMER
RELAY
(a)
CURRENT TRANSFORMERS
TO TRIP CIRCUIT
VOLTAGE TRANSFORMER
RELAY
AUXILIARY VOLTAGE TRANSFORMER
TO OTHER INSTRUMENTS
(b)
CURRENT TRANSFORMERS
TO TRIP CIRCUIT
VOLTAGE TRANSFORMER
TERTIARY WINDING
RELAY
(c)
TO OTHER INSTRUMENTS

FIG. 6.—Connections for directional relays for earth-fault protection.

these being connected in series with the contacts of the residual-current relay, is unsatisfactory, as the power flow in the healthy phases may be in the opposite direction to that on the faulty phase and would then give incorrect selection as to direction.

There are, however, several methods by which it is possible to obtain a voltage for the directional element that will have the correct phase relationship with the faulty phase, and these are indicated in Figs. 6 and 7. The simplest method is that shown by Fig. 6(*a*), but this can only be applied if the neutral point of a power transformer is available.

The second method, shown in Figs. 6(*b*) and 6(*c*), is much more flexible and can conveniently be used whenever there is a voltage transformer available. The auxiliary transformer [Fig. 6(*b*)], which has a ratio of 1 : 1, is only necessary when the main voltage transformer is connected star/star. A delta-connected tertiary winding on the latter [Fig. 6(*c*)] can be used instead of the auxiliary transformer. It should be noted that it is essential to earth the neutral point of the voltage-transformer primary winding, and it is preferable to use shell-type voltage transformers or 3 single-phase units in order to avoid errors due to magnetic interaction.

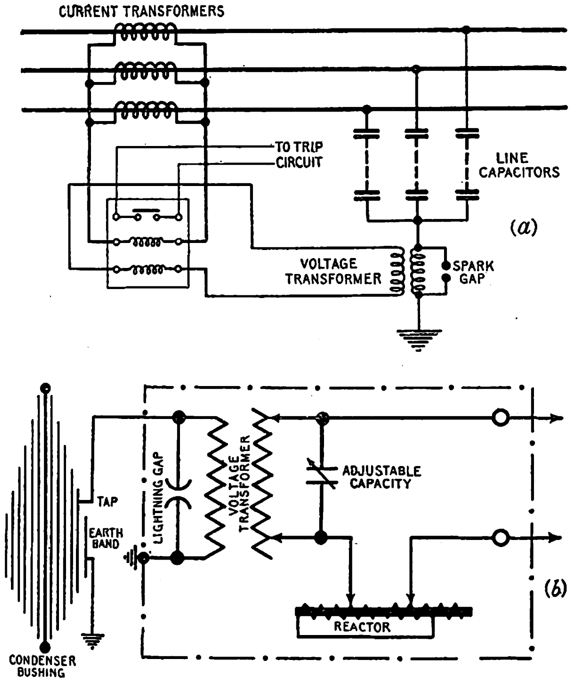


Fig. 7.—Connections for directional relays for earth-fault protection.

It will be understood that so long as equal voltages exist between each phase and earth, no voltage will appear between the two points in the delta winding where the relay is connected, but when one phase is connected to earth a voltage will be present which under the most favourable conditions will have a value three times as great as that across each phase of the delta winding under healthy conditions.

The third method [Fig. 7(*a*)] is practicable only on systems operating at 22 kV or above, and depends upon the use of condensers suspended from the lines. Normally the currents in the condensers of the three phases will sum to zero and the voltage transformer connected between the star point and earth will not be energized. With an earth fault on any line, however, this symmetry will be upset, and a secondary voltage can be obtained from the voltage transformer; this voltage will be of the same phase as the normal voltage of the faulty line.

In the case of lines of 88 kV and above, a voltage can be obtained from the condenser bushings of oil circuit-breakers or power transformers by the method indicated in Fig. 7(*b*). The charging current of each bushing is utilized by connecting a voltage transformer in parallel with the last stage of the bushing. The normal charging current is thus divided between the last stage of the bushing and the voltage-transformer winding, so that a secondary voltage can be obtained, which will, however, differ in phase from the line voltage. It is therefore necessary to correct for this phase difference and this is done by means of a network consisting of capacity and inductance, as shown in the diagram. When used for earth-fault protection, three of these devices will be required with their output circuits connected in series. Normally the three voltages will produce no resultant, but under earth-fault conditions this balance will be disturbed as already described.

It will be appreciated that in all these methods the voltage across the relay voltage winding is zero until an earth fault occurs.

THE APPLICATION OF WATTMETER-TYPE RELAYS TO EARTH-LEAKAGE PROTECTION.

On Systems with Insulated Neutral.—One of the drawbacks to an insulated system is that when a fault takes place between one phase and earth there is usually insufficient fault current to operate ordinary overcurrent relays, and therefore earth faults must remain on the system until they are cleared by manual operation of the circuit breakers, or until they develop into faults between phases. There are two distinct reasons why it is undesirable to allow earth faults to remain on the system, (*a*) because in the case of overhead lines the arc may be carried by a breeze until it strikes another phase and so causes a short-circuit, and (*b*) because an "arcing earth" can cause a considerable voltage-rise on the healthy phases and can also cause unnecessary damage by burning. By employing arc-suppression coils it is possible to avoid these difficulties, but even in these circumstances it is very often an advantage to clear persistent earth faults automatically. The fault current on an insulated system is, of course, the charging current due to the electrostatic capacity of the healthy phases of the whole system and will be approximately in quadrature with the voltage producing it. While it is possible to use ordinary non-directional earth-leakage relays which would be operated by such charging currents, correct discrimination is not always possible owing to unsymmetrical charging currents also appearing in the healthy feeders. A type of directional relay has, however, recently been designed, which, while sensitive enough to operate on the charging current between the two healthy phases and earth, will remain perfectly stable for short-circuits between phases and simultaneous earth faults on two separate phases, as well as on healthy feeders connected to the same busbars. These relays can be connected as indicated in Figs. 6 and 7.

In order to obtain sufficient sensitivity for satisfactory operation on the comparatively small capacity charging currents which may exist on some systems, the relay is designed to be operated by the product of the residual current and residual voltage of the line. As the fault current will be greatest at the switching points nearest the fault, the relays on the faulty feeders will have greater operating torque and it becomes possible to dispense with the overcurrent relay element which is used for directional overcurrent relays and obtain both time and directional selective tripping with a single element.

As already explained, the directional feature is also essential to prevent incorrect operation of the relays protecting other outgoing feeders connected to the same busbars as the faulty feeder, because on an insulated system the fault current must return as charging current through the sound phases of all the feeders, and consequently will energize the residual current coils of all the relays. In the case of the healthy feeders such return current will, however, be 180° out of phase with the fault current in the faulty feeder.

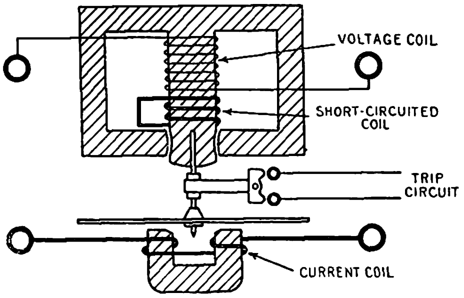


FIG. 8.—Internal connections of earth-fault relay for insulated systems.

When the neutral point of the system is insulated from earth, a comparatively high-resistance earth fault will always establish a practically constant residual voltage which will be almost in quadrature with the earth-fault current. The relays must therefore be designed to operate as reactive power relays having a torque which increases as the sine of the angle between current and voltage. A relay designed in this way will therefore have a torque proportional to $IE \sin \phi$, and as E and ϕ are practically constant the torque will actually vary as the fault current. It is thus possible to use an inverse time-delay relay with definite minimum time features, and thus obtain time discrimination as indicated in the characteristic curve, Fig. 2.

Fig. 8 gives the internal arrangements of the relay, which has the usual voltage and current elements similar to a wattmeter, but with an additional winding, short-circuited on itself, on the voltage element. This latter winding modifies the phase angle of the magnetic flux of the voltage element so that the relay will operate as a reactive power relay. The current coil of such a relay will have an impedance of approximately 1 ohm and, if set at 0·15 ampere, will operate, for example, with 6 amperes earth-fault current when connected to average 33-kV bushing current transformers. Relays of this type are not suitable for the protection of sections of ring mains or closed networks having insulated neutral points, because the direction of the reactive power will vary according to the position of the fault, owing to the distribution of the return fault current through the healthy sections. It is, however, possible to make use of these relays in protecting parallel feeders, as in this case the direction of the return fault power is always such as to give correct selectivity.

On Systems with Earthed Neutral.—As the earth-fault current will in most cases be nearly in phase with the voltage between the faulty phase and earth, an ordinary wattmeter type of relay can be used for directional earth-fault protection. The relay should be connected as indicated in Fig. 6 and will have load/time characteristics similar to those of the reactive power relays for insulated neutral systems. Time and directional discrimination is thus embodied in the same relay and, moreover, an increased sensitivity is obtained since part of the operating torque is provided by the voltage coil, thus allowing a lower-impedance current coil to be used. As the system neutral is earthed the direction of the fault power will always be known and the relays can be applied in the protection of all types of networks.

IMPEDANCE OR DISTANCE RELAYS.

As networks grow in size and as more linking-up between systems takes place, it becomes more difficult to obtain satisfactory protection by overcurrent and directional time-limit relays and, unless pilot wires or special cables are provided, dependable discrimination is practically impossible. This is due to two main causes, (*a*) the possible variation of feeding points, and (*b*) the greater number of substations in series. The former difficulty can to some extent be overcome if the relay times are re-graded whenever the feeding point is altered, but to overcome the latter difficulty would necessitate longer maximum time-delays than are practicable. The impedance relay, however, offers a solution to this problem and in the last few years many such relays have been installed.

The principle which governs the design of all impedance relays is that the relation between the fault current and the voltage at the point where the relay is connected will depend upon the impedance of the feeder or line between that point and the fault, or $Z = E/I$. Thus a relay having a current element the torque of which is opposed by the torque of a voltage element could be so designed that it would only close its contacts if the ratio E/I were less than the impedance of the section of line or feeder to be protected. Such a relay would, therefore, only operate for faults in its own section, since with more distant faults the torque of the voltage element would overcome that of the current element and produce a torque in the reverse direction. There is, however, a practical difficulty in applying such relays, as, owing to the variable resistance of the arc, it is impossible to estimate correctly the exact impedance of the feeder, with the result that the relay must be adjusted for an impedance greater than that represented by the latter.

Successive relays will thus overlap each other and might operate for faults within a part of the next section, but this is overcome by introducing a time-delay feature which causes the operation of the relay to slow down as the distance between it and the fault increases. A fault close to the relay would therefore cause quick operation to trip the circuit breaker before the slower-acting, more distant relay could operate.

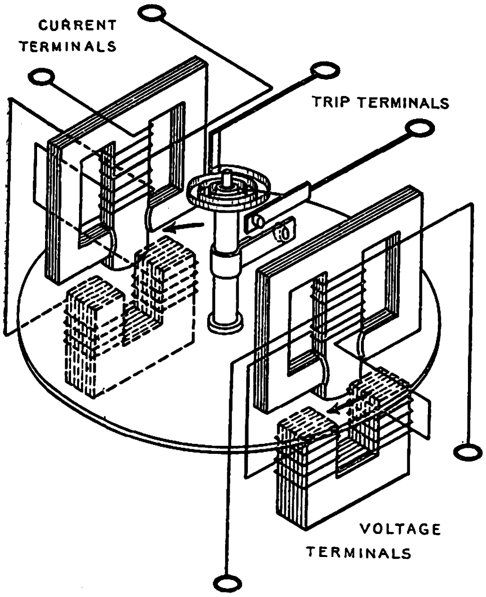


Fig. 9.—Induction-type definite impedance relay.

Definite Impedance Relays.—Fig. 9 is an isometric view of a relay of this type, which may be called the "definite impedance" type, and Fig. 10 shows time/distance curves for two relays in series. From the latter it will be seen that the relay is set for an impedance 15 per cent greater than that of the feeder. The relay, which is of the induction type, has two elements operating on a single disc, the current element producing a torque which tends to close the contacts, while the torque of the voltage element tends to open them.

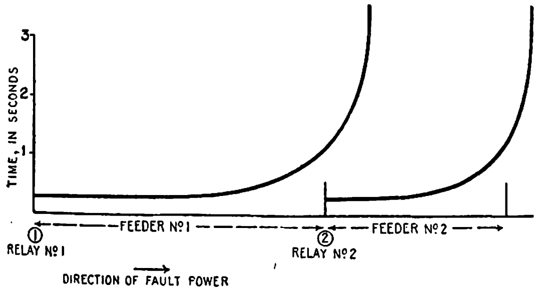


Fig. 10.—Characteristic curves of definite impedance relay.

One of the difficulties in the design of impedance relays of this type is that the voltage element must be designed to operate over a large range of voltage. This is due to the fact that at comparatively low voltages it has to produce a torque equal to that of the current element at comparatively high currents, and has also to withstand full voltage continuously under normal conditions. It has therefore been found necessary to use an "economy" reactance connected in series with the voltage coil and to short-circuit it by an instantaneous auxiliary relay when faults occur. By this means the voltage element of the impedance relay is kept cool during normal conditions and yet has sufficient operating torque at low voltage to compare with the torque of the current element. The value of this reactor must be so proportioned that when it is in series with the voltage element the latter will produce sufficient torque to overcome that of the current element at loads below the setting of the auxiliary relay.

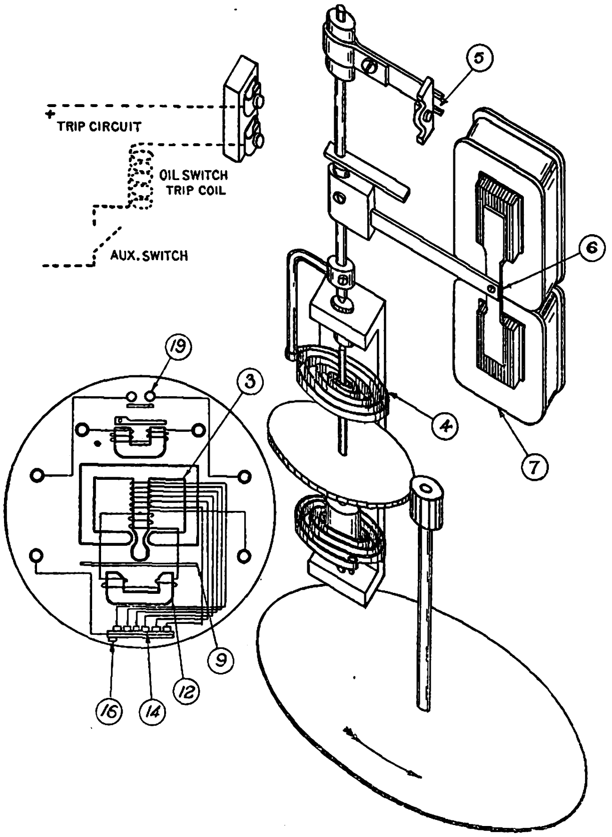


Fig. 11.—Diagram to illustrate action of impedance element of impedance-time relays.

Impedance-Time Relays.—Fig. 11 is an isometric view of another type of impedance relay which may be called the "impedance-time" relay, because its selective feature entirely depends upon the time-delay between relays in series. The relay is so designed that the time-delay is proportional to the impedance between the relay and the fault, that is, the more distant the relay the slower will be its operation.

The driving element of the relay operates on the induction principle, and the restraining element on the attracted-armature principle. The induction element comprises electromagnets (3) and (12), the resultant magnetic field from which reacts on the eddy currents induced in the non-magnetic disc (9) and produces a torque tending to rotate the disc against the braking effect of a permanent magnet. The brake magnet provides the control necessary to obtain a disc speed proportional to the driving torque. The spindle of the disc is geared to a counter-shaft and to this is attached the inner end of a spiral spring (4). The outer end of this spring is fixed to a bent lever the movement of which controls the position of the moving contacts (5) mounted on an entirely separate shaft, on which is also fixed a flat armature of soft iron (6) which is normally held against the face of the restraining electromagnet energized by the voltage coil (7).

The position of the moving contact is therefore under the joint control of the current and voltage elements of the relay, and at the end of its travel the moving contact bridges the two fixed contacts (19). On the occurrence of a fault the disc will rotate at a speed depending upon the current value and so wind up the spring (4) which accumulates a rapidly increasing torque tending to force the armature (6) away from the electromagnet (7). At the same time the pull exerted on the armature by the voltage-restraining coil prevents movement of the moving contact until the spring has been wound up sufficiently to force the armature away from the attraction of the electromagnet. This takes a time which is, in consequence, proportional to the pull of the voltage coil and inversely proportional to the speed of the driving disc. The time is therefore proportional to the impedance between the relay and the fault.

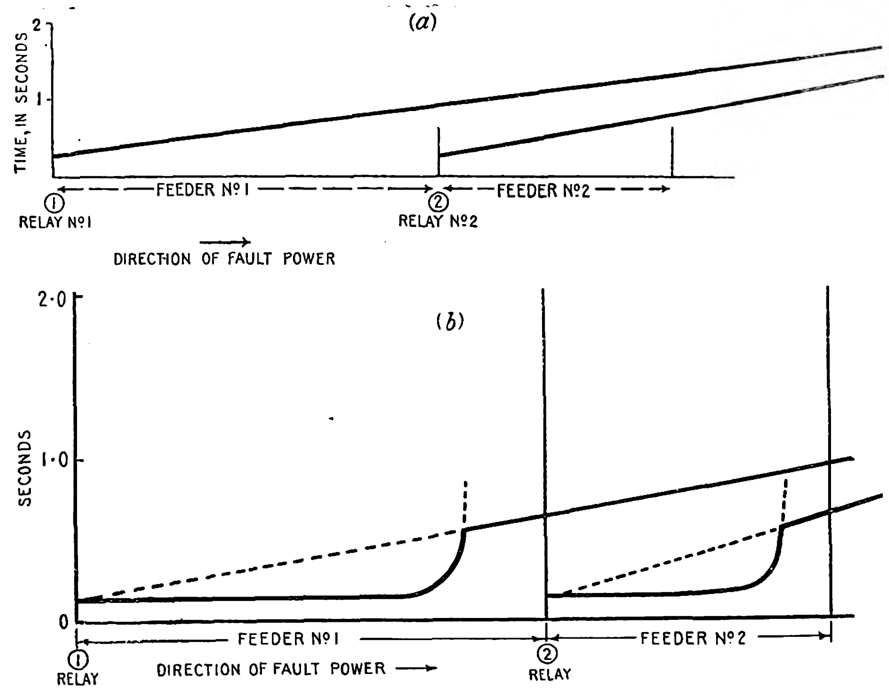


FIG. 12.—Characteristic curves of impedance relay.

(a) Impedance-time relay. (b) Combined impedance relay.

The method of applying this relay is to adjust the setting values of the current and voltage elements so as to produce operation of the relay with a maximum time-delay of not more than, say, 0·8 sec. for all faults on the particular line being protected. This means that the relay will operate in 0·8 sec. when the fault is at the remote end, but with decreasing time as the position of the fault is nearer to the relay (see Fig. 12, which gives the time/impedance curves for two relays in series). The settings are adjusted by means of tappings on the current coil and an adjustable resistance connected in series with the restraining coil.

The design of the restraining element of this relay is such that "economy" reactances are not necessary. Both relays are suitable for simple radial feeder systems having no complications other than several switching points in series, but it is of course necessary on ring mains or loop systems to have directional features which should be applied in a similar manner to that already described for directional overcurrent relays.

It is desirable at this point to compare the characteristics of the two relays just described and to investigate their fields of application. In the first place, whilst the definite impedance relay operates more quickly than the impedance-time relay for faults over the greater part of the feeder, it makes no provision for variation in the fault impedance beyond the 15 per cent overlap already mentioned. It is usually assumed that for phase-to-phase faults the impedance value remains nearly constant for a given length of feeder, but this does not hold good for earth faults, when the impedance of the earth return may vary considerably.

The impedance-time relay has the advantage that variation in the fault impedance does not prevent the relay from operating, although it may somewhat increase the operating time. In fact, each impedance-time relay acts as a "back-up" relay to the next in the sequence, so that, even if the correct circuit breaker fails, the fault will still be isolated in a slightly longer time.

A relay which would combine the characteristics of both these relays would appear to have a slight advantage, and this arrangement is adopted in some cases. The characteristic curves for such an arrangement are shown in Fig. 12(*b*). It is doubtful, however, whether the advantage gained justifies the extra complication, and the authors consider that the impedance-time relay meets most conditions.

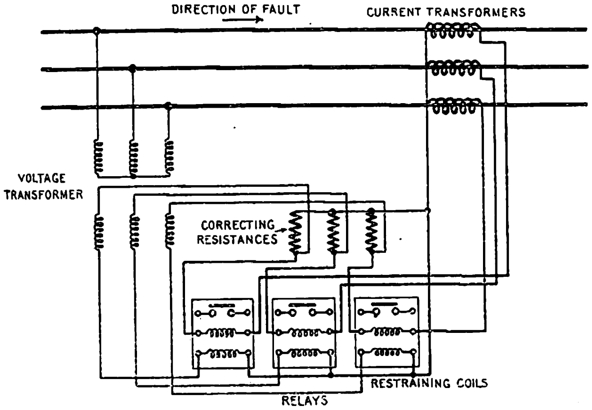


Fig. 13.—Impedance relays. Correcting device for arc resistance.

Since the voltage plays a large part in the discriminating feature of impedance relays, it is essential that the voltage across the restraining coil should accurately reproduce the voltage on the line at the point where the relay is connected. To this end it is necessary to have two distinct sets of relays for the protection of earthed systems, one set connected for phase-fault protection and the other for earth-fault protection. The reason for the different connections is that a phase fault affects the voltage of two or three phases, while an earth fault involves one phase only. Thus, while the current coils of both sets of relays are connected in series on the respective phases, the restraining coils of the phase-fault relays must be connected across phases and those of the earth-fault relays between each phase and earth. In this connection it should be noted that earth-fault protection cannot be obtained by means of impedance relays unless the system neutral is connected directly to earth or through a comparatively low resistance, otherwise insufficient voltage gradient occurs along the line and the difference in potential between the relays at the various switching points is too small for discriminative operation. It is preferable to use single-phase potential transformers for impedance relays and particularly for earth-fault relays, but if 3-phase transformers are contemplated they should be of the " shell " type as opposed to the " core " type. The reason for this is that with the " core " type of construction the flux in the limbs connected to the two healthy phases tends to maintain an appreciable secondary voltage in the limb connected to the faulty phase.

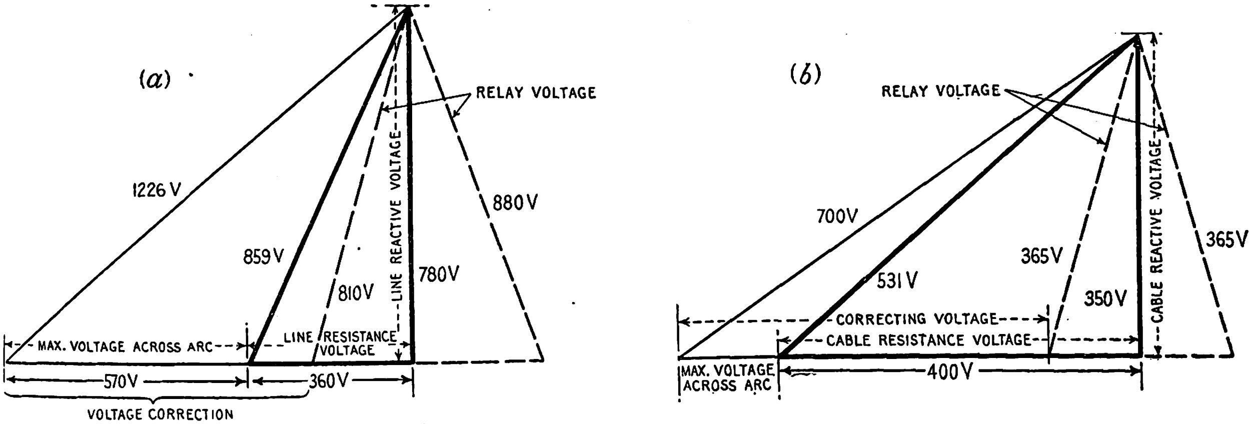


Fig. 14.—Vector diagrams of correcting device for arc resistance.

(*a*) Overhead line. (*b*) Cable.

Effect of Resistance of Arc.—Mention has already been made of the variable resistance of the arc which may accompany a fault and the fact that this variable factor must be taken into consideration when, as in the case of the impedance relay, discrimination depends upon the apparent impedance of the line between the relay and the fault. It might be as well to point out here that there is very little or no inductance in an arc, and that it is only the resistance which is in question. Fortunately for the success of the impedance relay the resistance-drop across an e.h.t. arc is comparatively small, and the variable factor resulting therefrom can be compensated for in such a manner that its effect upon the operation of the relay will be negligible. In estimating the effect of the arc resistance on the apparent impedance of the line or cable it is, of course, necessary to take into consideration both the resistive and reactive components of the line drop. One method of effecting compensation for arc resistance would be to design the relay so that it only measures the reactive voltage instead of the impedance voltage. This, however, is difficult, if not practically impossible, to accomplish, and in some relays a compromise has been made in that the relay is more sensitive to reactive voltage than resistive voltage. Such relays are, however, comparatively complicated or fail in the essential point of reasonably quick discriminative operation. A simple and effective method has, however, recently been developed which can be applied to any impedance relay and which reduces the variable effect of the arc to negligible proportions. The compensation consists of an adjustable resistance connected in series with the current coil of the relay (see Fig. 13). From the diagram it will be seen that the potential-drop across this resistance is applied to the restraining coil in such a direction that it opposes the resistance component of the impedance voltage. By adjusting the value of the resistance it is possible to compensate entirely for the resistance component of the impedance of the line or feeder and, in addition, reduce the error due to the maximum variation of the arc.

Tests which have been carried out indicate that the voltage-drop across even long arcs does not exceed 3 per cent of the normal voltage and that this figure is considerably reduced when the arc current exceeds 250 amperes. It is thus possible to estimate with reasonable accuracy the maximum effect of arc resistance when either overhead lines or cables are in question. It can also be assumed that in the case of the former the length of the arc will usually be greater than that due to a cable fault where the conductors are closer together and also closer to earth. Thus if the maximum arc voltage for an overhead line is taken to be 3 per cent, that for a cable can be assumed to be not more than 1 per cent of normal voltage.

The vector diagrams, Fig. 14, show the effect which the compensator has on the apparent impedance of a line and a cable as measured by an impedance relay. From these diagrams it will be seen that the 15 per cent overlap in the setting of the definite impedance relays will make allowance for the maximum variation in the arc resistance. In the case of the impedance-time relay the maximum difference in the time when the compensator is in use is only 0·2 sec.

Low-Voltage Release Relays.

It sometimes happens that the maximum short-circuit current when the connected generating capacity is small is actually less than the normal full-load current when the maximum generating capacity is in use. If, therefore, overcurrent or impedance relays are set to operate at the estimated minimum short-circuit current they would probably operate or tend to operate at normal maximum loads, unless the settings were increased during the period at which such loads exist. The following method has been successfully employed to overcome this difficulty and allows of the overcurrent or impedance relays being set low enough to operate on the lowest possible short-circuit current. The arrangement includes a low-voltage relay which will allow the overcurrent or impedance relay to operate only in the event of the voltage of the system falling owing to a short-circuit. The contacts of this low-voltage relay are connected in the secondary winding of the overcurrent or impedance relay (see Fig. 15), and until the contacts of the former are closed there can be no operation of the latter. The relays will therefore only operate when current is flowing and the voltage has dropped to a predetermined value. As such conditions will only exist during a short-circuit, selective operation can be obtained without re-adjustment of the relays.

This method is also very useful as a means of providing busbar protection when several incoming feeders are connected to the same busbar, since a short-circuit on the latter under low-load conditions may not draw sufficient current from the individual feeders to operate the separate overcurrent relays if they are set high enough to prevent operation at normal full load. It will be appreciated that it is not permissible to connect the contacts of the low-voltage release relay in series with the trip contacts of overcurrent or impedance relays, since, although this would prevent the tripping of the circuit breaker, it would not prevent the overcurrent or impedance relays operating and consequently the selective features would be lost.

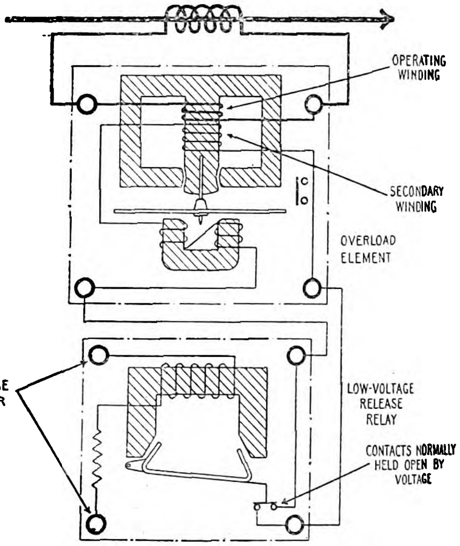


Fig. 15.—Low-voltage release relay with overload relay.

Pilot-Wire Protective Gear.

The types of protective gear already described are not always suitable for the protection of networks feeding dense load areas such as exist in industrial centres, and it is probably for this reason that the balanced type of protective gear has been so largely used in Great Britain. The original balanced protective gear was that due to Messrs. Merz and Price, and until recent years this system has proved satisfactory for feeder protection.

Balanced-Voltage Protective Gear.—This system consists of balancing the secondary voltages of current transformers connected at either end of the feeder, by means of pilot wires and through instantaneous relays. It is usually known as the balanced-voltage system because, as distinct from other balanced schemes, no current flows from the secondary windings of the protective transformers until a fault occurs in the feeder.

As power systems have increased in size and distribution voltages become higher, certain difficulties have arisen which have necessitated modifications to the original scheme. These modifications were designed with the intention of preventing incorrect operation due to variable characteristics of protective transformers or to the other difficulties already referred to in the paper.

It was early realized that ordinary current transformers were unsuitable for the balanced-voltage scheme since, due to the absence of secondary or back ampere-turns, the iron circuit of the transformers would quickly reach magnetic saturation and thus render it very difficult to obtain satisfactory balance, even between transformers of similar design. Balanced-voltage transformers were then designed with an air-gap in the iron circuit which prevented magnetic saturation up to fault currents of the order of 3 000 amperes. It was then found that, due to the fringing flux from this gap, the presence of adjacent magnetic material upset the balance between pairs of transformers and it became necessary to provide several smaller air-gaps equally spaced round the iron circuit. This lack of balance due to disturbance of the fringing flux became more serious with increase in length of the air-gaps necessitated by the larger fault currents. The advent of metal-clad switchgear further aggravated the difficulty owing to the smaller clearances between the transformers and extraneous ironwork.

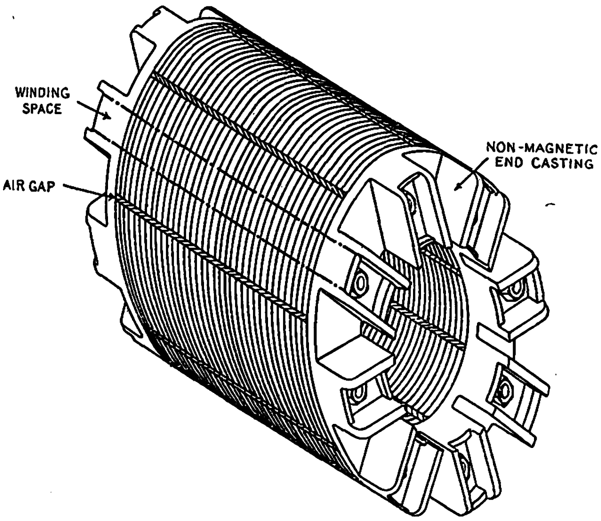


FIG. 16.—Isometric view of balanced-voltage transformer.

A recent research has shown that if the transformers are fully to meet modern requirements the minimum number of air-gaps which can be employed is 8. A protective transformer of recent design is illustrated in Fig. 16. From its mechanical design the transformer possesses great rigidity and the secondary windings are well protected under all conditions, whilst its characteristics are practically unaffected by neighbouring magnetic material or currents of fault magnitude in adjacent conductors. The secondary-voltage characteristic for this transformer is shown in Fig. 17. It should be appreciated that the voltage characteristic of such a transformer cannot be actually a straight line, owing to the shape of the magnetization curve of iron, but it will be seen from this curve that in this transformer the approximation to a straight line is exceedingly close.

In testing the balance of balanced-voltage transformers it is not sufficient to compare the secondary voltages, because considerable out-of-balance currents may be set up by phase differences between the voltages. The only satisfactory method is to connect the primary of a standard transformer in series with that of the transformers being tested and, with the secondary windings connected in opposition, to measure the out-of-balance current by means of a low-impedance milliammeter when a large primary current is flowing. This is more stringent than the most severe working conditions since the circuit normally will contain both pilot-wire resistance and the impedance of the relays. Fig. 18 is a curve plotted between values of primary current and secondary out-of-balance current obtained with two transformers of this type, the relays and pilot wires being replaced by a milliammeter having an impedance of only 3 ohms. The primary currents used in this test exceed 60 times full-load current and, since the presence of the relays and pilot wires will reduce the out-of-balance to less than half, and the relays will not generally be set for less than 60 mA, it will be seen that the factor of safety against operation due to transformer unbalance is ample.

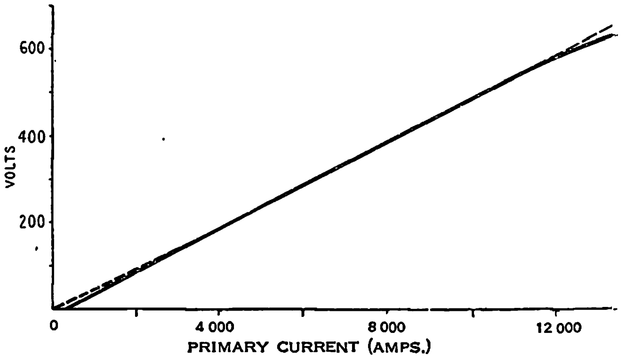


FIG. 17.—Voltage characteristic of balanced-voltage protective transformer.

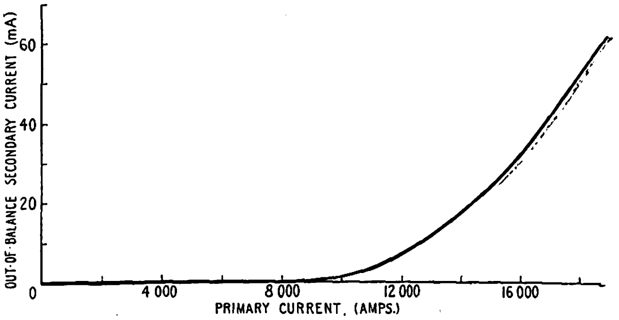
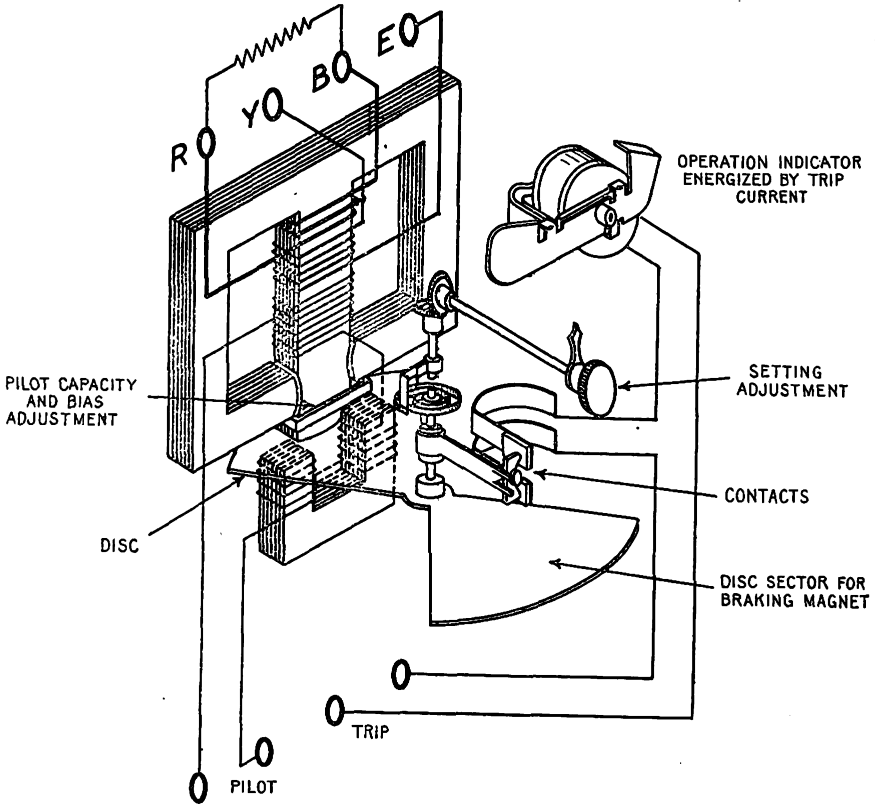


FIG. 18.—Balanced-voltage protective transformer; out-of-balance against standard.

Difficulties with Balanced-voltage Protective Gear.—Mention has already been made of causes other than lack of balance between protective transformers which may give rise to incorrect operation, and these will now be briefly considered.

Instability of balanced-voltage gear due to capacity currents flowing through the capacity of the pilot cables has been successfully avoided by the use of the screened pilot suggested by Mr. Beard. This arrangement prevents wrong tripping due to currents in the pilot capacities at both normal and super-normal frequencies, provided that the voltages in the pilot system are symmetrical with respect to earth. If, however, for any reason the voltage of the pilot sheaths differs substantially from earth potential, very puzzling wrong operation may take place.

When earth faults occur on a system the normal symmetry of the currents in a 3-phase feeder is upset, and in effect a single-phase current equal in value to the fault current flows through all feeders, sound and faulty, to the fault. This single-phase current induces voltages in all pilot wires lying near to the feeders. In one instance of which the authors have a record, this voltage amounted to 0·13 volt per ampere of fault current per mile. Where the pilots terminate in protective transformers having considerable capacity to earth, the voltages consequent upon a heavy earth fault may easily cause currents of sufficient magnitude to operate relays. It must be remembered, also, that the magnitude of these currents will be increased where fault currents have components of higher frequencies, because the voltages will be increased and the capacity reactances will be diminished.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TRIP
PILOT

Fig. 19.—" Translay " relay element.

In cases of earth fault, the returning fault current flows to a great extent along all metallic paths lying in the direction of the fault, and this includes all cable sheaths and armourings as well as pilot wires if these are earthed at one or both ends. For this reason it is necessary at both ends of the feeder to insulate from earth the secondary windings of balanced-voltage transformers. Even an earth connection at one end of the pilot wires may lead to wrong operation of relays, the path of the vagabond currents being completed through pilot-core capacity to earth. Here again the trouble is aggravated where higher-frequency components exist in the fault current. Safety can be assured and this trouble minimized by earthing one or both ends through spark-gaps either air- or paper-insulated, but care must be taken so to adjust the gaps that they do not break down at the maximum induced voltages met with in practice, which may attain high values during through-faults.

When a high-voltage cable is energized, as well as when a fault is cleared on the system, heavy charging currents flow momentarily and may assume abnormal values due to the distortion of the voltage wave-form. This is particularly the case at times of fault on the system due to the serious voltage fluctuation, and is equivalent to currents of frequencies higher than the normal. Unless steps are taken to prevent it, the resultant secondary currents may cause relay operation. This can be avoided by shunting the inductive winding of the relays by a non-inductive resistance which will tend to shunt a larger proportion of higher-frequency currents. Where these transient charging currents reach very large values, it may be necessary to use condensers also in shunt with the relay windings. The use of condensers without resistances is not to be recommended, owing to the danger of breakdown of the condenser insulation. Immunity from wrong operation due to this cause can also be obtained by the use of relays tuned electrically or mechanically to respond to the fundamental frequency only.

It will be seen from the foregoing that difficulties are met with in the application of balanced-voltage pilot-wire protective gear to high-voltage feeders, particularly where these feeders form part of extensive systems, and, with these difficulties in view, several new forms of balanced feeder protection have recently been developed. Two of these systems which are typical and which have been successfully tried out in practice will be briefly described. Both systems make use of ordinary current transformers without air-gaps, and, while one introduces a biasing arrangement to take care of variations in the current transformers, the other relies upon the current transformers having exactly similar characteristics to give stability on through-fault conditions.

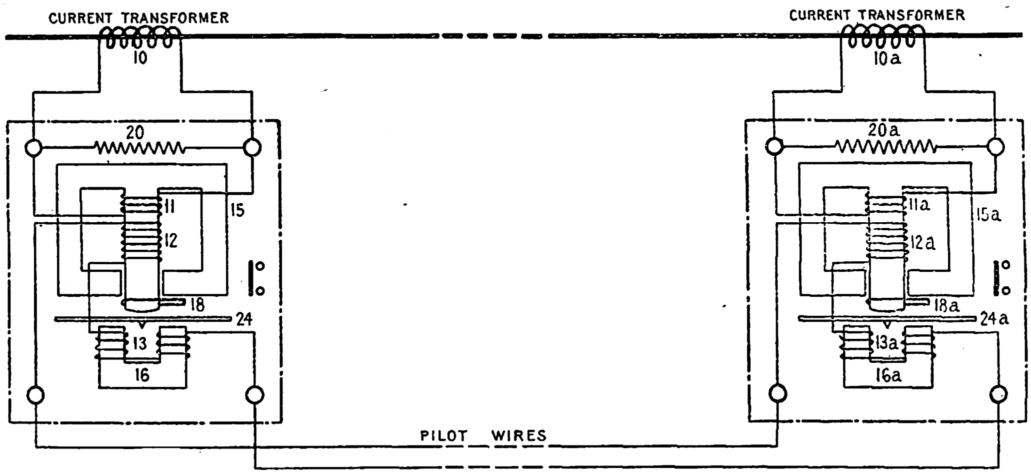


FIG. 20.—" Translay " protection for single-phase feeder.

" Translay " System.—The first of the two systems to be described has many novel features which are confined chiefly to the design of the relay. This is of the induction type instead of the electromagnetic type usually employed in pilot-wire schemes (see Fig. 19). The arrangement can be best explained by illustrating its application to a single-phase feeder as shown in Fig. 20. The relay primary winding is energized from the secondary of a current transformer, and in addition to setting up a leakage flux which, in conjunction with a suitable flux from the lower magnet, will cause the non-magnetic metal disc to rotate, it acts also as the primary of an air-gap transformer, causing a voltage to be generated in the secondary winding. The value of this secondary voltage depends upon the current flowing in the primary winding, and as the secondary windings of the relays at opposite ends of the feeder are connected in opposition through the pilot wires no current will flow in this circuit under normal operating conditions. If, however, owing to a fault on the feeder there is a discrepancy between the currents flowing at the two ends, the resultant difference between the secondary voltages will cause a current to flow in this circuit. This current will set up a flux which, by interaction with the leakage flux from the primary winding, will cause the relays to operate.

Several important advantages follow from this simple arrangement. In the first place, the necessary interaction between the fluxes only causes forward torque on the disc when their relative phase displacement lies between certain limits. An adjusting device is provided by which the phase of the leakage flux can be so adjusted that forward torque is only produced when the pilot current is in phase with or lagging behind the pilot voltage. Consequently any current flowing through the capacity of the pilot cables, which will lead the pilot voltage, can only exert backward torque on the disc. The necessity for pilot sheaths is thus avoided. Also, since the pilot current has to supply only a small portion of the energy necessary for relay operation, the pilot currents are only small, and heavy pilot wires are not necessary. A third advantage is that the insulation of the pilot circuit from the current-transformer secondary circuit permits the earthing of the current-transformer secondary windings at both ends of the feeder without danger of untoward operation. Further, owing to the small pilot currents the voltages set up in the secondary winding need only be small, with important resultant economy in pilot-cable insulation.

Since in many cases it may be necessary to employ current transformers of slightly different characteristics at the two ends of the line, it has been deemed advisable to incorporate a bias device in the relay. The bias is obtained by an asymmetrical arrangement of the adjusting winding. This sets up a backward torque on the disc, this torque being the greatest when the flux in the electromagnet is large, which is the condition of through fault, and this is sufficient to overcome any small forward torque due to slight out-of-balance between the transformers at the two ends. In case of fault, however, the resultant secondary back ampere-turns on the electromagnet reduce the main flux and consequently the bias, leaving the relays free to be operated by the out-of-balance secondary current.

As a further precaution against operation under transient conditions the relay is given a slight inverse-time characteristic, which rapidly approaches 0·1 sec. for faults exceeding three times the setting; also the provision of non-inductive shunts across the primary and secondary windings renders the relay less sensitive for currents of frequencies higher than the normal. Where special circumstances make it desirable, a frequency filter circuit can be added which renders the relays inoperative at 80 cycles and above.

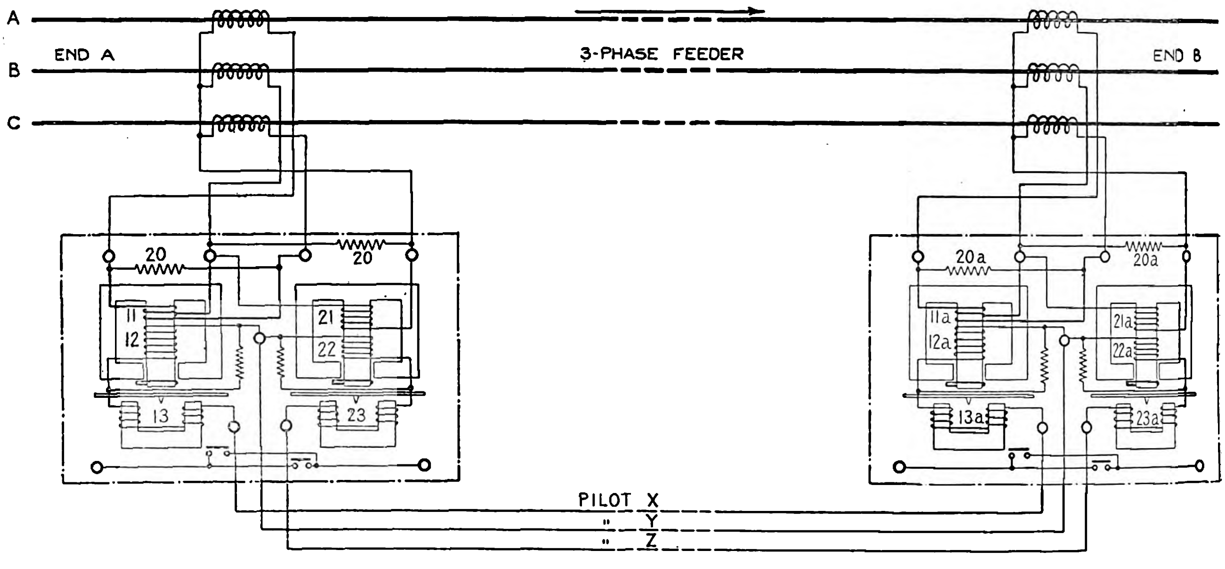


Fig. 21.—Three-phase protection—" Translay " system.

When applying this type of gear to 3-phase feeders, protection against earth faults can be obtained by the use of a single relay element, as already described, at each end, the operating coils being energized from the residual current of the current transformers (see Fig. 21).

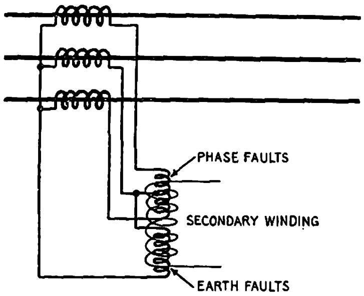


Fig. 22.—Diagram illustrating summation of 3-phase currents for protective relays.

For protection against phase faults, the phase currents at each end are summed in a second element. The two earth-fault elements and the two phase-fault elements are separately balanced through the medium of three pilot wires, one of these being common to the two pairs of elements.

In the choice of a method of obtaining an energizing current for the phase-fault elements, many methods have been considered, and that adopted is shown in greater detail in Fig. 22. Under normal conditions a small effective magnetizing current built up from the red and blue phases flows, but under fault conditions this is completely swamped by the fault current. This arrangement has the advantages that the variation in sensitiveness for faults in the various phases is never more than 2 : 1, that under no conditions do the magnetizing currents cancel one another out, and also that the secondary burden on the current transformers can be kept low. For a fault between outer phases the whole coil is energized, whilst for a phase fault between either outer phase and the centre phase one of the half coils will be energized. A symmetrical 3-phase fault produces an effect between these two.

It has been found feasible to operate such relays with earth settings of 30 per cent of full load of the current transformers. Phase-fault settings should preferably be higher, and these can be chosen to suit conditions. The actual fault settings obtainable vary slightly with the resistance of the pilot wires. Throughout the normal range of pilot loop resistance, say up to 500 ohms, the variation of minimum setting is only 30 to 50 per cent. The setting is, as already described, a function of the normal full load of the feeder, and, subject to the usual limitations of current transformers, settings can be made proportionately smaller on small feeders. These settings compare very favourably indeed with the settings obtainable with older types of gear.

An alternative arrangement employs one relay element at each end and a pilot cable having two cores only. In this case the earth-fault coil is wound on the same core as the phase-fault windings, and consists of a larger number of turns than either of the latter. Sensitive earth-fault settings are thus afforded in addition to phase-fault protection by means of two pilot wires only and one single-element relay at each end of a 3-phase feeder. The limitations to this arrangement are that the setting for earth faults cannot be varied independently of the phase-fault settings, and in general less sensitive settings are obtained. The arrangement is shown in Fig. 19.

Self-compensated System.—This method also employs pilot wires but is a circulating-current system and not a balanced-voltage system, and the general arrangement is illustrated in Fig. 23. The current transformers at either end of the feeder are employed to energize a summation transformer which has primary windings arranged on the principle already described (see Fig. 22). The iron circuits of the current transformers and summation-transformer are liberally designed so that saturation will not be reached with the burden due to the impedance of the pilots up to the maximum through-current anticipated. As a result of this a circulating current will flow through the two outer pilots, this being of the order of 0·3 ampere at full load. The two single-pole relays situated one at each end of the feeder are connected in series with each other through the third pilot core between two equipotential points on the circulating-current system.

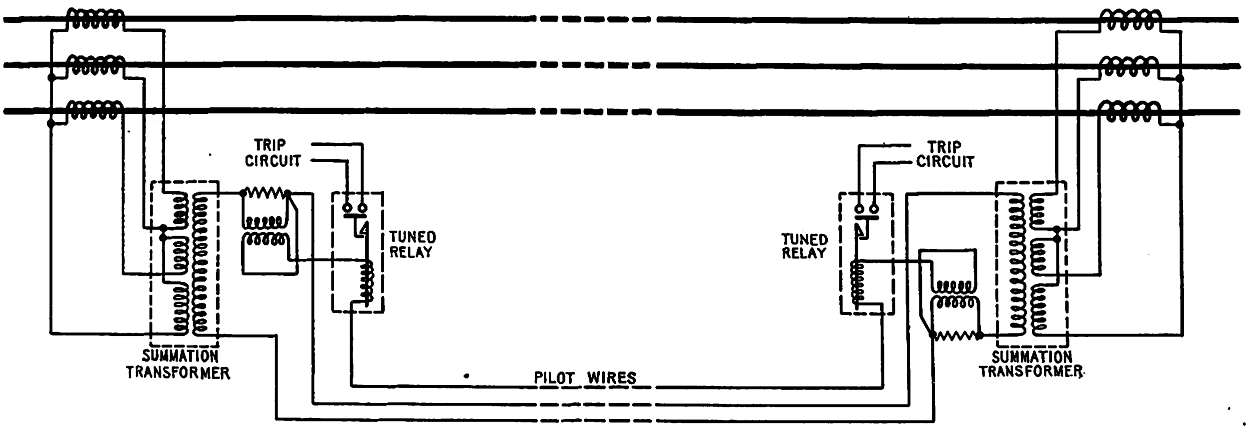


FIG. 23.—Theoretical diagram of self-compensated feeder protective gear.

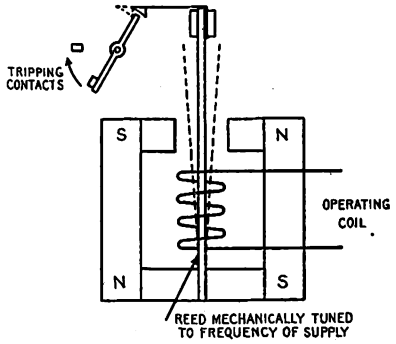


FIG. 24.—Principle of tuned-reed relay.

This simple arrangement requires two modifications to guard against incorrect operation due to capacity currents in the pilot wires and to high-frequency transient currents. The first consists of a device to maintain the potential of the relay pilot core always midway between those of the outer cores. This is done by the inclusion of a resistor in series with one of the circulating-current pilot wires and having a resistance a predetermined fraction of the pilot resistance. The voltage-drop across the resistance is multiplied by a small voltage transformer to represent the voltage-drop in half one pilot and is then applied to the relay pilot core. The two ends of the centre core are thus held at the potential of the centre points of the outer pilots, and the capacity charging currents flowing to and from the relay pilot core will neutralize each other.

To render this gear immune from operation consequent upon high-frequency disturbances, a special relay is used which, by mechanical tuning, is rendered comparatively insensitive to currents of frequencies other than the fundamental frequency of the system.

Details of the relay can be followed by reference to Fig. 24. The magnetic reed is so designed that its natural frequency of vibration is the same as the system frequency. It is polarized by a permanent magnet, and when currents of the correct frequency energize the two operating coils the reed responds and releases a catch which permits the contacts to close. The response of the relay to frequencies other than the normal is shown in Fig. 25. After operation the relay must be reset by hand before the circuit breaker can be reclosed.

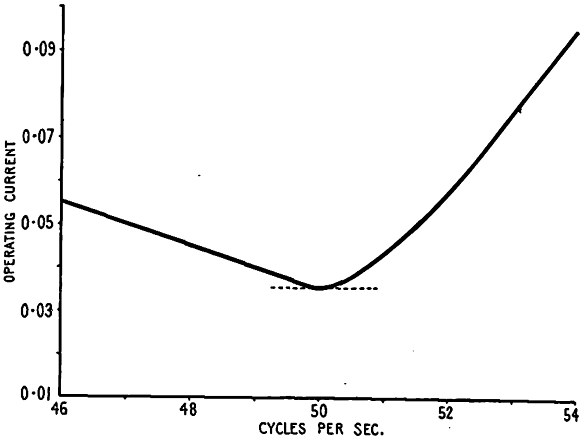


FIG. 25.—Frequency characteristic of vibrating-reed relay (setting 0·035 amp.).

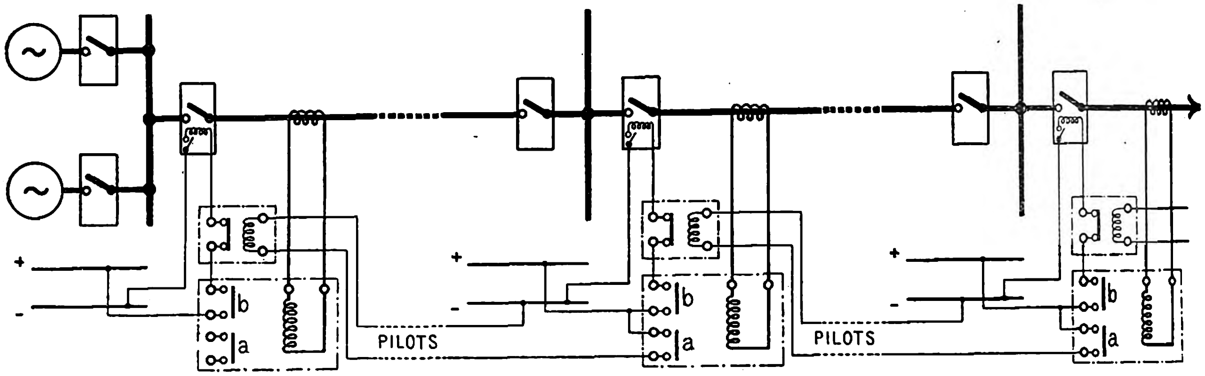
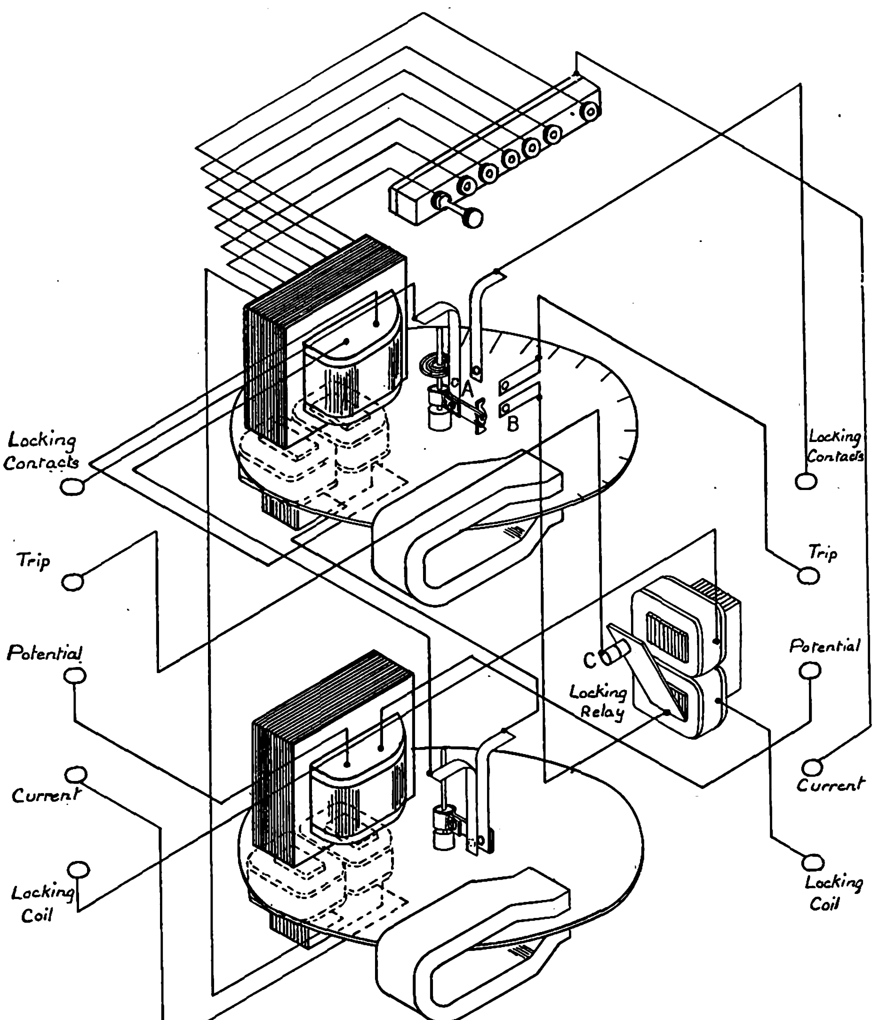

+
-
b
a
PILOTS
+
-
b
a
PILOTS
+
-
b
a

FIG. 26.—Interlocking overload protection (Longfield system).
Overload relay contacts "a" operate instantly, and contacts "b" after 0·1 second.


Locking Contacts
Trip
Potential
Current
Locking Coil
A
B
C
Locking Relay
Locking Contacts
Trip
Potential
Current
Locking Coil

Note:- Contacts A close immediately on overload
" B " on overload after short time-lag
" C open when locking coil is energized

FIG. 27.—Directional time-delay leakage relay (with locking device).

D.C. Pilot-Wire Methods.

As an alternative to balanced systems, there are now several systems which employ pilot wires to operate, by direct current, relays for locking or tripping. These systems have the advantages that balancing of the protective apparatus at the two ends of a feeder is not necessary, and if suitable relays are used it is also possible in some cases to use an earth return and so save a pilot conductor. Alternatively, the fact that pilots carry only direct current permits the use of standard pairs in telephone cables without any possibility of interference taking place.

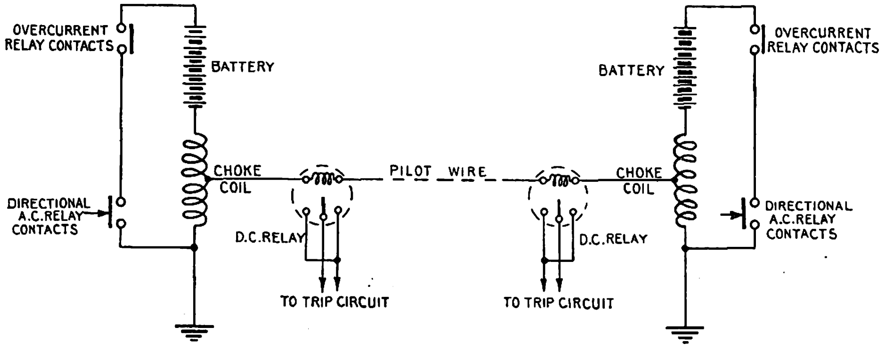

OVERCURRENT RELAY CONTACTS
BATTERY
CHOKE COIL
DIRECTIONAL A.C.RELAY CONTACTS
D.C.RELAY
TO TRIP CIRCUIT
PILOT WIRE
CHOKE COIL
D.C.RELAY
TO TRIP CIRCUIT
BATTERY
OVERCURRENT RELAY CONTACTS
DIRECTIONAL A.C.RELAY CONTACTS

Fig. 28.—Direct-current balance system of a.c. feeder protection.

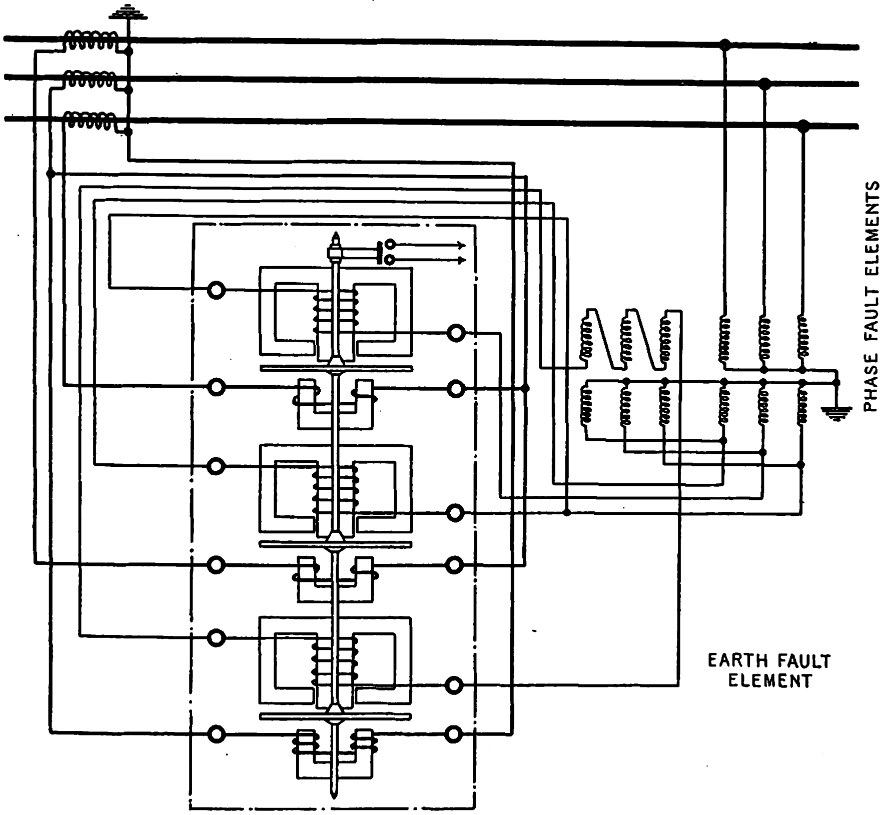

PHASE FAULT ELEMENTS
EARTH FAULT ELEMENT

Fig. 29.—Combined phase- and earth-fault relay for d.c. pilot-wire balance system.

One of the earliest of these systems was due to Mr. C. E. Longfield and belongs to the "locking" class. In effect the system as applied, for instance, to a radial feeder comprises an overload relay at each switch in the sequence, which operates to energize a pilot circuit instantaneously and the tripping circuit of the switch after a short time-interval. The pilot circuit operates a locking relay at the preceding substation nearer the power source to prevent the completion of the tripping function at that point (see Fig. 26). The only relay able to complete the tripping function is therefore the relay nearest the fault, which is cleared after a delay not exceeding 0·1 sec., wherever the fault may be upon the system. The time-lag need only be long enough to allow for the operation of the very rapid locking relay before the tripping contacts close.

The design of a relay suitable for use on a ring main or in any other situation where a directional relay is necessary, is illustrated in Fig. 27. The method of combining the overload and directional features is similar to that already described for overcurrent directional relays, and the locking feature is obtained by the introduction of the normally closed contacts of the locking relay in series with the tripping contacts of the fault relay. The pilot-energizing contacts are normally held open by the resetting torque of the induction disc, and they close immediately this begins to move forward.

Another system of this kind operating on the tripping principle instead of the "locking" principle is illustrated in Fig. 28. In this instance the direct current is passed through the pilot wire and operates d.c. relays whenever the flow of fault power at the two ends of the feeder is in opposite directions, or whenever fault power flows in at one end only. Directional overcurrent a.c. relays are, of course, necessary to indicate the direction of fault power, and if a single pilot circuit is used in protecting a 3-phase feeder these relays must be of special design because it is necessary that the relay should sum up the 3-phase power at each end and operate a single contact. It is not permissible to connect the contacts of separate phase relays in parallel as this might result in the relays in healthy phases operating in the reverse direction to those in the faulty phase. A special directional relay (see Fig. 29) is therefore required for this purpose. It will be seen that the relay consists of three wattmeter elements, the moving portions of which are mounted on a common shaft which also carries the moving contact. The two upper elements are connected in the well-known two-wattmeter method and the bottom element is connected as a directional leakage relay, but is wound to produce a higher torque for a given current than the two upper elements. The upper elements will therefore indicate the flow of power on short-circuits between phases, and the lower element will indicate the flow of power for faults between any phase and earth.

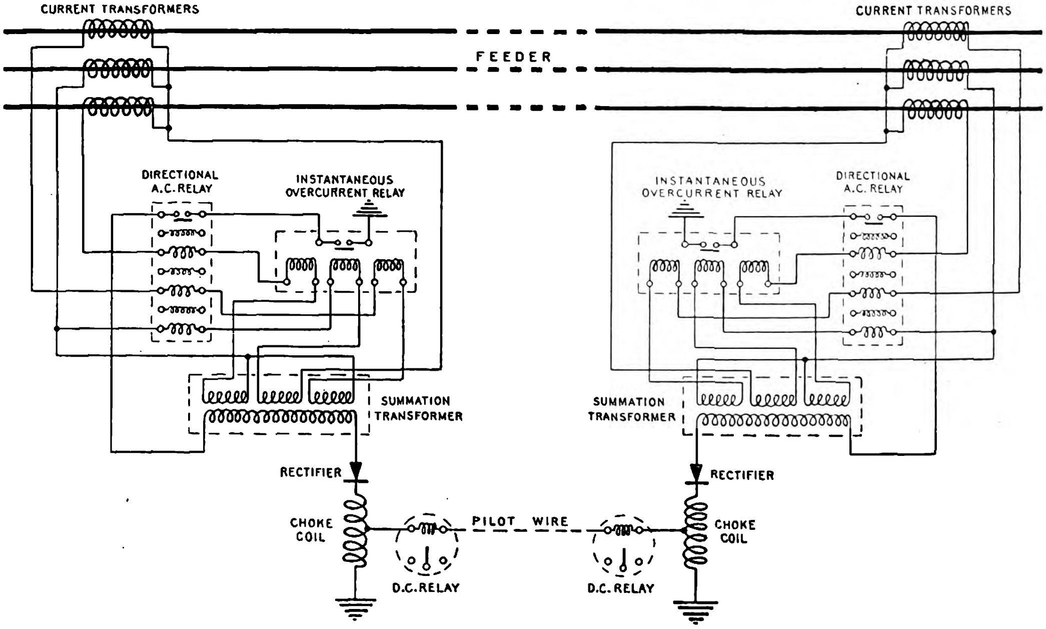


FIG. 30.—Theoretical diagram of d.c. pilot-wire balance scheme.

The application of this relay to the protective scheme may be followed from Fig. 28, from which it will be seen that its contacts are so arranged that when closed they complete a circuit from a suitable battery through a choke coil, the mid-point of which is connected to the pilot wire and one end of which is connected to earth. The choke coils are necessary to prevent excessive alternating current flowing through the pilot relay due to any difference in potential between the earth connections at each end during heavy earth faults. Such currents, although they would not operate the d.c. relays, might damage them by excessive heating.

The operation of the scheme is as follows: Through faults in a direction to close the contacts of both directional relays would result in both batteries—which must have approximately equal voltages—being connected in opposition through the choke coils and pilot wire. This would result in little or no current flowing through the pilot wire and pilot relays, and the latter would remain inoperative, whereas faults on the feeder would cause one of the directional a.c. relays to close its contacts and the other a.c. relay to open its contacts, which condition would allow direct current to flow through the pilot circuit and operate both pilot relays, to trip both circuit breakers.

A further development of the scheme is to use rectifiers to provide the direct current for operating the pilot relays. This has the advantage that batteries of equal voltage are no longer necessary, because the direct current for the pilot circuit is supplied from the protective transformers through the rectifiers. The connections for a feeder are shown in Fig. 30, from which it will be seen that a small summation transformer, so arranged that there will always be a secondary voltage derived from the fault current on any phase, is used to obtain the a.c. voltage for the rectifier. This transformer is designed to saturate at about four times the minimum fault-setting, which assures that the d.c. voltages at each end of the feeder will always be approximately equal, even when the protective current transformers have dissimilar characteristics.

The rectifier must be of a type which starts to rectify immediately the a.c. supply is applied to it. Such a rectifier is the copper-oxide type, which has proved to be very reliable in service and is largely used for railway signal purposes. The saturated summation transformer prevents an over-voltage being applied which might break down the rectifying copper-oxide film, and, moreover, as the rectifiers are connected to the supply only during fault conditions, they will be practically everlasting.

Little operating experience has yet been obtained with interlocking schemes such as these, but several experimental installations have been made. It is possible that in the future there will be a wide field of application, especially on long lines or feeders, for schemes of this general type, and further developments are to be anticipated.

Balanced Protection for Parallel Feeders.

Whenever two or more similar feeders are connected to a common busbar at each end, it is possible to employ an instantaneous unit protective equipment of the balanced type without pilot wires. This form of protection has many advantages and well deserves the consideration of supply authorities.

An equipment comprises differential relays connected to current transformers associated with corresponding phases of two feeders, the principle being the simple comparison of the currents in the feeders. The relay remains inoperative until the balance of currents is disturbed by a fault on either feeder, when the difference is effective to energize the relay to cut off the faulty feeder.

In the case of two dead-ended parallel feeders, the fault current passing to a fault in the immediate neighbourhood of the "receiving" substation may have two paths of nearly equal impedance, so that the difference in the feeder currents is insufficient to cause relay operation at the outgoing end. At the receiving end, however, the fault power flows in opposite directions in the two feeders, and, by using relays with a sensitive directional element at that end, advantage can be taken of this condition to trip the circuit breaker at the receiving end immediately a fault occurs, thus leaving only a single path through the faulty feeder for the fault current. The difference is then a maximum at the outgoing end, and operation of the relay follows immediately on the clearing of the receiving end. If directional relays are arranged for overload and sensitive earth leakage, the potential coil of the leakage relay must be energized according to one of the methods already described for directional leakage relays.

What may be classed as a limitation of this form of protection is that its satisfactory operation involves vigilance on the part of station operators to ensure that the circuit breakers at both ends are opened whenever a feeder is taken out of commission. The reason for this is that auxiliary switches on the oil circuit-breakers are generally used to disconnect the differential relays when the balance is disturbed owing to one of the associated feeders being unloaded; and to leave a circuit breaker closed at one end may result in wrong operation of the

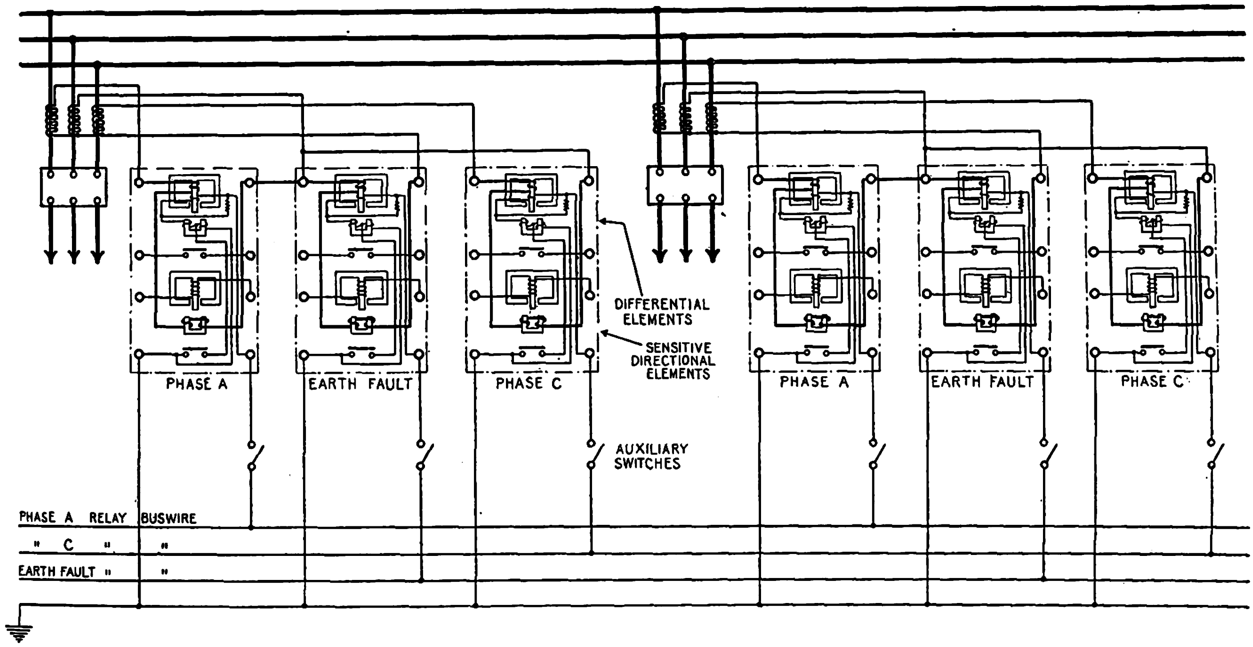


Fig. 31.—"Translay" parallel-feeder protection for phase and earth faults.

relays, with consequent tripping of the healthy feeder at times of fault on other sections of the system.

In the event of settings equivalent to full load or less being necessary, they can be obtained for earth faults only, by connecting one pole of the balanced relay to be operated by the residual currents of the current transformers in the feeders. Any convenient settings for earth faults can then be chosen. With such an arrangement it is possible to carry out switching operations without danger of incorrectly tripping loaded feeders under normal load conditions, since although the phase-fault relays tend to operate before the incoming feeder picks up its load the high setting would prevent the contacts from closing; whilst the earth-fault relay with a lower setting will remain stable because no current will flow through either of its coils under healthy conditions.

In applying such protective gear to parallel feeders it has been the custom to group feeders in sets of two or three. A recent development has made it possible to employ larger groups, with considerable gain in flexibility. This is illustrated in Fig. 31, which shows the application of differential directional relays to a group of similar feeders, the relays being arranged for phase-fault and sensitive earth-fault protection.

The differential elements of the relays are similar in type to the Translay relays already described for pilot-wire feeder protection, but the secondary voltages of all the relays associated with similar phases of the various feeders are connected to a common wire, and the two coils of the operating magnet are connected in opposition. So long as equal primary currents flow in the various feeders, equal voltages will be generated in all the secondary windings and the relays will remain stable. During through faults the stability of the relays will be assisted by the biasing arrangement just as in the case of Translay pilot-wire feeder relays. Owing to the arrangement of the operating magnet coils, no relay can operate under any conditions unless power flows into the feeder, thus causing the contacts of the directional element to short-circuit one of the two opposing coils.

In the case of a fault on one feeder when the group is carrying load away from the busbars, the secondary voltage of the corresponding relay will be increased and the resultant secondary current will cause that relay to trip. The same current returns through the secondary windings of relays on other feeders and will give a stabilizing torque to those relays. In the event of a fault on one feeder when all are carrying load towards the busbars, the reversal of the secondary voltage of one relay would tend to operate all relays, but since the lower operating coils of all relays of healthy feeders can produce no flux (the two coils of each relay being in opposition) only the relay of the faulty feeder, in which one of the coils is short-circuited by the directional element contacts, can operate, so that the faulty feeder will be correctly isolated.

In conclusion, the authors would emphasize that it is possible, by a correct choice from the various systems described in this paper and others of generally similar types, to obtain stable and discriminative protection of feeders even under the most difficult conditions obtaining to-day, so that the art of protection may truly be said to have overtaken the present demands made upon it. In the future new requirements, some already envisaged, will no doubt arise, and the limits of application of even these methods may be reached, but we may safely anticipate that any new requirements can again be met as they arise, and that protective problems will not constitute a limiting factor in the development of transmission systems.

The authors wish to acknowledge assistance received from colleagues, and their indebtedness to the Metropolitan-Vickers Electrical Co., Ltd., for permission to publish details of apparatus of their manufacture, and to the British Thomson-Houston Co. for details of self-compensated gear.

APPENDIX.

(*Received* 6*th June*, 1930.)

As there is a difference of opinion as to the effect of arc resistance upon the performance of impedance relays it will no doubt be of interest to engineers to include, in the form of an Appendix, extracts from a description of a recent research on this subject. The research was carried out at the instigation of the authors and the results indicate that the resistance of an arc is so low that, for all practical purposes, its effect on the behaviour of impedance relays may be neglected.

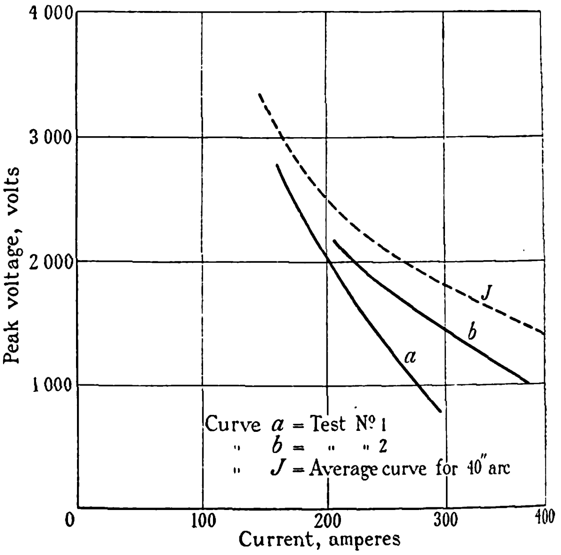


FIG. 32.—Curves for 15-in. arc; also average curve for 40-in. arc.

In order that the results of the tests should be as comprehensive as possible, arcs were struck across a pin-type insulator suitable for 33-kV lines and also across a string of insulators as used on 132-kV lines. In the latter case the insulators were fitted with arcing tips and galvanized-iron rings, and tests were made with the strings mounted (*a*) horizontally and (*b*) vertically.

The approximate length of the arc in the case of the pin-type insulators was 15 in. and 40 in. in the case of the 132-kV type.

Seven different tests were carried out with varying conditions, particulars of which are given in the table. The curves in Figs. 32 and 33 have been plotted to indicate the results, and the values from which the curves are plotted are the instantaneous values of voltage and current obtained from oscillograms. It should be noted that each curve represents the average of a series of values recorded for a particular condition. There is actually a dispersion of about ± 30 per cent about the mean curve, although the majority of the points were within 10 per cent of the mean.

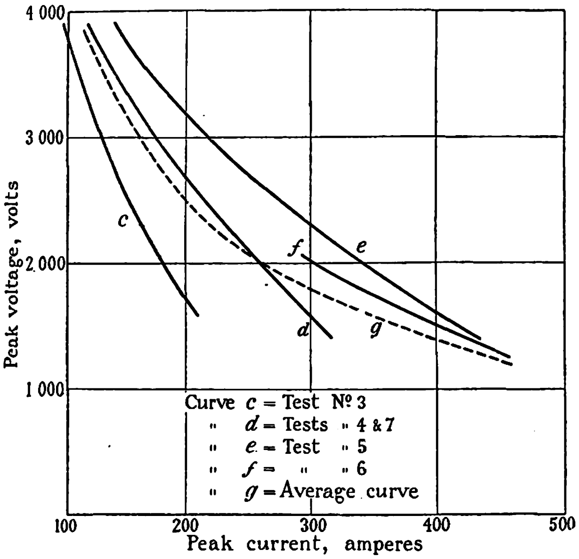


FIG. 33.—Curves for 40-in. arc.

The current was supplied by an alternator of 2 500 kW capacity through a 3 000-kVA transformer giving a secondary voltage of 6 000 volts. An adjustable resistance, connected in series with the arc, limited the current to a convenient value.

Table giving particulars of the Tests.

Test No.	R.M.S. line voltage	Value of limiting resistance	Length of arc	Position of insulator
	volts	ohms	in.	
1	3 230	15·2	15	Vertical
2	4 480	15·2	15	Vertical
3	4 700	20·3	40	Horizontal
4	5 200	20·3	40	Horizontal
5	5 470	15·2	40	Horizontal
6	5 470	15·2	40	Vertical
7	3 520	15·2	40	Vertical

On analysis the oscillograms show fairly smooth curves of peak voltage against peak current. It will be seen from the general shape that the voltage-drop across the arc is in inverse ratio to the arc current, and that for the larger values of current the resistance is comparatively low and will therefore have a negligible effect upon the impedance of the line.

A comparison of the values for the 15-in. arc with those for the 40-in. shows that there is no great variation of resistance with arc length.

The authors wish to express their thanks to Messrs. Metropolitan-Vickers Electrical Co., Ltd., for permission to publish these results.

DISCUSSION BEFORE THE INSTITUTION, 9TH JANUARY, 1930.

Lieut.-Col. K. Edgcumbe: I am glad to see that the authors emphasize the value of the "distance" relay. I am sure that this form of protection has a great future before it, particularly for overhead lines where the cost of pilots is usually prohibitive. I agree with the authors in their preference for the impedance as opposed to the reactance principle, for such relays. The idea underlying the use of reactance relays is that the high-voltage arc behaves as a true ohmic resistance, so that the fault current flows through the reactance of the line in series with the resistance of the arc. Consequently, a relay sensitive to reactance only should be able to pick out the reactance component due to the line, whilst taking no account of the resistance component due to the arc. Unfortunately, experience shows that whilst the resistance of the high-voltage arc is negligible for currents exceeding 200 or 300 amperes, it may amount to as much as 100 to 200 ohms at currents of 100 amperes or less. It must be remembered that the impedance of the line is possibly less than 10 ohms, and it would tax the capabilities of even a sensitive laboratory wattmeter to pick out an inductance "swamped" by an ohmic resistance of more than 20 times its value. It is clearly impossible for a robust protective relay to do so. In my view, therefore, the effect of the resistance of the arc can be neglected at all fault currents likely to be met with in practice, and for abnormally low fault currents no form of distance relay, whether of the impedance or reactance type, can be relied upon. Consequently, the extra complication and delicacy of the reactance pattern is certainly not justified. It may further be pointed out that where the fault is close to the relay the arc resistance tends to keep up the voltage, a fact which is of considerable advantage in the case of the impedance relay but is of no value in that of the reactance relay, which suffers accordingly. The authors' suggested method of compensating for arc resistance is not clear to me. As I understand it, their proposal amounts to deducting, at all currents, an almost constant resistance from that of the line. But the resistance of the arc increases rapidly, as I have said, at small currents. It would, in fact, seem more logical to deduct a constant voltage rather than a constant resistance. This could well be done, in the case of the relay shown in Fig. 11, by giving the attracted iron armature a definite bias away from the poles by means of a spring, for example. In my view, however, no such precautions are necessary and the arc resistance can be neglected. The authors express the opinion that the most satisfactory form of time-lag overload relay is one with an inverse time-characteristic tending to a definite minimum value at high currents. As to the necessity for a definite minimum, I am in agreement with them, but it is, I think, doubtful whether under modern conditions the inverse characteristic is of any value. The old idea that a small overload should be allowed a longer time than a heavier one in which to clear itself seems to me to be out-of-date. Fault currents do not behave in this convenient way and in 99 cases out of 100 they almost instantly reach such a high value that the sooner they are cleared the better. Consequently, the relay should operate within a definite time, the exact value of which has been predetermined to meet the special requirements of the system. In this respect, very much closer accuracy is attainable with the definite time-lag relay than with one of the combined inverse and definite minimum time-lag type; an accuracy of timing of 2 per cent is quite easily obtained with the definite time-lag pattern.

Major A. M. Taylor: My remarks will apply to underground cables rather than to overhead lines. Consideration must be given to the protection of long super-tension underground trunks, such, for example, as the 10-mile main underground trunks which are connected to the Hams Hall station, Birmingham. On such lines freedom from interruption due to surges, high-frequency charging currents and magnetizing currents demands attention. The question of freedom from operation by the 3rd and 9th harmonics, etc., is also very important. In my opinion, the arrangement shown in Fig. 21 would fail to distinguish high-frequency and triple-frequency charging currents in the trunk line from fault currents. Such currents are produced when something unforeseen occurs at a generating station at one end. It is possible that a generator may be put in without a field, so that oscillations of great force and rapidly varying frequency are set up in the line. The practice of having a current transformer at either end of the transmission line, and balancing the one against the other, cannot take account of the capacitance currents. In the case of a 6-phase system or of two 3-phase feeders with one of the phases reversed, it is possible, by means of a suitable arrangement,* to balance *everything* except the fault current. When the transformers are thus suitably connected the relays can be set to very close limits; pilot wires and their troubles are eliminated, and the earth fault is the only point which requires attention. In Birmingham, leakage protective gear has been installed at either end; it was thought that the system would be satisfactory, particularly because S.L.-type cables were being used. There is no doubt, however, that charging currents and harmonics are capable of operating the relay. I know of no relay at present on the market which would give the desired security and allow of the fault setting being reduced to, say, 5 per cent. A device which will remove the fault on a single-core cable immediately it occurs, and before it burns through sufficiently to heat the next cable, is urgently needed.

Mr. F. J. Lane: This paper describes, under the section dealing with pilot-wire protective gear, three different methods of attacking the problem of the provision of balanced protection by means of current transformers. The first is the Merz-Price or balanced-voltage system, the second is the Translay system and the third the self-compensated pilot-wire system. In considering this subject it is important to remember that the ampere-turns input of a current transformer is equal to the sum of the ampere-turns output and the ampere-turns used for magnetization. Thus, if the burden is increased and the input remains constant, the output decreases because more ampere-turns are required for magnetization purposes. In the balanced-voltage system the current transformers are being used entirely to produce voltage; in other words the ampere-turns are completely absorbed as magnetization ampere-turns. It is consequently essential that the magnetic characteristics of the transformers concerned in the balance should follow each other very closely. The curves and the illustration of the opposed-voltage transformer which have been shown have emphasized the precautions necessary. These precautions include very careful design, a multi-gap arrangement to prevent interference from external iron, special methods of assembly and, finally, very accurate balancing in the laboratory. Thus, in the opposed-voltage system, the magnetizing characteristics are the criteria of balance. The Translay system also makes use of the opposed-voltage principle. It is so arranged that it is permissible, within certain limits, to take any pair of current transformers and to employ them at opposite ends of the balanced circuit, since the bias feature will prevent any instability arising from small inherent differences. This system is an important advance in that it permits the use of the ring-core type of current transformer without air-gaps, thereby reducing the magnitude of the magnetization quantities. Such quantities are still important, however, for without the feature of bias accurate balance would still be necessary to ensure stability. If the magnetization quantities can be reduced so that they are not in themselves of sufficient magnitude to produce operation of the protective relays, differences between these quantities are of negligible importance; the difficulties met with in providing special balanced transformers or a biased form of relay then disappear. One of the essential features of the self-compensated pilot-wire arrangement is that it comprises a circulating-current circuit in which the magnetizing losses have been reduced to quantities of the second order of magnitude. The current transformers are of the ring-core type. Pilot currents, iron circuits, and primary ampere-turns have been so chosen that the magnetizing characteristics are negligible with respect to the relay-operating current. Thus, even with considerable variations in the iron or the secondary burden, no unstable operation is experienced. In the systems described there are, therefore, three different methods of dealing with the magnetization quantities. Balanced-voltage systems require very careful design and accurate balance. The Translay system reduces the magnitude of the quantities, but depends on the bias feature as an alternative to balancing. The self-compensated pilot-wire system reduces the quantities to a negligible order of magnitude so that differences between them cannot disturb the stability.

Mr. H. W. Clothier: I am in agreement with the authors upon the main issues of their paper. Whilst overload, parallel feeder and time-limit systems of protection are satisfactory, up to a point, for the protection of small plant, unimportant feeders and connections, the necessities of maximum efficiency in the maintenance of continuity of supply on the present-day large networks and all-ring mains involve the use of one of the reliable pilot-wire systems of protection. Where, however, the cost of pilot wires is excessive (as for long overhead lines), the improved British designs of pilotless time-distance protection provide a good substitute. The Merz-Price balanced system will always hold the preference because of its simplicity, absence of potential element, and short time-characteristic or so-called instantaneous operation, although in this last respect the performance of the pilotless system now approaches very nearly to that of the Merz-Price type over the major length of the feeder protected. It may not be generally realized that it is now 25 years since the original Merz-Price voltage-balance feeder and current-balance transformer types of protection were put into practical operation. The plans for the British grid, which have been under consideration by so many authorities, have recently had an important effect upon the designs of relays; many new ideas, as well as revivals of earlier ones, have been given serious attention. The paper is very complete in its description of some of these, but three systems which are established in production and are at least of equal importance have been omitted. These are (1) the Split pilot, (2) Interlock and (3) Ratio balance systems.* The first is purely a Merz-Price current-balance feeder system and it retains the ideal of easily-measured current values in balance. Stability on through faults is secured by the known principles of split-conductor and self-balance protection. It is used with the ordinary 3-core pilot cable. The second requires only the momentary use of an ordinary telephone pair. It is a unit system which combines the use of directional relays with time-limit overload relays at each end, and uses the lock-out principle to prevent operation on through overload current, the lock-out being effected by the d.c. current signals. The third is the time-distance type of protection in which the time function is regulated by separate clockwork mechanism. The relays are of the reactive type, when used on overhead lines, so that the resistance of the arc does not affect the correct measurement of the distance of the fault. The selection of one or other of these three systems satisfies any conditions and provides, in each case, a comprehensive unit protection—that is to say a faulty line is isolated without interference with sound lines under all the conditions of service which have yet been experienced. I agree with the authors regarding the design of transformers of the multi-air-gap type, as shown in Fig. 16, although such equipment can hardly claim, at this stage, a place among recent developments. The voltage characteristic and general design correspond to the 4-gap transformers of which there are many thousands in use, and presumably the new 8-gap transformer will balance reasonably well against the old standards, which have a similar (Fig. 17) straight-line characteristic up to 10 000 amperes, or thereabouts. The wattmeter-type relay used in pilot-wire protection was also tried many years ago because in theory it was not operated by pilot-wire capacity currents, but it never came into extensive use in practice. In Translay protection the special air-gap transformer is eliminated in favour of solid-core instruments, compensation for the resultant poor balance being provided by the old method of increasing fault setting on the bias principle. There is no mention in the paper of how the difficulties which led to the abandonment of wattmeter-type relays have been overcome in the present Translay protection. Apart from the details, there is the main difficulty of discriminating by phase-angle displacements and even of measuring the latter, particularly when in service. The original basis of Merz-Price protection lay solely in the balance of easily-measured current values, and the alternative split-pilot system, because it retains this feature and the other ideal features of Merz-Price protection, seems to satisfy in a better form the authors' plea for stability. The split-pilot system is one of self-balance and it incorporates the ideal characteristics of split conductor and self-balance protection. Would the authors find any difficulty in protecting a line with a T-connection, on the Translay plan? The modern call is for the use of telephone pairs, and assuming that this is theoretically possible on the Translay system because of the small amount of energy necessary for operation over the pilot wire, is it practicable on Post Office lines under the existing Post Office Regulations, and, seeing that the pilot is in constant service, is it reliable? If, on the other hand, a special pilot is installed, has it much advantage in cost over the ordinary pilot wires as used in the past for other types of Merz-Price protection? Where the use of telephone pairs is the predominating demand, the system of interlock protection is an alternative of some merit. For example, it is free from the limitation of the non-unit type of protection shown in Fig. 26, and has the universal unit application of a Merz-Price system with a qualification in respect of time function only. The d.c. pilot-wire system shown in Fig. 28 might be used with telephone pairs, but it seems to be defective in that it will only operate with fault current fed in one direction. The earthing of the pilot at both ends might render it liable to inadvertent operation from d.c. vagabond currents, as, for example, when it is used in the vicinity of tramway systems. With regard to time-distance protection, the curve [Fig. 12(*b*)] is on the right lines. So far as instantaneous tripping over the major length of the line is concerned, it corresponds to the ratio balance system, but the latter provides an improved characteristic in respect to the "back-up" part of the protection. This is due to the clockwork timing-device, which enables the shape of characteristic best suited to the length and relative positions of the feeders to be incorporated. Moreover, on this system the relays measure the reactive voltage rather than the impedance voltage, when used on overhead lines. This feature, as the authors suggest, renders the system independent of the resistance of the arc constituting the fault and of variation in earth-plate resistance. Thus the compensation suggested in Figs. 13 and 14 is superfluous: it is, at best, based upon a rough estimate only of the resistance of the arc in any particular fault. This quantity cannot be predicted with the necessary degree of accuracy. The distance of the fault selected by the impedance relay with arc resistance in circuit may cause isolation of the wrong feeder, but with reactance relays the arc resistance does not affect the correct measurement of the distance of the fault, and hence, irrespective of the amount of arc resistance, it gives correct discrimination. In the case of cables, where the reactive loop is much less than for overhead lines, the measurement of distance by impedance voltage is preferable, but there is more scope here for the Merz-Price system as pilot wires and cable can be laid at the same time.

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* British Patent No. 200194, 1922.

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* Also see written communication by Messrs. H. W. Clothier and B. H. Leeson on page 827.

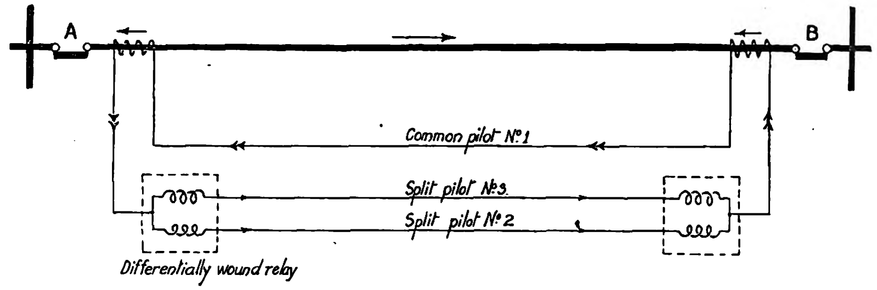
Mr. J. R. Beard: So far as this country is concerned, the real starting point of the striking developments in high-voltage feeder protective equipment dates from the years 1900 to 1905 when Charles H. Merz was engaged in developing the Tyneside district as our first extensive power supply area. He soon realized the economy resulting from the use of ring mains for high-voltage distribution. The operating difficulties, however, proved considerable. Attempts to solve these by graded overload and inverse power relays demonstrated that the protective problem was an essential feature in the design of high-voltage networks. Bernard Price solved the problem, as it then existed, by putting forward the fundamental idea of balancing the input and output currents to each section of network. This —at that time revolutionary—idea abolished all time-limits and enabled faulty lines to be disconnected almost instantaneously. It was certainly the greatest advance in protective gear ever made. Price has since devoted his life to work in South Africa and one sometimes wonders whether his outstanding contributions to electrical engineering are sufficiently appreciated in this country. Another name which should be associated with early development is that of E. B. Wedmore who, I believe, worked independently of Price on very similar lines. Why is mains protection so important in electrical work? I think the reason is the same as that which gives electricity its chief advantage; that is, its ease of transmission. This makes it necessary to regard every leakage as a serious fault and equivalent to a burst gas-main or water-main. Protective systems have proved a peculiarly attractive field to amateurs, as may be seen from the Patent Office files. To each beginner his scheme seems infallible, but those who have been through the mill hesitate to admit finality and are always suspicious that methods claimed to be improvements may introduce old difficulties. I just remember the first Merz-Price tests in 1905. The balancing was arranged to cover not only the high-voltage feeders but also the complete substation apparatus—transformers, switches and busbars. This was tested in the most vigorous manner by artificial faults, such as bullets fired into the cables, and everything worked perfectly. Shortly afterwards, due to delay in the completion of the cable tunnel under the Tyne, some high-voltage cables were laid in the bed of the river and protected by the new method. One of these was parted when dragged up by a ship's anchor and the protective gear disconnected it, very surprisingly as it then seemed, without shock to the system. At that time the protective problem seemed to have been permanently solved. However, the growth of systems to cover larger areas, to carry bigger loads and to operate at higher voltages has introduced further difficulties. The start due to Price and the fact that British conditions necessarily involve congested areas and cable networks have combined to keep this country in the forefront of balanced protection schemes. Each technical problem has been solved as it arose, and I recently had striking confirmation of the efficiency of one of the solutions with which I have been associated. The 33-kV network in Sydney is protected by the compensated-pilot method and this network has of recent years had a considerable number of cable failures. Mr. Forbes MacKay has, however, recently told me that in the course of 63 faults in no case did the protective gear fail to operate correctly. I believe Manchester has had a similar satisfactory experience with the same method. Pilot protection is, I think, universally admitted to be a complete technical solution of feeder protection problems. The chief difficulty is that of capital cost. While this is not of great importance on cable systems, where the pilots can be laid at the same time as the cables, it is very important on overhead lines. On wood-pole lines it is possible to suspend the pilot from a catenary carried on the poles, but the cost is rather high and for steel-tower lines with long spans the cost of suspension becomes considerable. In fact, in many instances it is preferable, if pilots are essential, to lay these underground in a separate trench along the route of the lines. Several methods have been devised with the object of overcoming the difficulty of capital cost. A number of these aim at reducing the number of cores to two or even one; others reduce the momentary voltages induced in the pilot under fault conditions and thus enable less insulation and, therefore, a lighter cable to be used. Kapp and Carrothers propose a system in which the pilot is embedded in the ordinary earth wire. Carrier-wave systems have also been employed, using the power wires themselves for pilot purposes. I believe one of the features of the Translay system described in the paper is that it reduces the size and number of the pilot conductors and also diminishes the peak voltages imposed upon them. I should like to ask the authors whether these can be reduced to such an extent that ordinary telephone pairs can safely be employed. Another promising means of reducing capital cost is the use of rectifiers to apply direct current to the pilot and I am glad to note the references to possible developments on these lines. In connection with the 132-kV lines of the grid, it has been necessary for economic reasons to abandon the general use of pilot protection, although this is still being used on the shorter sections. For the longer lines, pilotless arrangements of the impedance type such as have been developed in America and on the Continent are adopted. British experience in protective gear has, however, proved of great value in adapting and improving these forms of protection in the direction of giving greater discrimination and shorter time-settings. The paper describes one of these improved British methods and I believe there are at least two others which have been developed commercially. I look forward with great interest to practical experience of these methods over the next 2 or 3 years, as the grid system comes into commercial operation. I was surprised to note the omission from the paper of the problem of protecting feeders with direct-connected transformers. The use of such transformer-feeders is on the increase because of the endeavour to economize in the use of switchgear, and their satisfactory protection is, therefore, of great importance. A typical example of the difficulties which arise is that of ensuring that a fault on the lower-voltage winding will disconnect the transformer-feeder at the end remote from the transformer. Anything which the authors may be able to add regarding proposals for dealing with the protection of feeder-transformers will be useful.

Mr. R. O. Kapp: The paper contains references to several systems of directional relays; where these are to be employed for protection, certain difficulties arise. One of them is that a directional relay often depends on voltage for its correct operation. If the fault is near the relay, the voltage may be very low. Another difficulty is that, on systems with a high circuit impedance, for example on comparatively low voltages with a small generating plant or a source of supply through transformers, the fault currents are comparatively small. Some of the load current may be fed past the fault, thus swamping the effect of the load current towards it, and preventing correct operation of the relays. I should like to ask the authors whether they have used phase filters to overcome these troubles. Fortescue has shown that a 3-phase unbalanced system can be represented as three balanced superimposed systems, one of them a symmetrical 3-phase system with normal phase rotation, the second a symmetrical 3-phase system with reverse phase rotation, and the third a single-phase system. A phase filter picks out one of these systems, namely, that of the reverse phase rotation. This does not exist so long as the line is sound, so that the load currents do not contribute to it and the relays can be made very sensitive. The reverse-phase sequence voltage is a maximum near the fault, so that the phase filter lets through just those operating effects which have the greatest magnitude where they are most needed. There are, no doubt, certain difficulties attending their use, and it would be interesting to hear more of these. In the past, the necessary connections involved a phase displacement of 60 degrees, and to allow for this a combination of capacity and self-induction was necessary. But a system developed by Messrs. Iliovici and Dubusc, which has been successfully employed in France for about a year, transforms the 3-phase current on the secondary side of the current transformers into a 2-phase system. A 2-phase filter requires a displacement of 90 degrees; this can be provided by a suitable adjustment of resistance and capacity and it is stated that the system overcomes the practical difficulties. The principle of impedance protection has a limitation in connection with the length of the line to be protected. Impedance relays or reactance relays on a section must be supplied with a sufficient voltage to prevent them from operating incorrectly. If the sections are very short this may not be possible. The greater the fault current, the higher will be the voltage at the end of a section of given length. It is, therefore, rather easier to protect lines on high-power systems at very high voltage than lines of the same length on small systems where the fault currents are not so great. The arc resistance has been mentioned by several speakers, and in my opinion the authors exaggerate its importance. They suggest a means of compensating for it. In large power systems with high voltages the arc resistance is likely to be so low that any compensation will be excessive and should be omitted. For example, consider a system capable of carrying 2 500 amperes to the fault; such a case would occur on the Scottish grid at Dundee, and is typical of very large systems. It is possible to calculate the relationship between voltage, resistance, and fault current. Supposing the arc resistance were only 0·1 ohm, the arc would absorb 625 kW at 250 volts. If the arc resistance were only 3 ohms, then approximately 19 000 kW would be absorbed in the arc, and 7 750 volts would be required to sustain it. An arc is essentially unstable; as the current increases the resistance drops. If the resistance were high, the energy absorbed by the arc would be equal to that required for the lighting of a whole town, and it is clear that such intense illumination is not provided by an arc. The earth-return path is a more important factor, but some of the investigations of the Research Association in conjunction with the Post Office and Central Electricity Board have shown that, with a variation in earth resistance between 5 000 and 20 000 ohms per cm cube, the effect of the earth resistance on the apparent impedance of the British grid lines would be about 8 per cent. The effect of the earth resistance, therefore, is not very marked in this connection. Fig. 12(*a*) of the paper shows characteristic curves which are, in my opinion, misleading because they are far too flat for practical purposes. It should be observed that, in addition to the theoretical minimum times, allowance must be made for incorrect adjustment, so that the actual curves are considerably steeper. I agree that it is essential to cut off a short-circuit in the minimum possible time, and therefore the characteristic of the curve in Fig. 12(*b*) is desirable in spite of the slight complication.

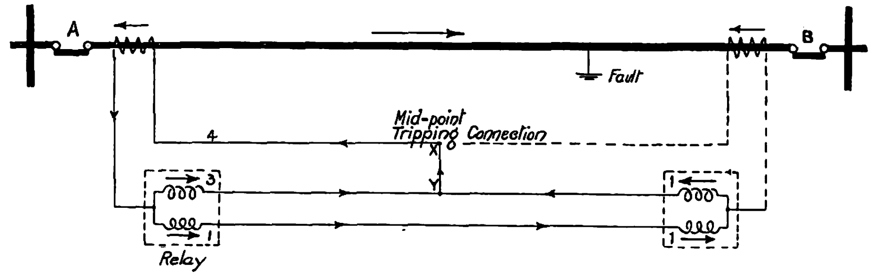
Messrs. H. W. Clothier and **B. H. Leeson** (*communicated*): The recent expansion of the demands made upon protective systems for 3-phase overhead transmission lines and cables, by reason of increased interlinking of power supply systems, has occasioned a revision of the methods used for discriminating protection which have been evolved during the preceding 20 years. The recent factors causing this expansion may be summarized as follows: (*a*) Transmission at higher voltages; (*b*) transmission over longer distances; (*c*) demands for more sensitive earth-fault settings; and (*d*) demand for displacement of pilot wires on the grounds of economy, particularly for long lines. A protective system, the stability of which is independent of protective systems or faults on other units, and the operation of which extends only over the unit it protects, is said to provide unit protection, and this is the chief feature of the Merz-Price pilot-wire type of protective system. Any new protective system is required to provide protection as nearly as possible equal to that of a Merz-Price pilot-wire system, and the three protective systems about to be described have been devised with this aim in view. These three protective systems are the "split-pilot," the "interlock," and the "ratio-balance."

"Split-Pilot" System.

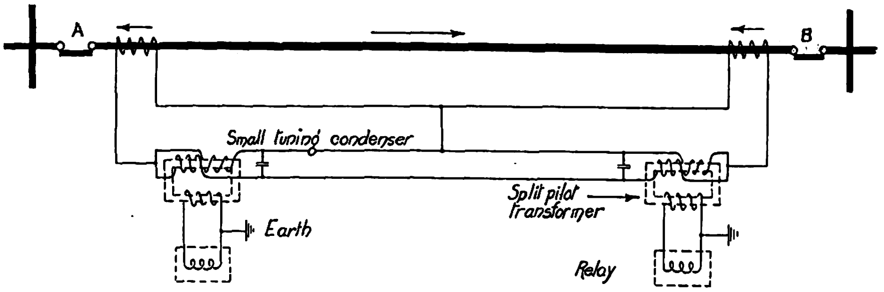
This is an evolution of the Merz-Price pilot-wire protective system with its instantaneous operation under fault conditions, and was designed upon the principle of devising first a scheme for obtaining stability of the relays under external fault conditions, and then a method of operating the relays under internal fault conditions. The system derives its name from the way it achieves this principle by using two of its three pilot wires on the split-conductor method so that pilot capacity currents are inherently self-balancing, and operation of the relays is effected by a tripping connection in the middle of the pilot cable which only disturbs the inherent balance in the split pilots when the feeder is faulty.



(a) Inherent Balance



(b) Operation



(c) Safety & Tuning

FIG. A.—Diagrams illustrating principle of inherent balance and tripping of "split-pilot" protective system.

The split-pilot system shown in Figs. B and C is of the current-balance type, and further features are the use of electrically-tuned relays only responsive to normal-frequency fault currents (and therefore immune from wrong operation by unbalanced oscillatory currents which flow in the feeder under straight-through fault conditions); the earthing of all relays on one pole for safety to operators; the current-transformer connections; and the adaptability of the system with a common tripping connection to protect tee'd feeders.

The evolution of the split-pilot system upon the lines just described is illustrated in Fig. A, the feeder and transformers being shown single-phase at this stage for simplicity. The 3-phase transformer connections are described later in conjunction with the practical applications shown in Figs. B and C.

From diagram (*a*) in Fig. A it will be seen that any current, capacity or other, flowing in the pilot circuit divides equally between the split pilots 2 and 3, thus producing no operating effect in the differentially-wound self-balanced relays at "A" and "B." Thus in this form the system has inherent stability for all fault currents, and it requires the addition of a means for operating the relays by the occurrence of faults on the feeder.

Diagram (*b*) shows how operation of the relays is obtained by what is termed a mid-point tripping connection. When the feeder is healthy and carrying a straight-through current of any value the points " X " and " Y " situated at the geographical centre of the pilot cable are equipotential points, and may therefore be connected together by the tripping connection without disturbing the self-balance of the system. The tripping connection, however, has the desired effect of disturbing the balance in the split pilots and operating both relays simultaneously when a fault occurs as shown at " F." With a fault fed from " A," and neglecting the portion of the pilot circuit shown dotted, the out-of-balance current divides in the two split pilots in the proportion of 3 : 1 as shown by the arrows, owing to this proportionality between the impedances of the two paths. This produces an operating effect on the relay at " A " of 3 minus 1, and a similar effect on the relay at " B " of 1 plus 1. Although the shunting

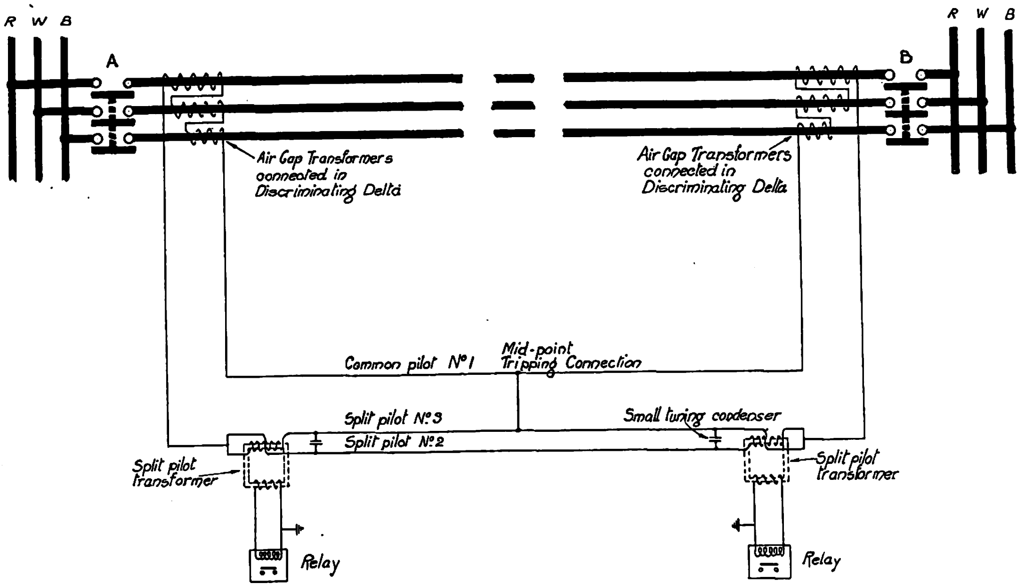

R W B
A
R W B
B
Air Gap Transformers connected in Discriminating Delta
Air Gap Transformers connected in Discriminating Delta
Common pilot Nº1
Mid-point Tripping Connection
Split pilot Nº3
Split pilot Nº2
Small tuning condenser
Split pilot Transformer
Split pilot transformer
Relay
Relay

FIG. B.—" Split-pilot " protective system for voltages up to 44 kV.

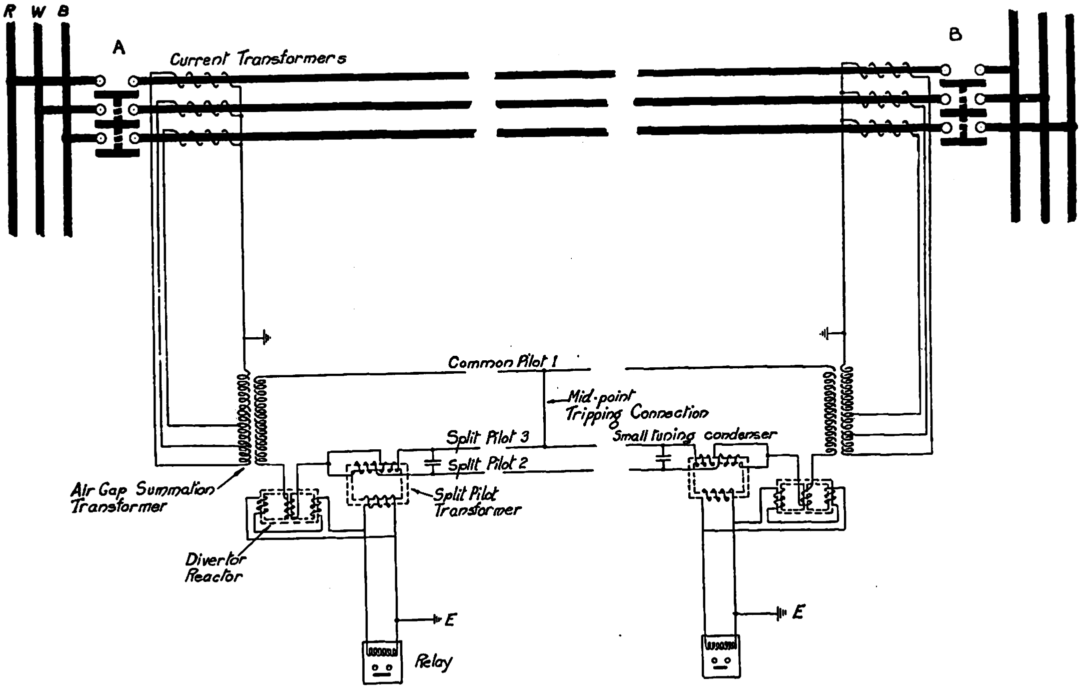

R W B
A
Current Transformers
B
Common Pilot 1
Mid-point Tripping Connection
Split Pilot 3
Split Pilot 2
Small tuning condenser
Air Gap Summation Transformer
Split Pilot Transformer
Diverter Reactor
E
E
Relay

FIG. C.—" Split-pilot " protective system for voltages up to 220 kV.

effect of the dotted path slightly alters the proportionality of the currents just described, the general principle that the difference between the two split-pilot currents at one end of the feeder is equal to the sum of the split-pilot currents at the other end is always true for any fault fed from one direction. For a fault fed from both directions the tripping effect is intensified but it is still equal in each relay at " A " and " B."

Diagram (*c*) shows how the substitution of a differentially-wound transformer for the differentially-wound relays enables standard low-voltage relays to be used and earthed on one pole to ensure safety to an operator. Owing to the mutual inductance between the two split windings of the split-pilot transformer a very small condenser will tune the circuit electrically, so that the relays respond to fault current only at the normal system frequency. Under normal and straight-through fault conditions the voltage across the small tuning condenser is negligible because of the current equality in the split pilots, and it is only during the period in which a faulty feeder is being isolated that a voltage exists across its terminals. Fig. D illustrates the electrical tuning characteristics obtained in this way, and it will be seen that the system is inherently stable for all frequencies which can occur above normal, including third-harmonic currents.

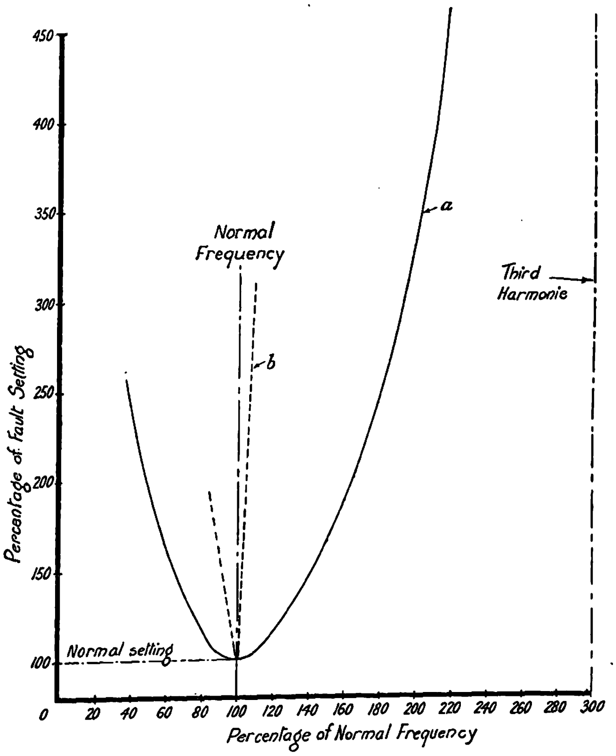


FIG. D.—Tuning characteristics of " split-pilot " protective system.

(*a*) With electrically-tuned relay.
(*b*) With mechanically-tuned relay.

When the tuning of protective systems by electrical or mechanical means was explored first,[*] mechanically-tuned relays using vibrating reeds were developed, and a typical characteristic is indicated by the dotted line (*b*) in Fig. D. Later, electrical tuning was adopted in view of the improved characteristic obtained, as shown by (*a*) in Fig. D, from which it will be seen that the fault setting is increased by only 5 per cent for a drop in network frequency of 10 per cent.

Figs. B and C illustrate practical applications of the split-pilot system to feeders up to 44 kV and 220 kV respectively, and in each system the transformers are connected up in " discriminating delta " or its equivalent. In Fig. B each transformer has a different turns ratio, in such proportions as 4, 5, and 6, which affords protection to the feeder for all types of fault, the earth-fault settings being more sensitive than those for phase faults. The use of distributed-air-gap transformers provides stability by nature of their straight-line characteristics, and the discriminating delta connection subjects the pilots to a minimum voltage for a given straight-through current and so reduces pilot capacity currents to a minimum.

Distributed-air-gap transformers have been used on voltages up to 66 kV, but for reasons of economy and interchangeability amongst various makers' products the split-pilot system as applied to the 132-kV British grid employs solid-core bushing-type current transformers of equal turns ratio, which are connected up in discriminating-delta to multi-air-gap summation transformers, the secondaries of which are connected to the pilot wires as shown in Fig. C. The two distributed-air-gap summation transformers are balanced by nature of their straight-line characteristics, but the solid-core current transformers are not self-balanced and may cause a small out-of-balance current to flow in the pilot wires, depending upon the value of the straight-through fault current. To nullify this out-of-balance current, a device called a " divertor reactor " is used, consisting of a small three-limbed iron core with an exciting winding on the centre limb in series with the pilots. The two outer limbs have divertor windings connected in series, so that the resultant inductive effect upon them from the exciting winding is zero. As the out-of-balance current in the pilots and exciting winding (due to the solid-core current transformers) increases, the flux density in the divertor-reactor core increases above saturation and therefore causes a diminution in the reactance of the divertor windings which shunt the relay terminals. This diverts or by-passes from the relay a current proportional to the out-of-balance current existing in the pilot circuit, and self-neutralizes any lack of inherent balance in the system caused by the solid-core bushing-type transformers.

Fig. E shows the split-pilot system applied to a tee'd feeder in which the 3-core pilot cable is tee'd off at the same place as the feeder. The mid-point tripping connection between " X " and " Y " is also made at the same place. With a tee'd feeder having three equal branches and a straight-through current fed from " A " towards " B " and " C " as shown by the arrows in Fig. E, it will be apparent that the voltage-drop in the pilots from " A " to the points " X," " Y," and " Z," is equal to the sum of the voltage-drops from " X," " Y," and " Z," to " B," and " X," " Y," and " Z," to " C." The points " X " and " Y " are therefore equipotential and the mid-point tripping connection between them functions in exactly the same manner as described for the plain feeder in diagram (*b*) of Fig. A, and this applies for any direction or distribution of current in the tee'd feeder. In practice, the three branches of a tee'd feeder are usually unequal, and such conditions are met by inserting a balancing resistance in the common pilot of one of the branches of the pilot cable so that they are artificially made electrically equal at the tee point.

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[*] Patent No. 227523, 1925.

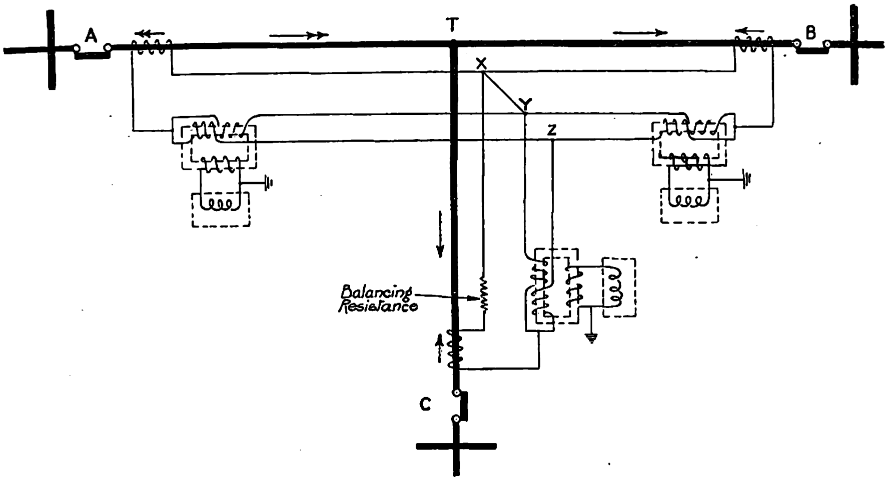
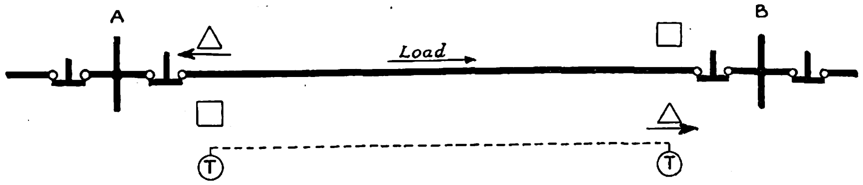
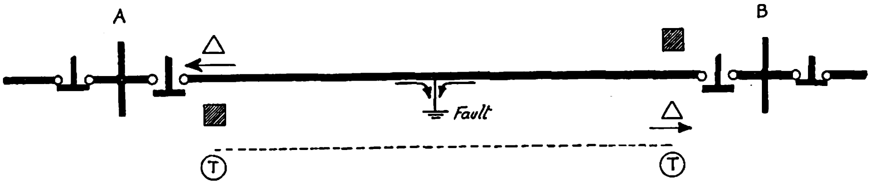


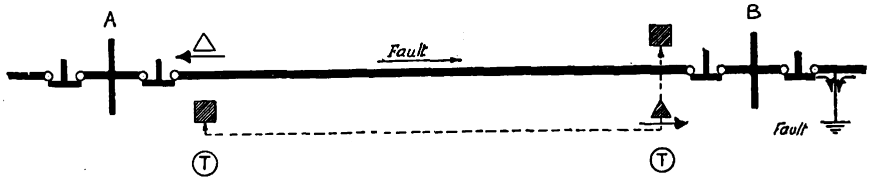
FIG. E.—Diagram illustrating principle of " split-pilot " protective system for a tee'd feeder.



(a) Normal conditions; pilots used for telephony



(b) Internal fault; pilots disconnected momentarily



(c) External fault; pilots used momentarily for stabilizing

Ⓣ	Telephone	△←	Directional stabilizing-element
☐	Overcurrent tripping element with time-lag	-----	Pilots
		▨	Elements operating

FIG. F.—Key diagram illustrating principle of " interlock " protective system.

To summarize: The chief characteristics of the split-pilot system are its universal application, the unit protection it provides, inherent stability by self-balancing, and " instantaneous " tripping.

"*Interlock*" *System.*

This system protects a cable or overhead line on the unit principle without incurring the cost and continuous use of pilot wires, or employing graded time-delays to obtain discriminative operation.

The system obtains its discrimination under these conditions upon the following principle, which is illustrated in Fig. F. When a fault occurs on the feeder, as shown in diagram (*b*), the fault-currents flow in a direction away from the busbars and operate overcurrent and earth-leakage tripping-elements (denoted by the shaded squares), which isolate the feeder. When a fault occurs external to the feeder, as shown in diagram (*c*), the straight-through fault-current at the end of the feeder nearest to the fault flows in a direction towards the busbars, and this characteristic is utilized to operate a directional stabilizing-element (denoted by the shaded triangle), which interlocks the tripping-element at each end of the feeder and prevents it from being isolated.

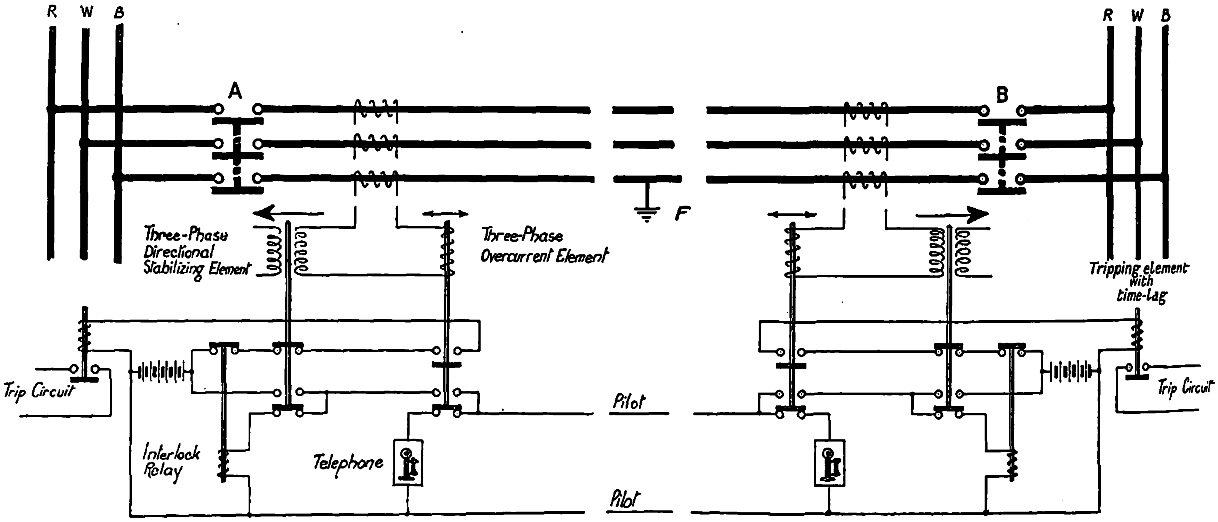

R W B
A
B
F
Three-Phase Directional Stabilizing Element
Three-Phase Overcurrent Element
R W B
Tripping element with time-lag
Trip Circuit
Trip Circuit
Pilot
Pilot
Interlock Relay
Telephone

FIG. G.—Diagram illustrating "interlock" protective system utilizing an existing pilot circuit.

While the external fault exists, the interlock of the tripping element at the distant end of the feeder "A" is performed by a signal transmitted over a pilot circuit. The latter is borrowed by the tripping elements, after which it is returned to its normal duty, as shown in diagram (*a*).

The interlock system is thus applicable to feeders wherever any form of pilot circuit or means of communication from one end of the feeder to the other may be borrowed momentarily to transmit a stabilizing signal. The interruption caused to the normal duty of the means of communication utilized in this way for feeder protection is negligible, because the interlock system borrows it on rare occasions only, and then for a period of something less than three-quarters of a second. Typical normal duties are telephony, remote indication, metering, and control, and such everyday use adds to the reliability of the protective system by indicating that the means of communication is in good condition.

A typical application of the interlock system to a 3-phase feeder of any voltage with existing telephonic communication between stations "A" and "B" is shown in Fig. G. The secondary current and voltage connections are omitted for simplicity, because they follow standard practice for overcurrent, earth-leakage and directional relays, and when applied to extra-high-voltage feeders the potential coils of the directional stabilizing elements may be energized by capacity currents obtained from the bushings of the circuit breakers.

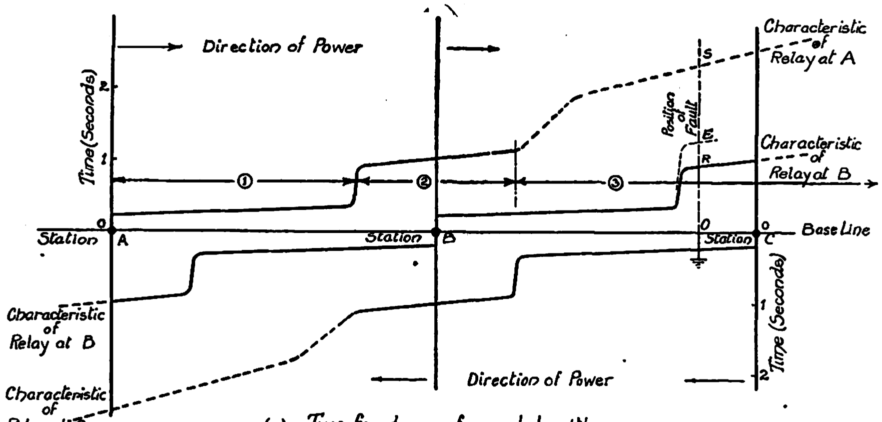
When a fault occurs at "F," corresponding to key diagram (*b*), Fig. F, the overcurrent elements momentarily isolate the telephone circuit and instantaneously energize the tripping elements, which close the circuit breaker trip-circuit after a time-lag of 0·3 sec, thus isolating the faulty feeder. When a fault occurs external to the feeder at "B," corresponding to key diagram (*c*), Fig. F, the overcurrent elements instantaneously borrow the telephone circuit, and the stabilizing element at "B" similarly connects its battery to the pilot circuit at "B" to operate the interlock relay at "A." The instantaneous operation of these elements stabilizes the protective system by de-energizing the tripping elements with time-hesitation at "A" and "B" long before either has had time to operate, thus preventing the isolation of the healthy feeder. The time-hesitation of 0·3 sec., divided by the time required for the so-called instantaneous elements to operate, gives a minimum stability factor of 2.

To summarize: The chief characteristics of the interlock system are that it is universally applicable for protecting a network of feeders on the unit principle, that its small time-hesitation and its stability factor are uniform on all feeders, and that its momentary use of pilots either eliminates their cost or reduces it to a mere fraction by reason of the other services for which they may be used normally.

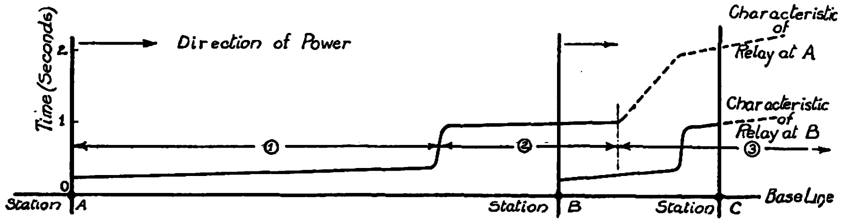
"*Ratio-Balance*" *System.*

This system belongs to the distance class of protective systems, which obtain their discrimination for operation and stability by automatically grading their time-settings in accordance with the voltage and current conditions produced in the network by the fault itself.

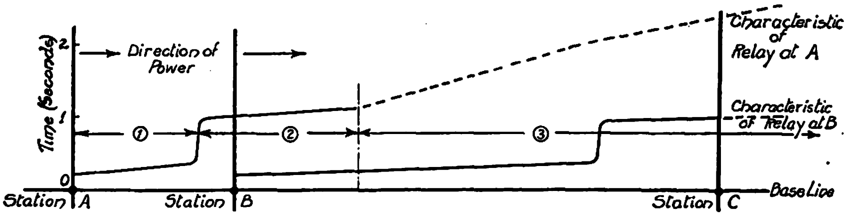
The system was designed to provide a pilotless protection having operating characteristics similar to those of the Merz-Price pilot-wire type. Although no system in the distance class of protection achieves this completely, the ratio-balance system approaches it closely because it provides instantaneous protection for faults over the major length of the feeder, and introduces a time-lag, of the order of 1 sec., for discrimination only when a fault occurs in the remaining length of the feeder.


Direction of Power
Time (Seconds)
2
1
0
①
②
③
S
E
R
O
Position of Fault
Characteristic of Relay at A
Characteristic of Relay at B
Station A
Station B
Station C
Base Line
Characteristic of Relay at B
Characteristic of Relay at C
Direction of Power
Time (Seconds)

(a) Two feeders of equal length


Time (Seconds)
2
1
0
Direction of Power
①
②
③
Characteristic of Relay at A
Characteristic of Relay at B
Station A
Station B
Station C
Base Line

(b) Long feeder followed by short feeder (Ratio 3:1)


Time (Seconds)
2
1
0
Direction of Power
①
②
③
Characteristic of Relay at A
Characteristic of Relay at B
Station A
Station B
Station C
Base Line

(c) Short feeder followed by long Feeder (Ratio 1:3)

FIG. H.—Diagrams illustrating principle of time-distance characteristics of " ratio-balance " protective system for securing stability and discrimination.

The time-distance characteristics for securing stability and discrimination are illustrated in Fig. H, and one feature of the system is that any desired characteristic can be provided to fulfil any particular condition to the best advantage.

Three conditions typical of service requirements are shown in the examples (*a*), (*b*), and (*c*), from which it will be seen that each time-distance characteristic is divided into three fundamental zones. The first is the instantaneous zone; the second is the time-discriminating zone; and the third is the overlap, or " back-up," zone. These three zones provide stability and discrimination under all conditions of fault as follows:—

With reference to the time-distance characteristics above the base line in Fig. H(*a*), a fault in the feeder AB occurring within the first zone is cleared instantaneously by the circuit breaker at station " A," and a fault on AB adjacent to station " B " in the second zone is cleared after a time-lag of approximately 1 sec. A fault in the feeder BC in the third zone, for example at " O," will not be cleared by the circuit breaker at station " A," because the time-lag of the relay at " A " will have increased to the value represented by OS, and the circuit breaker at station " B " will have cleared the fault in the time represented by OE, which is slightly longer than that of the relay characteristic OR, namely, by the time required for the circuit breaker to perform its opening duty. The stability factor is represented by the ratio OS/OE, the desirable value of which is an average of 2.

Two of the chief features of the time-distance characteristics shown in Fig. H are the flat portions of the characteristic in the first and second zones, and the flexibility of the characteristic, which can be altered at will to suit the different conditions of (*a*) two feeders of equal length; (*b*) a long feeder followed by a short feeder; and (*c*) a short feeder followed by a long feeder. Like other protective systems in its class, the ratio-balance system provides protection against busbar faults.

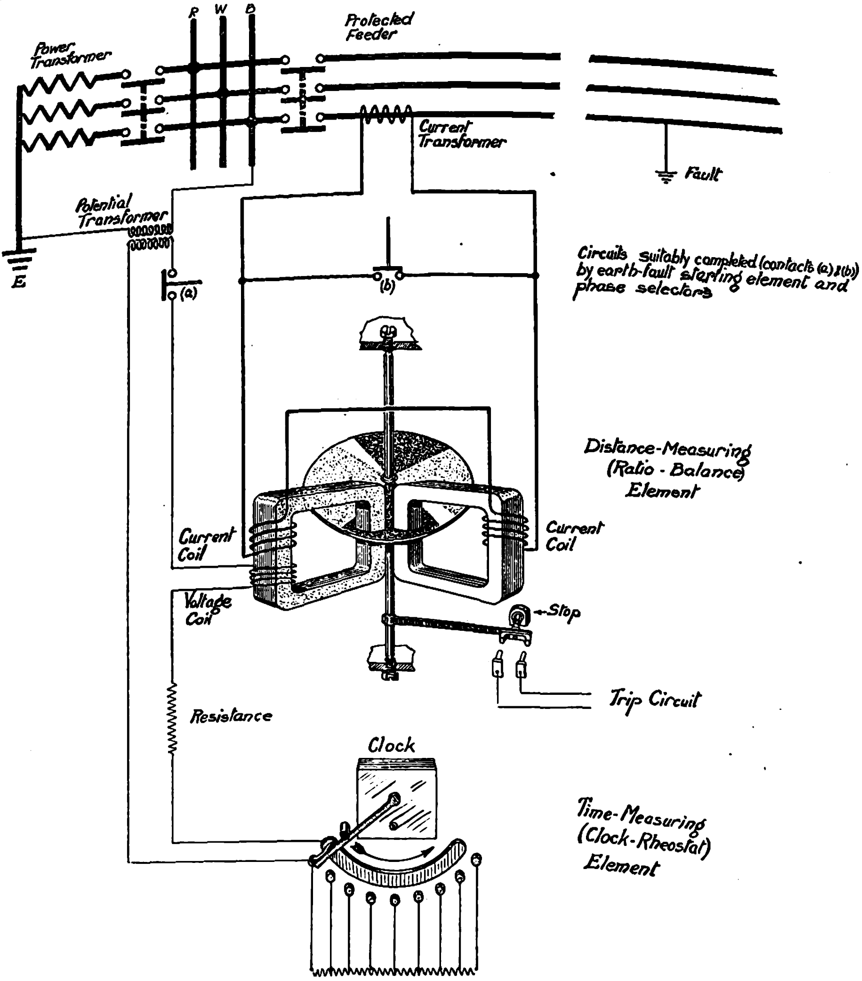

R W B
Protected Feeder
Power Transformer
Current Transformer
Fault
Potential Transformer
E
(a)
(b)
Circuits suitably completed (contacts (a) & (b)) by earth-fault starting element and phase selectors
Distance-Measuring (Ratio - Balance) Element
Current Coil
Current Coil
Voltage Coil
Stop
Trip Circuit
Resistance
Clock
Time-Measuring (Clock-Rheostat) Element

FIG. J.—Diagram illustrating principle of time-distance discriminating unit of the reactance-type "ratio-balance" protective system.

The most useful field of application for protective systems of the distance class is the protection of long overhead transmission lines, and many such systems adjust their time-lag by measuring the impedance of the faulty line on the assumption that it is proportional to the geographical distance of the fault from the relay.

In practice, the resistance of an arc in air forming a fault, together with the resistance of the earth connections, corresponds to a considerable length of transmission line, so that the impedance measured by a relay may represent not the real geographical distance of a fault from it but the increased distance of what may be called an apparent fault situated far beyond the real fault. In consequence, the relay may adjust its time-lag upon a false basis and discriminate wrongly. An alternative method, which eliminates the effect of arc and earth-plate resistance, is to measure the reactance of the faulty line and to adjust the time-lag accordingly.

The main innovation of the ratio-balance system is the time-distance discriminating unit shown in Fig. J, which measures the reactance of the line and adjusts the time-lag in accordance with the characteristics shown in Fig. H. The unit consists of two essential components, the distance-measuring element which measures the reactance, and the time-measuring element which measures the time-delay; and these two elements work in combination with one another by means of an electrical connection in the following manner: Normally, the induction movement of the distance-measuring element holds the contact-making member against the stop, and leaves the tripping circuit open. When a fault occurs, the voltage and current-coil circuits are energized by contacts (a) and (b) respectively by means of the starting elements and phase selectors referred to later on.

If the fault is in the first zone of the time-distance characteristics shown in Fig. H, the distance-measuring element, which is set to operate at or below a definite value of reactance, closes the tripping circuit instantaneously; if, however, the fault is outside the first or instantaneous zone the time-measuring element, which is also started up on the occurrence of the fault, gradually alters the setting of the distance-measuring element by inserting resistance in the circuit of its voltage coil. Thus, the time taken to complete the tripping circuit is equal to the time taken by the time-measuring element to insert sufficient resistance to cause the distance-measuring element to operate.

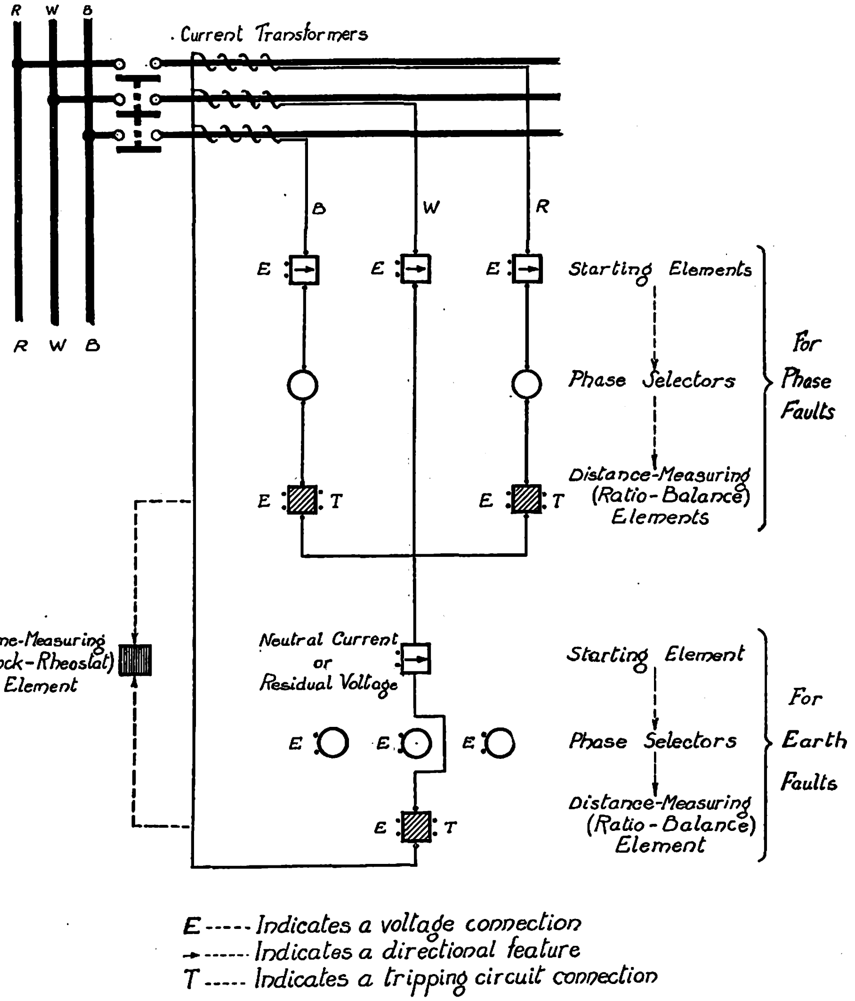

R W B
Current Transformers
B
W
R
E
E
E
Starting Elements
Phase Selectors
Distance-Measuring (Ratio-Balance) Elements
For Phase Faults
E T
E T
R W B
Time-Measuring (Clock-Rheostat) Element
Neutral Current or Residual Voltage
Starting Element
Phase Selectors
Distance-Measuring (Ratio-Balance) Element
For Earth Faults
E
E
E
E T
E ----- Indicates a voltage connection
→ ------ Indicates a directional feature
T ----- Indicates a tripping circuit connection

FIG. K.—Key diagram of elements forming "ratio-balance" protective system.

The torque on the induction movement is produced by the resultant flux caused by the current and voltage coils in the two magnetic systems, which are not provided with shaded poles, and hence it does not operate, as may be thought at first sight from Fig. J, by two mechanically balanced forces.

Fig. K shows a key diagram of the elements forming the ratio-balance system, and it will be seen that these are arranged fundamentally upon the well-known overload-and-earth-leakage principle. Thus, the elements divide into two groups, one dealing with phase faults and the other with earth faults. Both groups utilize the same time-measuring element, and for this reason the thick dotted lines with the arrows associate it with both the phase-fault distance-measuring elements and the earth-fault distance-measuring element. The operation of the elements in each group is identical in principle. On the occurrence of an earth fault, for example, the directional starting element and the phase selector on the faulty phase operate simultaneously and initiate the distance-measuring and time-measuring elements, as shown in Fig. J, and these two elements produce the time characteristics shown in Fig. H.

To summarize: The principal application of the ratio-balance protective system is to protect long overhead transmission lines, when, for reasons already described, it is required to measure reactance values. Its characteristics approach those of the Merz-Price system very closely, and it offers alternative protection when pilot wires cannot be provided.

Conclusion.

Each of the three protective systems described above has a distinct purpose, which may be briefly described as follows:—

The split-pilot system is for "instantaneous" tripping on more important and shorter feeders, and those in densely loaded areas.

The interlock system is for longer and less important feeders, or where pilot wires are too expensive but telephone wires are available, and where a time-hesitation is not objectionable.

The ratio-balance system is for longer overhead lines where no pilot wires of any description are available, and where a short time-lag variable with distance, and more complicated connections, may be regarded as a small price to pay for saving the cost of pilot wires.

These three systems cover the whole field of modern requirements, and each has a place in established British practice.

Mr. C. W. Marshall (*communicated*): The paper indicates clearly that a serious effort is now being made to protect overhead lines and cables without the use of pilot wires. In my opinion, only in cases where the importance of lines is extremely great is it possible to justify the installation of the expensive pilots commonly used, for protective purposes alone. Pilot protective schemes have set a high standard of reliability and excel all others, with the possible exception of parallel feeder systems, in sensitiveness and speed of operation; but the cost, and, to some extent, the vulnerability of the pilots makes the general use of such schemes commercially impracticable. It is possible that the sphere of useful application of pilot systems could be extended if the pilots were made to serve for communication purposes as well as for protection. A scheme has already been developed whereby it is proposed to "borrow" communication lines temporarily during fault periods to serve for duty in protective work, but, in my opinion, it would be better to have pilots in constant use for protection and at the same time to use them for communication. Communication-line pilots also appear to be somewhat vulnerable in themselves. Co-operation between protective gear and communication engineers might result in useful developments in this direction. Regarding the pilotless protective schemes developed by the authors, these are representative of the class in which time-lags are obtained by the joint action of springs and permanent magnets. Their weakness, to my mind, lies in their dependence upon accuracy of relay calibration (particularly in the matter of time-delays) for exact discriminative action. It appears to me to be better to incorporate a clockwork time-lag device, which is inherently accurate, rather than to use eddy-current effects produced by the action of permanent magnets, for this purpose. A further possible weakness is that the permanent magnets in the various relays on a system may change in relative strength due to ageing or to the effects of short-circuits. As the authors have long and intimate experience of the behaviour of permanent magnets in energy meters, they could probably give some exact information on the point and this would be appreciated.

Mr. A. T. Scott (*communicated*): The authors have left for discussion the question of earthing the neutral while, at the same time, they suggest that for voltages above 20 000 solid earthing of the neutral is preferable. The relays on any system, however high the voltage, cannot limit the fault-current value; but, provided that they can be relied upon to cut off a faulty line quickly, they can preserve the continuity of supply to a place fed by a duplicate line which forms part of a system having inherent stability. Relays contribute to the maintenance of system stability in proportion to their speed of operation, but the stability during the fault period must be maintained by other means and it is being found, even in America, that neutral impedances are becoming more and more necessary for this purpose. The objection to the earthing impedance is stated to be the excess pressure-rise that can occur on the unearthed phases during the fault condition, but if this excess pressure is less than, or not greater than, the pressure produced during switching operations or by external causes, it is not detrimental; and if, for other reasons, the insulation has been made sufficient to withstand the stress produced during the fault period by an earthing impedance, then the objection ceases to exist. The voltage-rise may not be an objection, as it can be controlled in amount by the value of the impedance. Since the desirable properties of the device are generally admitted, I would suggest that the best ohmic value and type of impedance should be the question for discussion, rather than the desirability or otherwise of a solid earth-connection. It has been shown by analysis that the maximum voltage during the arcing period on an insulated neutral system (i.e. a neutral impedance of infinite resistance) is about 5 times the normal phase-to-neutral voltage, while for a solidly-earthed neutral system the rise is approximately zero. Thus any degree of fault-current limitation can be arranged for between these limits of voltage-rise. On any reasonably well-designed system a voltage-rise up to twice the normal line-to-earth voltage would be permissible for a period of, say, 1 or 2 secs. If on such a system the fault were cleared (as it undoubtedly could be with relays as described by the authors) within ½ sec., a voltage-rise up to 2½ times the normal voltage could be allowed with safety. The actual ohmic value of the limiting impedance to give this result will depend upon the fault capacity-current, the length and voltage of the line, the impedance of the generating and transforming plant and that of the transmission line up to the fault. By the combination of an instantaneous earth-leakage tripping device and a limited earth-fault current system, stability during the fault condition can be very greatly improved; the power in any arc to earth is reduced so that the arc's tendency to spread and cause a short-circuit between lines is lessened, and the damage to insulators during flash-over is very much reduced. Also, the difficulty of running safely along routes parallel with Post Office lines is largely overcome and, as a consequence, the choice of routes for overhead lines is greater and wayleave difficulties are less. It is possible, particularly on short lines, that the fault current may safely be reduced to such a low value that it becomes a limiting feature with regard to relay operation. The improvements described by the authors, however, indicate that this limit is being considerably extended, so that instantaneous tripping of earth faults can now be achieved with small earth currents. The normal value of the harmonics of the third order must, nevertheless, be kept well below the relay settings.

[The authors' reply to this discussion will be found on page 849.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 20TH JANUARY, 1930.

Dr. C. C. Garrard: The subject embraces such a wide range of knowledge that the paper can only be expected to deal with the methods adopted by a single firm; a comprehensive treatment would require several volumes. There are many alternative methods for solving each of the problems which the authors have considered, so that it is impossible for the purchaser to decide between the conflicting claims of manufacturers by relying solely upon the evidence of the paper, valuable though it may be, Attention is drawn in it to the difference between the English and the Continental protective problems arising from the fact that in the first case the neutral point is earthed, while in the second that point is insulated. In spite of the statement quoted from the paper of Messrs. Wright and Marshall in support of the earthed neutral as a safeguard against interference with telephone circuits, I believe that the insulated neutral was insisted upon by the German Post Office because of its alleged superior merits in this connection. A device like the Petersen earth coil will not be readily accepted by British engineers, because it introduces undesirable complications and is of doubtful utility. Some years ago a device for suppressing arc-overs on overhead-line insulators which made use of a temporary earthing of the affected phase was developed in America, but it does not seem to have met with any success. I am in favour of solidly earthing the neutral point on all voltages above 33 kV and of earthing through a liquid resistance on lower voltages: such a resistance eliminates the danger of fire which occurs in connection with those of other types. Protective gear should be rapid in action and of high sensitivity; low fault-settings are a necessity if the latter feature is to be obtained. For example, consider the case of a 5 000-kW oil-filled transformer protected by the circulating-current system with a setting of 60 per cent of full load. A fault current of 3 000 kW, due to a defective terminal-bush for example, might flow for an indefinite period and the heat evolved would probably set fire to the transformer. Viewed in this light the sensitivity of 30 per cent or more which has been claimed for the Translay system is far from ideal. The figure of 5 per cent will have to be approached before a reasonable guarantee of safety can be given. Moreover, such a sensitivity can be attained combined with absolute stability on through faults. The key to the problem of low fault-setting is the bias system which was first applied in practice by Mr. McColl. The Translay system is only one of many of the same type which have since been evolved. On page 815 the authors indicate that the bias was adopted as an afterthought, although it seems to me to be the most essential feature. The use of a time-element characteristic is, I think, a disadvantage. The authors correctly point out the disabilities of the original simple opposed-voltage balanced system of feeder protection, and although such equipment has given good service in the past the biased systems now available are much to be preferred. These completely eliminate the necessity of sheathed pilot-wires. Referring to the systems of earth-fault protection (Figs. 6 and 7), are these only applicable to single dead-ended feeders? If they are unsuitable for protecting two feeders supplying a substation in parallel, the proposed systems would appear to have no advantage over ordinary leakage protection. The device shown in Fig. 13 for correcting for arc resistance is of interest. The figure of 3 per cent of the normal voltage, which is described on page 812 as the maximum voltage across the arc, surely does not apply to insulated systems in which an earth-fault current can be less than the load current. In such cases it is necessary to use a reactance-measuring element rather than one of the impedance type. The resistance of the arc has no effect upon the reactance in circuit and therefore does not alter the time of operation of the device. The calibration curve of Fig. 12(*b*) is almost ideal. The distance relay finds its most important applications on long overhead lines; in cable systems it is less suitable and the demand for it is not so keen because pilot wires are more easily applicable. The time element involved in the distance relay is a grave disadvantage which serves to provide the d.c. pilot-wire methods (page 819) with a claim to importance. They allow of the use of a single-core pilot and, although this has little, if any, advantage over a 3-core cable from the point of view of cost or protection with regard to underground cables, it does command a definite monetary advantage on the overhead system. The d.c. single-core pilot can be incorporated in the overhead earth-wire without much increase in cost. thus providing a protective system which combines economy and discrimination with an instantaneous release. The arrangement will probably be widely adopted in the future. As the distance relays shown in Figs. 9 and 11 have an operating torque proportional to the difference between E and T they cannot be true impedance relays. In a relay of the true impedance type the operating torque is proportional to the ratio of these two quantities.

Mr. A. E. Strong: I notice that the authors are in favour of multiple earthing. Apparently, when a switch is opened on a ring having more than one earthed neutral, there is a risk that the out-of-balance currents which are liable to be produced may operate other switches. I should be glad to know whether trouble is not also likely to be experienced as a result of triple-frequency disturbances, not only by the well-known interference with telephones but also by the production of high-frequency surges. When earthing systems on which the pressure exceeds 20 kV the use of resistances appears to be an advantage, at any rate up to 33 kV. Earth faults should be allowed to clear themselves before they develop into short-circuits, provided that the earth-leakage protection is sufficiently sensitive. The arrangement shown in Fig. 3, however, is not very satisfactory for this purpose. The induction-type relay with a definite time-lag is undoubtedly successful in providing discriminative protection, but it is well known that it suffers from the drawback that a greater time-lag is given to the switches nearer to the power station where fault conditions are more severe. Some engineers are on this account reluctant to set up their station switches, and I should be interested to know the authors' opinion as to the time-lag necessary for the feeder switches at the power station in order that discrimination may be obtained outside. What method would the authors adopt for testing directional relays at the end of parallel feeders without interrupting the supply, and, if possible, without disturbing the secondary connections?

Mr. J. Morton: The question of circuit protection, always one of great importance in connection with continuity of supply, has never been more serious than at present when so many large generating stations are being grouped on to a common transmission system, thus increasing the amount of energy which would be liberated in the event of a fault. With regard to that type of apparatus which is designed to provide the necessary protection without the introduction of pilot wires, it seems to me that the authors began by assuming that the older type of apparatus, the overcurrent relay either with or without the time characteristic, had proved reasonably satisfactory and that by the addition of suitable refinements it would be enabled to cope with present-day conditions. Owing, however, to the fragile nature of the numerous moving parts and the difficulty of solving the problems which arise in consequence of the feeble mechanical forces available, that assumption appears to me to be unwarranted. The higher voltages now in general use result in a reduction of the actual load current and necessitate the introduction of a type of protective transformer which is itself less reliable than the line with which it is associated. The acknowledged success of pilot-wire protective gear is, in my opinion, the result of the possibility of using a relay of greater electrical stability and more robust mechanical construction. This system admittedly introduces an additional capital charge, but it can be relied upon to clear the fault in the shortest possible time. The advantages of increased stability in the remainder of the system, reduction of damage and therefore of the period for which the faulty line provides no revenue, easily outweigh the additional cost. Although unaccountable interruptions have occurred on sections protected by pilot wires, the majority of these are the result of regulations which require the earthing of the secondary system of the protective transformer. If, for example, the point where the earth connection is made lies at one end of an 8-mile line, while the breakdown occurs at the other end between the primary and the secondary of the protective system, the voltage-drop between the fault and the earthed point will tend to maintain the dangerous pressure at the insulated end, thus cancelling the original reason for the necessity of earthing. By taking such precautions as will make it impossible for the secondary of the protective transformers to become charged from the primary side, and by using pilot wires efficiently insulated from earth so as to rule out the possibility of the admission of vagabond currents into the protective system, greater stability and rapid clearance will be obtained with settings lower than those which have hitherto been considered safe. The necessity for rapid clearance is great in view of the general tendency toward single transformer units of high capacity. With one of these transformers at each of two large stations operating in parallel a short-circuit power of 1 million kVA can easily be obtained. Consequently within a few seconds a temperature high enough to alter the physical properties and the mechanical strength of the materials in the line, can be produced.

Major A. M. Taylor: There are wide variations in standard practice regarding the correct settings for relays. The authors suggest the figure of 30 per cent, the General Electric Co. recommend 5 per cent, while many relays are set at 100 per cent of full load. Relay manufacturers are probably disinclined to employ fine settings because they have misgivings as to the effect of disturbances other than those produced by breakdowns in the cables of a transmission line; such for example, as the surges set up when a 30 000-kW generator is switched in without a field, or when a complete short-circuit takes place between two phases of the 5 000-volt system near a substation. A disturbance of the latter type which occurred in Birmingham resulted in a violent rupture of the connections between two stations, with temporary discomfiture of the whole system. Although I fully appreciate the argument advanced in London by Mr. Kapp, that a fault on a super-tension cable immediately develops into a short-circuit, it is my opinion that cable engineers really know more than has been suggested about what takes place in a cable when a fault develops. Mr. W. Wilson has shown in a recent paper* that 35 kW-sec. of energy are required for boiling *and* vaporizing a teaspoonful of oil. A fault almost invariably commences either just inside the lead sheath or just outside the copper core and the oil begins to boil locally —to a depth of about 1/10th or 1/100th of the dielectric thickness. This part is virtually short-circuited by ionization while the remaining portion of the cable begins gradually to warm up towards the inside. As the process goes on, an increasing proportion of the whole voltage is applied over the sound insulation. Soon both the voltage and the current in the faulty portion have greatly increased and, further, energy is liberated in the sound portion of the insulation. The voltage increase on that portion follows the curve given in Fig. 44 of Dunsheath's paper (vol. 64, p. 119) provided that the time intervals are measured from right to left; the current through the sound portion shows approximately the same kind of variation. Until the lead has burst and vaporization on a large scale has occurred there cannot be sufficient space to allow of the formation of an arc. I have made a preliminary attempt to calculate the increase of the instantaneous watts in the successive parts of the oil and paper on the basis of the data provided in Mr. Wilson's paper. Taking into consideration the limitation of the current through the faulty portion of the compound which occurs in the early stages, as a result of the residual wall of insulation, I find that an integration carried out over a complete second on a 33-kV cable cannot account for the liberation of more energy than is required merely to boil the oil which surrounds the faulty portion. Thus the energy necessary for complete vaporization cannot be liberated within the space of one second from the start of a serious local breakdown; *the process may require a period of considerably greater length.* The difficulty is that present forms of protection are only intended to act when the fault current has reached something like 100 amperes (50 per cent setting). At this stage the rapid rate of increase of the current makes effective protection impossible. It should, however, not be impossible to develop relays which will be as reliable and as stable in action with a setting of 1 per cent as those at present in use. In my opinion, it is important that a fault in one core of a 33 000-volt cable should not result in so much local heating that the dielectric characteristics of the other two cores are appreciably affected. Overload relays are of no value as a stand-by to protective gear unless their time-limit is such that, under the most severe conditions, such as those produced by a "through surge," their operation is delayed for the maximum time consistent with avoidance of damage to the cables and transformers. The latter could easily be designed to "hang on" without damage for 5–10 seconds, provided that the cables are run underground. The disturbance of the Birmingham system, to which I have referred, could have been avoided by rapid operation of the oil switches on the low-tension end of the circuit, if only the overload relays on the high-voltage cables had kept in.

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* "Insulation Faults: Their Causes and Behaviour," *World Power*, 1929, vol. 12, p. 432.

Mr. W. Wilson: The authors' opening statements as to the demands, due to modern conditions and requirements, upon protective gear are by no means exaggerated, and an advance in the general standard of this apparatus is much overdue. There is no doubt in my mind that an error of judgment was committed when the opposed-voltage principle was selected some 25 years ago for feeder protection, in place of that based upon circulating current. The latter has always been used for safeguarding other types of electrical equipment, including parallel feeders and machines of all kinds; but the designers seem to have been unduly influenced by the difficulty of modifying the circuit diagram in order to provide for a relay at each end of the feeder, and also by the fear that a balanced-current system would consume more power than is consistent with sensitivity. Thus a wrong choice was made, and a faulty method has been bolstered up with added complications without being able to render it either sensitive or definitely stable. The drawbacks of the split-core current transformer are well shown by the authors and, while admiring the ingenuity of the 8-gap pattern shown in Fig. 16, one can agree with them that it is better to avoid the use of such a device. The sheathed pilot is another complication due to weaknesses of the balanced-voltage scheme, and here again the authors are wise in eliminating it from their own designs. It is a very expensive component which, by giving an exaggerated idea of the cost of pilot-wire protection, has effectively hampered the adoption of pilot-wire schemes generally. Since the opposed-voltage method depends upon the current being nil when the feeder is sound, every small irregularity due to external or internal causes tends to produce instability. An open-circuit in the pilot wire will throw the whole protective system out of action without warning, and thus frequent testing of the pilot itself is essential. This last drawback is obviated by the schemes shown in Figs. 20 and 21, since the capacity current would be interrupted by such a disconnection, although the statement on page 815 that " no current will flow in this circuit under normal operating conditions " hardly seems to bear this out. I am glad to find that a circulating-current system has been worked out in Fig. 23, and I should have preferred the authors to have gone further and adopted the balanced-current principle instead of merely improving the other. It was clearly shown by McColl [*] 10 years ago that the circulating-current method can be effectively applied to feeder protection without involving elaboration, high fault-settings or large current-transformers. Moreover, he showed that a scheme consisting only of an ordinary current transformer, beam relay and resistance unit at each end of the line, without sheathed pilots or special devices of any kind, can provide completely for all the eventualities that may occur in practice. I am in complete agreement with the authors as to the advantages of using a bias, but question the correctness of their use of the term on page 806, in which they state that " The wattmeter element has very little bias or spring control." Bias implies that the restraint is proportional to the load; it is essentially different from control, which is constant under all load conditions and is possessed in some form by every instrument and relay. From their description of the method of biasing the scheme in Fig. 20, I gather that the authors are here using the term in its accepted sense, and the relay characteristic would actually appear to incorporate a fault-setting increasing with the load. It would, however, have been a useful confirmation of their description if a performance curve could have been given showing the actual variation of the setting with the load. Their reduction of the fault setting from something over 100 per cent, for the usual opposed-voltage scheme, to the figure of 30 to 50 per cent mentioned on page 816 is welcome, but their claim that " these settings compare very favourably indeed with the settings obtainable with older types of gear " is hardly accurate. I have for the last 10 years been designing relays for feeder protection with a setting of 5 per cent, and I can assure the authors that there has been no difficulty in securing stability at these settings. The above figure applies to ordinary underground feeders up to about 5 miles in length, but I have never employed a higher setting than 25 per cent even for long or overhead feeders, or those including step-up, step-down and regulating transformers in the protection. The scheme shown in Fig. 20 is a reasonably simple one, but I am sorry to see (on pages 815 and 816) that additions to it are contemplated in order to provide further stability. In particular, I consider tuning methods to be particularly undesirable in situations where reliability and robustness are so necessary as in protective equipment. The scheme of Fig. 23 suffers through possessing a cascade arrangement not only of current transformers but also of relays. Such a multiplication of parts means that the chances of failure are multiplied by the number of components used in cascade, and greatly decreased reliability is the result. When suitably designed, a circulating-current system is rendered immune from instability due both to capacity currents in the pilot wires and to high-frequency transient currents, by the capacity current flowing in the pilots themselves. This is accomplished by arranging that the capacity current restrains the relays, in which case it is found that excess currents due to high-frequency surges are actually by-passed through the capacity of the pilots and rendered incapable of causing improper tripping. The desirability of sensitiveness has been scouted by protective-gear designers in the past, although they were willing to admit its value for protecting machinery. One cannot avoid the suspicion that this opinion was dictated by their inability to secure sensitivity with the usual feeder relay equipment. Actually, all the functions carried out by protective gear are the more perfectly fulfilled the more sensitive the protection, and this opinion has been borne out by all my practical experience.

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[*] A. E. McColl: "Automatic Protective Devices for Alternating-current Systems," *Journal I.E.E.*, 1920, vol. 58, p. 525.

Mr. R. H. Rawll (*communicated*): The authors are of the opinion that, from the protection engineer's point of view, the earthing of the transformers at several points on the system has much to recommend it. The recent annual report of the Electricity Commissioners in which permission is granted to the Central Electricity Board to use multiple earths only in circuits connected to transformers is of interest in this connection. This permission is only given provided that the Post Office authorities are satisfied that it will not cause interference with their communication circuits. It is stated in the paper that, in order to improve the operation of Continental systems using an insulated neutral, arc-suppression coils have been installed. I suggest that where such devices are installed the neutral is placed in metallic contact with earth, although, on account of the special resonance effect set up by the arc-suppression coil, the result differs from that obtained with a solid earth or with an earthing resistance. In order to compensate for the capacity of any section of the network which may be switched in or out, it is suggested that each section should possess its own arc-suppression coil which could be brought into action simultaneously with the operation of the network section-switch. While this would be quite feasible on a number of feeders all proceeding from a common busbar adjacent to the earthed neutral of the transformer, it would be very difficult to apply the method to sections of the network which are switched at remote points. Either multiple earthing in the form of artificial neutral points, or pilot wires connecting these points to the main earthed neutral point of the system, would be necessary. With regard to the d.c. pilot-wire balance scheme, I notice that it is now proposed to use metal rectifiers of the copper-oxide type in place of batteries. I should like to know the voltage at which these rectifiers would be required to operate, as my own experience of them has proved that, at the usual supply pressure of 200–250 volts, a small transient voltage-excess is sufficient to cause a breakdown. The surge which would undoubtedly be present under fault conditions might have a similar effect.

[The authors' reply to this discussion will be found on page 849.]

North-Eastern Centre, at Newcastle, 10th February, 1930.

Mr. F. C. Winfield: During the past 2 years a very definite change has taken place in our attitude towards protective problems. The bulk of e.h.t. transmission work in this country has in the past been carried out by underground cables. Side by side with cable development came the development of the Merz-Price system of protection, which made possible the extensive interconnected system in this area and the high standard of service upon which this country prides itself. The Merz-Price system of protection, or one of its numerous present-day modifications, offers, as I think the majority of us will agree, the quickest, most efficient and most flexible type of protection available to-day. It has, however, one definite disadvantage—the cost of the pilot cables. So long as distribution was effected by cables this was not a serious matter, as the cost of the pilots was that of the pilot cable only, the excavation charges being borne in any case by the main cables. Even where overhead lines were employed, this factor was still not very serious with relatively low-voltage lines employing wood poles and short spans. In the period referred to, however, a distinct increase in the use of overhead lines has taken place and is fairly certain to continue. Two factors have been responsible for this, the development of schemes for rural and semi-rural electrification, and the operations of the Central Electricity Board. In the first of these, the relatively small revenue to be obtained and the high capital outlay necessary rendered imperative the utmost economy in construction, resulting in the extended use of overhead lines, the abandonment of pilot protection except for the more important feeders and, effectively, the acceptance of a lower standard of service. In the second case, in view of the very long spans employed, it was found to be economically impracticable to support pilot cables on the 132-kV lines of the Central Electricity Board, and accordingly pilot cables, if provided, must bear separate excavation charges or the cost of a separate pole line. When it is remembered that some of the line sections under consideration approached 50 miles in length and that the minimum cost for a separate pilot cable is of the order of £600 per mile (or, say, £30 000 for a 50-mile length), it will be readily understood why the Central Electricity Board was forced to consider other forms of protection for this work. These two factors, however, whilst militating against pilot forms of protection for the classes of work mentioned above, have to some extent served the industry in forcing the development of alternative forms which, whilst falling short of pilot ideals, are still considerably in advance of previous non-pilot systems and, I think, somewhat ahead of similar types used abroad. It is for this reason that the present paper is so timely. Although it naturally does not deal with all the developments which have taken place, but only with those with which the authors have been directly concerned, it nevertheless serves its purpose in indicating the new point of view. Notable amongst these developments are the impedance protection described by the authors and the ratio-balance system developed in this area. With the latter, however, we are not at present concerned. The advocates of pilot-wire systems have not yet given up hope of outclassing their rivals in the two classes of work referred to, and strenuous efforts are being made to reduce the cost of pilots. The chief lines of investigation at present being followed are: (*a*) The reduction in the cost of laying pilots in the ground. This is a point which, I think, ought to be taken up by cable manufacturers. Considerable ingenuity has been shown by cable manufacturers in designing, but very little in laying cables. This art is still literally in the " pick and shovel " stage. (*b*) The use of telephone pairs as pilots (probably for forms of protection other than the Merz-Price type). (*c*) The provision of a cheap pilot circuit by insulating the centre conductor of the earth wire used on overhead lines and employing the surrounding sheath as a return circuit. This proposal is due to Kapp and Carrothers. (*d*) The substitution for physical pilot wires of a carrier-wave circuit superimposed on the main power-circuit. I should be glad to know whether the authors are in any way interested in schemes of this type. The impedance forms of protection so far developed have not yet proved practicable for lengths of less than 10 miles on the 132-kV lines, and for such lengths pilot forms of protection are being used. I am doubtful whether the use of impedance forms of protection, even for lengths as small as 10 miles, does not encroach somewhat on the margin of safety, and I should have preferred the minimum to have been set at 12 miles, pending experience. The most outstanding development referred to in the paper, in British practice at least, is the impedance protection developed by the authors, but at the top of page 811 doubt is expressed as to the advantage of the definite time element. In my view, one of the major disadvantages of impedance forms of protection as compared with protective systems of the Merz-Price type, is the long time of operation. Leaving out of account the practical problems involved, I feel that the contribution which the definite time element offers, as shown on the curve of Fig. 12, is of the greatest importance. One of the most serious troubles which confront us to-day in dealing with major power systems is the disturbance which occurs to synchronous load, particularly plant supplying railways, on the occurrence of close-up faults. It has been often and freely stated that provided a fault is cleared within 2 seconds no disturbance will occur. In actual practice this is quite wrong. Two factors are involved—voltage-drop and time. The first can be controlled only by the extensive use of feeder reactors, which are both expensive and awkward of application. If the time factor alone is to be relied upon, times considerably less than 1 second are imperative. In their remarks on page 811 about the effect of resistance on the arc, the authors appear to neglect two very important sources of variation—change of the impedance of the earth-return path and alteration of the resistance of earth plates. The first of these may give a variation of the order of 8 per cent, I believe, whilst earth-plate resistance may vary from, say, 2 to 20 ohms. The authors also remark that the resistance-drop across an e.h.t. arc is small. I have had very conflicting reports on this point. It certainly seems more reasonable to suppose that the arc resistance should fall with increasing current, but at least two authorities who have made tests allege that extremely high values of resistance are possible. The pure impedance system stands or falls by this decision, and I should be interested to know whether the authors can give any account of tests to substantiate their statement. The compensating arrangement indicated in the paper certainly improves matters, but its effect is hardly so direct or so complete as that of a reactance relay. Doubt is implied whether it is possible to produce a time-reactance relay, although I can assure the authors that I have seen and tested at least one example of this type. A serious difficulty with impedance-type relays is the necessity for a voltage supply. The authors refer to this difficulty in connection with earth-fault relays, but they omit any reference to its effect upon impedance relays. On the 132-kV lines now being erected there is generally a natural reluctance to compromise the reliability of the lines by adding 132-kV potential transformers, and the method adopted is to employ a potential transformer on the lower-voltage side of the connected power transformers, and to compensate this for changes in load-drop or in transformer-tap position. So far as I have seen, this solution is not very satisfactory and the probable error in voltage reproduction would appear to be of the order of 10 per cent. Changes which are being considered may reduce the figure to, say, 7 per cent, but even this is unsatisfactory and other means of obtaining a potential supply are being explored. I should be glad to have the authors' experience on this matter. No reference is made in the paper to the operation of the impedance system when simultaneous faults occur, and I should welcome the authors' comments on this. With regard to pilot-wire protection, a detailed consideration is not required as we are all familiar with such equipment in this area. The Translay scheme is a novel development of the Merz-Price system. In essence it appears to be promising, and it has been successfully applied in a number of cases already. It is our experience on the North-East Coast, however, that it takes some years to prove the worth of a new protective scheme, so that I hesitate to be more definite. The authors suggest that a non-inductive resistance is useful as a high-frequency shunt. Our experience on a large 33-kV system is that it is of little use except where the pilot cables are of the sheathed type, and I should certainly prefer to see some form of tuning adopted in connection with the Translay scheme. Time-delays as a preventive of high-frequency troubles are of little value where recurrent or arcing earths are possible. If there is any feature of Translay pilot protection which I am inclined to query, it is that the effect of pilot capacity-currents is supposedly eliminated by the fact that the relay is of the wattmeter type, so that capacity currents produce no torque in the relay. In practice, the phase angle of the capacity currents differs greatly from 90° and often is as low as 45°. I should be glad of information from the authors on this point. I am interested to hear that practical applications have been made of the self-compensating type of pilot-wire protection. Can the authors give any particulars of these applications and of operation under conditions of heavy through-fault? The authors make a number of references to fault setting, and I should like an expression of their opinion on this point. There is a school of thought which declares that the most sensitive settings possible should be employed. We in the North do not subscribe to this view, but consider sensitive fault-settings to be a snare and a delusion. The suggestion appears to be that super-sensitive protective gear can detect a fault in the development stage and thus reduce system disturbances. For overhead-line work it is extremely unlikely that there could be any appreciable development stage within the current-range of protective gear. For underground cables, it is our experience that up to voltages of 22 kV quick-acting protective gear of the Merz-Price type will generally disconnect an earth fault on a 3-phase cable before it becomes a phase fault, but this does not hold as yet for voltages of 33 kV. We have also encountered a serious practical disadvantage of super-sensitive protection for cables in that it is often difficult and troublesome to trace the cause of the interruption, and thus much time is wasted in re-commissioning. The most serious objection to super-sensitive settings is that they almost invariably result in stability troubles and inadvertent operation. My own view is that for feeder protection more satisfactory operation is obtained if the relay setting approaches the maximum permissible to ensure certain operation on all faults, rather than some hypothetical lower value, and that for generator protection it is not important to pay much attention to the possibility of earth faults low down near an earthed neutral. This is well borne out in North-East Coast practice. In this connection, it is also my view that in almost all forms of protection it is desirable, as a general contribution to the elimination of stability difficulties, to have a time-delay approaching 0·1 second in operation on all tripping relays, as I feel that this would give useful protection against incipient faults and occasional transient disturbances. Beyond this I would not go, for the reasons previously stated. In fact, I think one of the most desirable contributions to the protective problem would be the speeding-up of the tripping time of circuit breakers. The authors' remarks on the desirability or otherwise of earthing are interesting. I think that they omit one important consideration when they state that American practice is to earth the neutral and Continental practice to insulate the neutral. Until a few years ago, American practice was largely divided between earthed and unearthed systems and it is only recently that the earthed system has been generally favoured after considerable experience with the unearthed system. In my opinion, Continental systems which do not earth the neutral are considerably less complex than our own and, despite assertions to the contrary, there must inevitably be a practical difficulty in applying Petersen coils to systems so interconnected and so subject to variant switching conditions as our own. Without Petersen coils, a second fault due to the increased voltage-strain when one line is earthed by a phase fault would be likely to occur very frequently in this climate, if past experience with resistance-earthed neutrals is to be relied upon. On the other hand there is, I believe, a distinct opening in this country for the unearthed neutral in connection with rural supplies. Where the capital expenditure which can be justified is so small, the ideal way to deal with this type of supply would seem to be, as suggested by Mr. Gregory, to run a single-circuit line with unearthed neutral, eliminate as far as possible all expensive protective gear or switchgear and spend some of the money so saved in improving the line insulation. By adding to this a Petersen coil or other arc-suppression device it should be possible to obtain a very reliable supply at low cost. Our experience with earthed systems on the North-East Coast is that a second or third earthing-point often facilitates protection and, by ensuring disconnection of faulty lines, results in a considerable lessening of telephone disturbance. Such disturbance has only proved troublesome in this area during actual fault conditions, or where plant with excessive harmonics is used. The latter should be corrected. It is questionable whether the dispersion of earth current due to multiple earthing would not give more relief to telephone circuits than the concentration of earth-capacity and fault currents on a single earthing point.

Mr. H. W. Clothier: I should like to refer to the history of the subject, and to the pioneer work done under the guidance of Bernard Price about 25 years ago. Reviewing the position at that time, we had some experience of reverse power relays and a great deal of suspicion of them. We were acquainted with time-limit devices, and had a good deal of experience with mal-operation of fuses. Andrews had been working on discriminating protection for duplicate feeders. Price started to work on some definite lines which are exceedingly interesting to-day. He laid down as one of his principles that there must be no potential element; potential transformers in substations were a nuisance. They were liable to failure, and the ideal protection was by current alone. Instantaneous operation was essential and almost anything should be sacrificed to it. The protection had to be universal in application, that is, suitable for ring mains, loops, tees, interconnections, etc., and such that it lent itself to ready extension without interference with existing protective gear. The relay was to be of simple magnet construction, easy to understand and without springs or other delicate apparatus. Suspicion was always to be attached to anything complicated in a relay. Moreover, the protective system was to be free from additional apparatus necessitating extra terminal connections, every one of which meant something more to go wrong and give trouble. In reviewing these features of the ideal system, we find little in the paper which would have attracted us at that time. For example, in Fig. 1 there is no discrimination as required for ring mains or feeders in series. With regard to Fig. 5 we should have said that the time-limits up to 2·2 sec. were quite out of the question, as synchronous plant would be put out of step. The system of Fig. 6 would have been rejected because of the potential transformer. Fig. 21 would have interested us, except that the relay would have appeared complex and we should have asked for further information as to tee-connections. The scheme shown in Fig. 26 would have been discarded as lacking speed and discrimination on ring mains; its use is limited to a string of feeders in series. So also Fig. 28 would have failed to gain approval because of the directional relays requiring potential transformers. We were dealing then with comparatively short lengths of cable and heavy fault-current conditions. There were no arbitrary limits to the demand for sensitivity in fault settings, it being realized that the fault currents were large in relation to the load current, and so the accepted heavy settings of relays were based more upon the amount of the fault current than on the size of the circuit. The first place was given to reliability. The problem of balancing the current transformers was met by raising the straight-line characteristic to the maximum straight-through current to be expected in any feeder. 5 000 amperes was the amount first determined; it was afterwards increased to 10 000 amperes. Other interferences were experienced, such as those due to pilot-wire capacity current and interaction between the fields of adjacent current transformers and their neighbouring conductors. These were dealt with by using coarser settings on the relay, and 900- to 1 000-ampere fault settings were not considered to be impracticable. I have it on record that in 1908 there were 200 miles of cable protected in this district, with an aggregate plant capacity of 50 000 kW behind it. I believe that practically all of that gear is still in service and that 400 miles with protection of a similar kind have since been installed, the only modifications, other than mechanical improvements in constructional details and the sheathed pilot, being the alteration of the single to the multi-air-gap transformer similar to that shown in Fig. 16 of the paper, and even this was in use as long ago as 1914. However illuminating it may be to dwell on the past, I must not omit to refer to the differences shown by the practice of to-day. These differences include much greater lengths of lines, heavier fault conditions (although I do not agree with the authors that this constitutes the chief difference), higher voltages, a demand sometimes, though not always legitimate, for extreme sensitiveness (a more intimate knowledge of and experience with the phenomena which interfere with the perfect balance, allows a more scientific treatment of the design of systems and relays), and last, but by no means least, the economic necessity for the elimination of the pilot wire on long overhead lines. Mr. Winfield said that the paper did not include all the protective systems. I sympathize with the authors in their task of trying to keep the subject within reasonable limits, but in my earlier contributions to the discussion (see pages 824 and 827) I referred to three important omissions.

Mr. B. H. Leeson: Electrical undertakings in this country have a high reputation for continuity of supply, and it may be claimed that this is due in no small measure to the superiority of British protective equipment. The Merz-Price system is an example of the latter and it has been proved satisfactory in service on feeders 25 miles long and at voltages up to 66 kV, and it can be applied to higher voltages and longer feeders when required. Cables forming interconnectors, ring mains, tees, etc., and subject to heavy fault currents have been satisfactorily protected for many years, and in this respect I think that conditions have not changed very much during the last few years. The power transmitted through a feeder has increased, but this has been accompanied usually by a correspondingly higher voltage so that fault currents have not become materially greater; in many instances they are less on modern high-voltage systems than on numerous lower-voltage systems. In my opinion, the factors which have influenced the development of certain modern protective systems are to be found in the use of long overhead transmission lines, such as those forming the 132-kV British grid, and the reason for the development of new systems has been an economic rather than a technical one. Technically, the Merz-Price system is still the desirable protection, but the cost of running a pilot cable in the case of the 132-kV grid lines becomes uneconomic when a certain length is exceeded, because the spacing of the towers does not permit the pilot cable to be slung from them as it can be in the case of lower-voltage lines. Consequently, the pilot has to be either buried or run separately overhead, thus involving extra capital cost and wayleave charges. The advent of the 132-kV grid lines has thus given rise to a need for two types of protective systems—a pilot-wire type for the shorter lines up to, say, 15 miles long, and a non-pilot-wire type, having characteristics approaching as nearly as possible to those of the Merz-Price system, for longer lines. Neglecting the schemes shown in Figs. 26, 28 and 30, as being inapplicable to ring feeders, the authors' proposals for meeting the two needs just outlined are the Translay and self-compensated pilot-wire, or Merz-Price, systems, and the impedance-relay non-pilot-wire system. Dealing with the latter first, I would point out that discriminative operation cannot be obtained correctly with a relay which adjusts its time-delay by measuring the impedance value of an overhead transmission line upon the assumption that such a value is proportional to the geographical distance of a fault from the relay. In practice, the resistance of the earth connections (apart from that of the arc-in-air forming the fault) corresponds to a very considerable length of transmission line, so that the impedance value measured by the relay represents not the real geographical distance of a fault from it, but the increased distance of what may be called an apparent fault situated far beyond the real fault. In consequence, the relay adjusts its time-delay upon a false basis and discriminates wrongly. To eliminate the effect of arc and earth-plate resistance I am of the opinion that distance-type relays should measure reactive voltages as stated on page 811, and such reactive relays are being used in the ratio-balance systems which are being installed on the 132-kV grid lines. Referring to protective systems of the pilot-wire type, the authors have given a very useful record of the characteristics they should possess. The use of distributed-air-gap transformers balanced against a standard, compensation of pilot capacity-currents, the tuning of protective systems to render them immune from oscillatory effects, immunity from the harmful effects of induced voltages, and safety, are all characteristics which have for a number of years been embodied in protective systems associated with this district. On examining the Translay and self-compensated pilot-wire systems I find that neither has all the meritorious characteristics advocated by the authors, but, instead, these characteristics appear to be distributed between the two in the following manner. The good balancing characteristics of the distributed-air-gap type of transformer, as shown in Figs. 17 and 18, are not used in either system; on the other hand, although the Translay system is provided with a bias to compensate for the unbalance which the authors associate with solid-core transformers, the self-compensated system has no such compensation and appears to be prone to the effects of transformer unbalance. The self-compensated system is immune from oscillatory effects by reason of the characteristic of its mechanically-tuned relay, but the Translay system is only partially compensated by the use of shunting resistances and it appears to be liable to be affected by unbalanced oscillatory currents in the feeder. The self-compensated system has the desired characteristic of tripping the circuit breakers at each end of a feeder irrespective of whether the fault is fed one way or both ways, but with a fault fed one way in a feeder protected by the Translay system only the switch through which the fault current is fed will trip. If the feeder protected is an interconnector between two generating stations, one of which is used to earth the neutral of the interconnected network, and if the feeder develops an earth fault the earthed generating station and its section of the network will be isolated from the fault by the switch opening at the near end. The other station and its network, however, will be left as an insulated system with one phase earthed, because the switch at the far end of the interconnector will not have opened. In neither the Translay nor the self-compensated system does the operator appear to be protected from the effects of the induced voltages, mentioned on page 814, should he happen to touch the relay connections. Applying the authors' figures to a 10-mile line with a straight-through current of 5 000 amperes, the operator would appear to be liable to a voltage of 6 500 volts. The self-compensated system is given the characteristic of simplicity and is easier to test on site than the Translay system, because the operation of the relays depends upon a current value only, whereas in the Translay system the operation of the relays depends not only upon the value of the out-of-balance current in the pilot wires but also upon its phase relationship with respect to the voltage vectors. I think that the use of current, voltage and their phase relationship for the purpose of discrimination in the Translay system is tending towards complication rather than simplification and this is an important point to remember because the measurement of the quantities mentioned is more difficult to carry out on site than the measurement of current only. I should like to know whether the Translay and self-compensated pilot-wire systems can be applied to the protection of tee'd feeders. With regard to Fig. 25, I note that with mechanical tuning a 10 per cent drop in system frequency results in the fault setting of the protective system being nearly doubled. I therefore prefer the alternative method of electrical tuning, because with the same drop in frequency the increase in setting does not exceed 5 per cent. I do not agree with the statement on page 814 that safety can be assured by earthing one or both ends of a pilot-wire system through spark-gaps. If the gap is set to break down at a voltage low enough to protect an operator mal-operation of the protective gear will result. In my opinion, it is essential for pilots to float electrostatically in respect to earth; complete safety can then be afforded to the operator by interposing an auxiliary transformer between the pilots and the relay, which can then be earthed on one pole, and this method is incorporated in the split-pilot protective systems which are being installed on the 132-kV grid lines.

Mr. H. Leben: Although I agree with the authors that pilot protection of the Merz-Price type, owing to its simplicity, is superior to non-pilot protection, and that the former can be designed to give satisfactory service on e.h.t. overhead lines of any length, I also think that considerations of cost make it desirable to have some form of pilotless protection available for use on long overhead transmission lines. Of the pilotless types of protection described by the authors the distance relay appears to be the only one suitable for an interconnected network, and I wish to comment on the section dealing with this type of protection. It is stated on page 810 that "it is usually assumed that for phase-to-phase faults the impedance value remains nearly constant for a given length of feeder, but this does not hold good for earth faults, when the impedance of the earth return may vary considerably." This appears to me to be the most important statement about distance relays, because the great majority of faults on e.h.t. overhead lines are earth faults, and the distance-relay type of protection therefore stands or falls by its ability to clear these faults discriminatively. Distance relays cannot, however, give satisfactory discrimination if the variation in the quantity upon which their operation is based (i.e. the impedance, in the authors' system) exceeds certain limits. This consideration has led me to an investigation of whether it would not be desirable to base the discrimination of the distance relay upon one of the components of the impedance, namely, the reactance; that is to say, to make the distance relay of the reactance type rather than of the impedance type. In order to arrive at a definite conclusion, it is necessary to take into account the effect of the variation of the components of the impedance, viz. reactance and resistance, upon relays of the distance type, and the probability that such variations will occur in practice. The position may be summed up as follows:—(1) Since reactance is the preponderant component of the impedance of e.h.t. overhead lines, any variation in its magnitude will produce a practically equal percentage variation in the impedance, and therefore, as regards variation of the reactance component, there is little to be gained by making the distance relay either of the impedance or of the reactance type. (2) A variation in the resistance component does not affect the reactance component, but it does affect the impedance. The reactance relay is therefore to be preferred to the impedance relay if there is any likelihood that the resistance component will vary to an appreciable extent. (3) The reactance of the earth-fault loop of an overhead line provided with a multiple-earthed earth wire is sensibly constant, as can be shown by calculation based upon tests. Physically, this may be explained by the fact that a change in the reactance of the loop formed by the line conductor and the earth does not produce a proportional change in the total reactance of the earth-fault loop because of the presence of the multiple-earthed earth wire, which has a constant reactance. In any case, as has been shown in (1) above, the effect upon distance relays of a change in the reactance of the earth-fault loop is practically the same irrespective of whether these relays are of the impedance or of the reactance type. (4) An increase in the resistance component may easily occur, and may be due to the arc resistance, to the earth-plate resistance, or to other variable factors that cannot be calculated or predicted with any degree of accuracy. This variation, however, as has been shown above, does not affect the distance relay of the reactance type. These considerations have led me to the conclusion that it is preferable to base the discrimination of distance relays in respect of earth faults on overhead transmission lines, on the reactance rather than on the impedance of the line, and this reactance principle has been embodied in the so-called "ratio-balance" feeder protective system. The authors' endeavour, illustrated in Fig. 13, to devise a means for correcting for arc resistance appears to bear out my contention that the operation of distance relays applied to the clearance of earth faults on overhead lines should be based on a quantity other than the impedance of the line. Apart from the fact that the problem is much wider than one of correction for arc resistance only, it seems to me that the authors' correcting device will not fulfil the purpose for which it is provided, but will in some circumstances produce the opposite effect. A definite example will help to make this clear. With a very heavy fault quite close to the busbars of a station in which an impedance relay fitted with the correcting device illustrated in Fig. 13 is in use, the voltage across the potential transformer will collapse practically to zero, but owing to the heavy fault current a large voltage will be injected into the restraining coil of the relay by the voltage-drop in the correcting resistance. This restraining voltage will prevent the relay from operating instantaneously, as it should operate, and thus not only will the object of the correcting device be defeated but a definitely harmful effect will be introduced, which would not be present without the device. On page 812 it is stated that the voltage-drop across the fault arc does not exceed 3 per cent of the normal voltage. To those unfamiliar with distance protection this may appear to be small, but a glance at Fig. 14 will show that it is actually of the same order of magnitude as the voltage available for discrimination under fault conditions. The values given in Fig. 14 (*a*) are (i) line impedance voltage, producing discrimination, 859 volts, and (ii) arc voltage, producing an error in the correct measurement of the line impedance, 570 volts. The results of recently published tests indicate, however, that the arc voltage may be considerably greater than the value which the authors give. It has been reported, for example, that in a 50-kV system with comparatively large generating capacity connected to it the average arc voltage was found to be from 10 to 12 per cent of the normal voltage. In reply to the authors' comments (page 811) about the design of reactance-type relays, I wish to say that this is not, as they state, "difficult, if not practically impossible, to accomplish." On the contrary, such relays have actually been made quite successfully and form the main feature of the ratio-balance feeder protective system.

Mr. D. A. Murphy: I should like to make a few remarks from the operator's point of view. Relays operating on a vertical spindle are much in evidence throughout the paper. This form of relay is usually very sensitive to vibration, and such relays operating on the shaded-pole principle can hardly be classed as instantaneous. This becomes more pronounced when an effort is made to overcome vibration trouble by increasing the amount of travel of the moving parts. Time-limit fuses for shunting trip-coils or relays are strongly denounced for their lack of discrimination on heavy faults. It is quite true that they have this failing, but when carefully selected they are satisfactory in the majority of cases and are used extensively in this area. Their success is probably due in a large measure to the system being fairly well equipped with balanced protection. One feature of the time-limit fuse, however, which is apt to be overlooked, is its ability to prevent damage to the relay coil on a very heavy fault—a trouble which was not uncommon before such fuses were adopted. Low-impedance earth leakage relays are in most cases unnecessary. A 0·8-VA relay of either 20 or 80 ohms impedance gives almost the same fault setting with an ordinary current transformer, the setting being about 5 per cent of full load of the latter. Low-impedance relays are, however, essential if current transformers of very low impedance are employed, and especially where the protection is of the definite time earth-leakage type combined with overload, so as not to increase unduly the overload setting in case of earth faults. I should like to ask whether the relay mentioned on page 806 which will operate with 4 per cent of full load and 1 per cent of normal pressure, would safely withstand short-circuit conditions. So sensitive a relay could not be very robust for general use. With regard to distance relays, this type of gear seems to be promising, but it does not lend itself to adequate protection for a long transmission line from a generating station, as an earth fault or even a short-circuit at the far end would not affect the busbar pressure sufficiently under modern working conditions. With automatic voltage regulators on the generators and lines without continuous earth wires, the satisfactory application of this gear would appear to be very difficult to accomplish. The time-lag with this equipment is inclined to be rather long, and when this exceeds 1 second the copper conductor of an overhead line is invariably burnt through. The severing of a conductor on a modern line with long spans necessitates an awkward and expensive repair. From this point of view, the title of the paper does not coincide very well with recent developments in the construction of transmission lines. With regard to Translay protection, as the pilot only supplies a fraction of the energy necessary to operate the relay, an earth fault fed from one end would not trip the feeder at the far end. This may in some cases leave a faulty feeder, such as a line on the ground, alive from the far end. The same thing could be effected with a simple earth-leakage relay. The Translay system has many possibilities, but it does not appear to be suitable for tee protection, a failing with many other protective devices. Is it suitable for combined feeder and transformer protection where the currents to be balanced are unequal and 30° out of phase? Directional earth-leakage protection is adaptable to many circuits between generating stations; its drawback lies in the provision of a suitable potential. In many cases with ordinary directional overload protection the potential supply is derived from the most convenient source and is not necessarily directly connected with the apparatus to be protected. The arrangement shown in Fig. 6 (*b*) could readily be adopted in most cases. The Longfield system shown in Fig. 26 is good as far as it goes, but as the pilot, which is the chief objection to the Merz-Price system, is already provided a more satisfactory scheme of protection could in such cases be arranged at little extra expense. The direct-current balance system shown in Fig. 28 is rather vague, and I should like the authors to describe it in greater detail. The arrangement shown in Fig. 30 would be inoperative for short-circuits between the two outer phases, as the currents in the corresponding elements of the summation transformer would cancel out, but this could be easily remedied. With regard to balanced protection for parallel feeders, any protective arrangement which requires vigilance on the part of the station operatives, as this does, is most unsatisfactory. Another bad feature is its function in rendering the protection on the sound line inoperative in the event of a fault on the other; this it has to do as the load on the sound feeder is then in a condition of maximum out-of-balance, in which case it must be backed up with overload. Otherwise, on double-circuit lines a fault on one spreading to the other would not be catered for. This protective arrangement also does not discriminate in the event of faults near the far end. Overload at one end and reverse power at the other is a much simpler and more reliable arrangement. The Translay system as applied to this form of protection does not, unfortunately, remove any of the bad features inherent in the principle, as the Translay appears to be applicable only at the far end.

Mr. E. W. M. Scott: A resistance inserted between the neutral point of a supply system and earth serves the dual purpose of permitting sufficient current to flow to earth, in the event of a fault in a remote part of the network, for operating selective protective gear and limiting such current so that it does not cause undue shock to the system. It is my opinion, therefore, that systems operated at voltages between 6·6 kV and 33 kV should be earthed through a resistance capable of passing at least 500 to 1 000 amperes, depending upon the size of the system. Systems below 6·6 kV are preferably earthed solid, as the earth-plate resistance, which on an average may be about 3 to 4 ohms, will limit the earth-fault current as much as is necessary. Usually it is not permissible for systems above 33 kV to be earthed through a resistance, owing to insulation difficulties. I am interested in protective systems of the "locking" class as I am convinced that there is a great future for them, particularly where existing telephone pairs are available. The Longfield system illustrated in Fig. 26 of the paper, however, seems to me to fall short of the ideal in that it is of the non-unit type, that is to say, the stability of the protective gear of one feeder depends upon the operation of the protective gear on feeders and apparatus in series with it. This is likely to lead to complications; for example, in a substation having two incoming feeders, two outgoing feeders and two step-down transformers for supplying a local load, the locking of each incoming feeder must be so arranged that tripping is prevented in the event of a fault on any of the five other circuits in the station, viz. the other incoming feeder, the two outgoing feeders and the two transformers. Such complications do not enhance the reliability of the protective system. I should like to know whether the system illustrated in Figs. 28 and 30 is applicable to ring mains. It seems to me that in the arrangements illustrated tripping would not be accomplished for a fault fed into the line from right to left. Do the authors recommend the use of an earth return? Might not this render the system liable to incorrect operation from vagabond direct currents? The limitations of parallel feeder protection, whereby vigilance on the part of station operators is involved to ensure that the circuit breakers at both ends are opened whenever a feeder is taken out of commission, can be overcome by the use of a device known as a "surge-proof" relay. This cuts out the differential relay when no current is flowing in the circuit breaker concerned, and enables unfettered switching operations to be carried out.

[The authors' reply to this discussion will be found on page 849.]

WESTERN CENTRE, AT CARDIFF, 17TH FEBRUARY, 1930.

Mr. W. F. Cooper: I wish to ask the authors three questions. First, do they consider that the fuses provided in the Merz-Price circulating-current system for the purpose of overload protection are of any value, in view of the fact that, if these fuses were sufficiently small to blow on a reasonable setting, the chances would be that a heavy straight-through fault current caused by trouble external to the protected circuit might easily rupture these fuses and isolate healthy apparatus? Secondly, what do they consider to be the maximum time in seconds at which definite time-delay relays can be set? Finally, what do they consider to be the minimum safe difference in time between two adjacent relays in substations protected on the graded definite-time principle?

Mr. T. H. Haigh: The authors asked for expressions of opinion as to whether a system should be run completely insulated or with an earthed neutral. The South Wales Power Co. in their early days employed an insulated system and found that breakdowns never came singly, but that there were always two or three simultaneous troubles, usually at points many miles apart. To prevent this, the neutral of one of the generators was earthed through a 6-ohm resistance. This answered very well until a single-phase fault occurred which burnt out a portion of the resistance, thus turning the system into an insulated one and resulting in 7 breakdowns in the course of 4 hours, due to surges set up by persistent arcing earths. Since that time the neutral has been solidly earthed, and I am of opinion that this is the best practice. The authors state that the violence of faults may be reduced by installing reactors at suitable points on the system. I should like to hear of a reactor that can be depended on not to break down when a heavy fault occurs close to it, as the South Wales Power Co. has had a rather unhappy experience with reactors. My experience with relays covers the impedance and directional overcurrent types. In 1923 I noticed an advertisement of the Westinghouse impedance relay, and later I obtained literature stating that relays of this type could be placed at substations 1¼ miles apart on a system such as that of the South Wales Power Co., and would successfully select the length of feeder in which the breakdown occurred. Three sets of these relays were obtained by the company and placed on a ring main at three substations separated by 3½ miles and 6½ miles, but although much time and trouble was spent on them, and Mr. Ross (one of the authors of this paper) was called in to give advice, it was found that on heavy through faults all three relays would operate. I understand that impedance relays have been much improved since 1923, and I should like to ask the authors what distance apart these relays must be to ensure proper selectivity. Three years ago, the South Wales Power Co. installed in three substations on one ring main Metropolitan-Vickers directional overcurrent relays such as are described in the paper. These have been quite successful and have cleared 6 feeder faults, in each case opening the faulty section only. The great drawback to these relays is that half a second must be allowed between each setting, with the result that if the maximum time-setting of the feeder switches at the power station is 2 seconds, it is possible to place only three sets of relays on the ring main, and if, as is the case on the South Wales Power Co.'s system, there are some 20 or 30 substations on each ring, the operation of a relay means that 5 or 6 substations are cut off and steps have to be taken to send switchmen out to locate the faulty section. However, if a ring main has only three substations in it, I consider these relays to be ideal for the purpose. I have considered the use of Translay relays on a feeder some 5 miles long, working at 22 000 volts, and consisting partly of overhead line and partly of underground cable, and have been informed that no special pilot cable is necessary and that it would be quite in order to erect open wires on the poles immediately below the power wires. I should like to ask the authors if trouble is to be expected through induced charges from the power lines, and if these can be minimized by transposing the pilot wires at every pole. Also, I should like to know exactly what class of pilot cable is generally used and whether it is lead-sheathed and armoured.

Mr. W. Holley: As a generating station engineer, I am only concerned with the feeder switch at the station end and with the effects of a heavy fault on the generating plant. To such engineers, faults are divided into two categories, those close to the station and those at a distance. The latter do not trouble us as they are equivalent to added load, and we are quite willing for our switch to remain closed while timed relays near the fault clear. But faults near the station are different, and cannot be cleared too quickly for our liking. We have found it best to have two separate relays on the station switchboard: one to operate at 500 amperes with a delay of 2 seconds and to take care of faults at a reasonable distance, say, beyond the first substation; the other relay is set at about 750 amperes, with a very small time-limit (about 0·1 sec.) and this takes care of faults near the power station. We have found that this method works exceedingly well and faults of both kinds have been cleared with almost no disturbance. There is no reason why both relays should not be combined in one instrument. I think that an ideal relay should not require pilot wires or any special kind of cable such as a split conductor, and I hope that the discovery of some new principle will lead to the production of the perfect relay.

Mr. I. Jones: Reliability of power supply is of the greatest importance, and the rapid disconnection of faulty lines or apparatus used in connection with the power supply is an essential idea at which to aim. The difficulty on large interconnected systems lies in the choice of protective gear which will automatically isolate only the faulty lines or apparatus, without disturbance to the remaining healthy lines or equipment, although the latter may have to carry the heavy fault current momentarily. For ring mains and interconnected feeders the balanced-voltage system of protection, combined with a definite minimum time overload relay, has much to commend it. The objection to this system is the use of pilot cables, particularly in the case of overhead lines, as the maintenance of suspended pilot cables is an item to be considered, especially when the overhead-line routes pass through very hilly districts. For such routes I prefer the split-conductor system of fault protection, and on quite a number of lines in use I find that this system of protection is extremely satisfactory. With some of the relays described in the paper protection appears to become more complicated, as there are so many variables affecting the stability of the system. With regard to the question of the insulated versus the earthed neutral, the latter is undoubtedly the more favoured in this country and it also gives a more stable condition for the adoption of leakage or balanced-current or balanced-voltage systems of protection. Earthing of the neutral point through a low resistance, or earthing solidly, is, I think, preferable. In one case, on a 33-kV system with split-conductor protection, it was the practice to earth the neutral point of the 33-kV system through a resistance which limited the fault current to earth to 330 per cent of the leakage current necessary to operate the relays; this represented approximately 60 per cent of the full load of the main transformers. Whilst this arrangement permitted easy disconnection in the event of earth faults, the disadvantage was that during wet weather an earth fault on one phase often resulted in a flash-over on one of the two remaining phases, due to the momentary rise in voltage of these two phases above earth. Another trouble due to voltage-rise which occurred on this system arose where the line was tee'd off to a step-down transformer: the neutral point of the 33-kV windings was left free and the insulators provided on the neutral point were for 11 000 volts working pressure. It was found that this insulator flashed over when an earth fault occurred on one of the lines. It was then decided to cut out the resistance and to earth solidly, since when these troubles have disappeared.

Mr. T. R. Kernick: Impedance relays were tried on the mains of the South Wales Power Co., but due to the distance between substations where the relays were installed (about 4 miles) their operation was unsatisfactory. Where a ring main over a scattered district is to be protected, it is essential that relays should be positive in their action, as indiscriminate tripping means having the system split up into sections. Engineers then have to be sent to various points to find out which switches have tripped; this means more inconvenience to some of the consumers than when main station breakers come out. Incidentally, it was found difficult to estimate the value of the average fault current, but by adjusting some old ammeters with an independent " tell-tale " pointer a value of about 500 amperes (average fault current) was obtained. Moreover, judging by the class of fault on a " mixed " system, the voltage at the point of fault was, in the majority of single-phase faults, nearer to line voltage than zero. Whilst mentioning fault current, there is decidedly a field of usefulness for an ammeter with a good torque which would register fault current by means of a " tell-tale " pointer and give approximate fault-current values in less than half a second. What I have in mind is an instrument with a circular scale, calibrated into four or more sections, say, 230, 500, 750 and 1 000 amperes. The readings need not be critically accurate, for as long as the pointer registers correctly in each section the operating engineer knows between what values his fault current lies. Time-limit relays have been tried with success and have proved reliable in service, but they should be tested on site for overall timing, the minimum overall timing being about $\frac{1}{2}$ sec., half of which time is taken by the mechanical mechanism of the switch. In connection with this subject, a plea must be made for the old plain protection breaker of the overload-fuse type. On a ring main fitted with time-limit relays it was found necessary to link up in various ways for voltage regulation, which interfered with the time-limit relays by splitting the fault current. On fitting certain circuit breakers with current transformers of suitable size these breakers came out under fault conditions in less time than the lowest relay setting ($\frac{1}{2}$ sec.), thus clearing the relay ring for discriminative operation.

Mr. H. J. Norton: The subject of the paper is of very great importance, especially at the present time when super-tension lines are being erected all over the country, and also in view of the necessity for adequate leakage protection of a discriminating nature against faults in order to maintain continuity of supply. The authors appear to favour protection by systems involving in all cases the use of pilot wires connected with relays of types suited to the particular conditions involved, whether those of a network or of ring mains. The use of pilot wires when lines are of moderate length does not represent an important addition in the way of price, but as the lines are extended over a considerable area the cost of pilot wires becomes prohibitive. Moreover, there is always the question of maintenance, and there are many lines protected by means of pilot wires and installed 15 years or less ago, for which the pilot cables have had to be completely renewed owing to deterioration of the lead sheath or other protective covering of the insulation. The result of this deterioration had been that faults in the insulation of the pilot wires had developed, making the protection unreliable. Since those days vast developments have taken place in protective systems, innumerable systems have been put on the market and installed, and a number have been found wanting, or lacking in discrimination. Undoubtedly the simplest method of leakage protection for straight line feeders is that of the Merz-Hunter, more commonly called the " split-conductor " or " split-phase " system. This system of protection for straight lines possesses inherent characteristics which have the advantage of obviating the use of complicated current transformers and relays, as in its simplest form it depends on current balance alone in the split phases, provides complete stability on through surges and can be designed to give satisfaction down to a very small leakage current. But when the system develops and tee-off lines become necessary owing to demands for power, and when ultimately the system becomes an extensive network of lines and cables coupled up in various ways to meet the prevailing demands, the split-conductor system is found to lack the necessary fine discrimination. Further protective systems have been developed with a combination of split pilot-wires, in order to minimize the effect of circulating and other currents, and it has been developed still further until ultimately a system has been evolved which completely obviates the use of pilot wires in any form. This is known as the " ratio-balance " system of protection, and the apparatus may be divided into two classes: (1) Initiating apparatus comprising the starting elements and phase selectors, which serve the purpose of connecting time discriminating elements to the circuit on the occurrence of a fault, and (2) discriminating apparatus consisting of time discriminating elements and a definite timing device, which together form the main discriminative feature of the relay and trip the circuit breaker when required. The main advantage of the system is that it uses a null method of reactance measurement which gives accuracy and consistency of performance. It provides practically instantaneous tripping on the occurrence of faults on the greater portion of the protected feeder. Improved discrimination is obtained by a greater rate of increase of time-delay with increasing distance outside the " instantaneous zone." Stability is maintained on straight-through currents by the introduction of a definite and accurately measured time-delay, the time discriminating elements (which may be called the reactance elements) operating independently of voltage-drops. The operation of the system on the occurrence of earth faults is entirely unaffected by a drop in voltage. The correct discrimination of earth faults is not impaired by the simultaneous occurrence of a phase fault. The time/ratio characteristics of relays are easily adjusted to suit any special conditions of service. Busbar protection is also included, and a feature which will appeal to users is that the equipment is of standard component parts which are exactly alike for any part of the protected network. It is obvious that such a system, eliminating as it does the use of pilot wires with their prohibitive cost over long distances, will be preferable to a supply authority on account of the substantial saving entailed, not only in first cost but in subsequent maintenance.

THE AUTHORS' REPLY TO THE DISCUSSIONS.

Messrs. T. W. Ross and **H. G. Bell** (*in reply*): The discussion can in general be divided under five separate headings and we propose to reply to the remarks of the various speakers as they arise under these headings. This we consider to be preferable to replying to each speaker individually, particularly as their remarks in many cases cover the same ground.

Pilot-Wire Protection.

Mr. Beard has given a very interesting résumé of the early history of pilot-wire schemes and we should like to associate ourselves with him in paying tribute to Mr. Price and Mr. Wedmore, because there can be no doubt that they were the pioneers in the development of what may be termed the " British " method of feeder protection. With balanced protective systems stability must of course be the first consideration of the designer, and whilst the Merz-Beard system is in successful use to-day there are also cases in our knowledge where conditions render this system unstable. It is for this reason that the systems described in the paper and also other systems such as that mentioned by Mr. Clothier have been developed.

Mr. Clothier and Mr. Leeson both refer to the " split pilot wire " system as a Merz-Price system, but like all other recent developments the split-pilot system is very different from the simple system developed by Mr. Price. The greater complexity has been brought about by changed conditions, and to compare the relative characteristics from the point of view of simplicity is misleading. The fears they express of difficulties in commissioning and testing " Translay " gear *in situ* are quite unfounded, as the relays cannot by any stretch of the imagination be termed wattmeter relays but are in principle and construction little different from the well-known induction overcurrent relay. The Translay system is essentially a current-balance system and as such it offers no greater difficulties in testing than any other pilot-wire system. We would also point out that in all systems of balanced protection the secondary current at which the relays operate is not necessarily a measure of the fault current which must flow to obtain operation. With regard to the compensation of the Translay relays against unbalanced oscillatory currents, we find in practice that the non-inductive shunt is satisfactory on cable systems up to 15 miles at 33 kV, but for cables longer than this a small shunting condenser is used which renders the relay inoperative at frequencies above 80 cycles per second. The resonant characteristics of the relay used in the " self-compensating " system have proved entirely satisfactory in practice, which is, of course, the " acid test " of any protective scheme. There seems to be some misapprehension as to the possibilities of the two d.c. pilot-wire schemes described in the paper, and in order to clear up any misunderstanding it should be explained that Figs. 26, 28 and 30 are intended for explanatory purposes only, and slight modifications in the arrangement make the scheme suitable for any condition. It would be as well to point out that the essential difference between the scheme shown in Fig. 26 and that shown in Figs. 28 to 30, is that in the former one pair of telephone wires can be used to protect any number of parallel feeders between two stations, whereas the latter necessitates a pilot circuit for each feeder. It should also be pointed out that in both schemes telephone communication is possible over the same wires. These systems are simple interlocking systems using telephone wires, and although it is also possible to use telephone wires for the Translay system we have had no experience with this arrangement. However, apart from the regulations of the Post Office, we see no difficulty in this direction. The Translay gear has been successfully applied to the protection of feeders with " T " connections.

Mr. Lane and Dr. Garrard have raised the question of the " bias " device for balanced relays and it will be noted in the paper that we make no claim to be the originators of this suggestion, which has been adopted by many designers in the past. We have, however, devised a novel method of obtaining this bias and, moreover, a method which has many advantages over previous attempts to adopt this principle. We quite agree that there are methods by which the bias may be eliminated, but these methods must be confined chiefly to those requiring special current transformers, whereas with the Translay system standard current transformers are successfully employed. We do not agree with Dr. Garrard that the slight time-delay which can be introduced into the Translay gear is any practical disadvantage, as at the most it is only about 25 per cent of the time taken by the oil circuit-breakers to open, and it has so many practical advantages that we are satisfied that it is desirable, this conclusion having been confirmed by results.

The multi-air-gap balanced voltage transformers described in the paper are the result of a demand for more accurate transformers for Merz-Price protection than were procurable in the past, and in reply to Mr. Clothier it would be too much to hope for a balance between this type and the less accurate 4-gap type mentioned by him. Mr. Baird and Mr. Murphy ask whether the Translay gear can be applied to the protection of combined transformers and feeders, and in reply to this important point we can state that Translay gear is in successful use for this purpose.

Distance Relay Protection.

The application of this type of protection is of course new to this country, although relays of British design and manufacture have been in use in other countries for some years. As the discussion has indicated, there are two schools of thought as to the principle upon which distance relays should operate, since the distance can be determined by measurement of either the impedance or reactance of the feeder from the point where the relay is connected to the position of the fault. Those engineers who favour the reactance method do so on the assumption that by measuring the reactance a more accurate indication is obtained of the distance of the fault, because any variation in the impedance due to the resistance of the " fault " arc will not be included in the measurement. Tests which have been carried out, have, however, shown that for currents above 200 amperes the arc resistance is comparatively small and can in practice be neglected. It is also significant that 75 per cent of the firms manufacturing distance relays have designed them on the impedance principle, and that a conservative estimate is that more than 90 per cent of the distance relays in successful operation are of this type. There can be very little doubt that a relay, or more correctly a combination of relays, which will pick out the reactance component of the voltage will, as Col. Edgcumbe points out, be a much more complicated design than the simple impedance relays in use to-day. We must therefore carefully balance the doubtful theoretical advantages against the known practical disadvantages of delicate and complicated apparatus, the maintenance of which may be a difficult matter. It is chiefly for this reason that we advocate the type of relay described on page 809 and illustrated in Fig. 11. We do not agree with Mr. Leeson that the basis of the impedance relay is fallacious. There has never been any doubt that the impedance relay is the better solution of the distance relay problem, unless its operation is adversely affected by high arc-resistance at the fault. Even if high values of resistance did exist in the fault arc, failure to discriminate could not result from this cause, the worst result being a slight lengthening of the tripping time under the most adverse conditions. Actually the fault arc on high-voltage systems has been found to have a very low value, particularly where heavy currents are involved (see Appendix), so that in our opinion it is almost impossible to justify the additional complexity and cost of reactance relays. Mr. Kapp suggests that the curves in Fig. 12 (*a*) are too flat and presumably Mr. Clothier also holds this view, but we submit that in this matter it is only possible to make a compromise between longer back-up clearance times and the possible lack of discrimination due to sluggishness in circuit-breaker operation. The relays can, of course, be adjusted to give any desired " slope " in the curves. We agree with Mr. Kapp that the characteristics illustrated in Fig. 12 (*b*) are superior to those shown in Fig. 12 (*a*) in view of the quicker clearance time obtained in the former case for faults over the first 60 per cent of the feeder length. Against this, however, must be set the disadvantage of greater complication; in many cases we believe that this will outweigh the advantage of reduced clearance time. Mr. Marshall appears to favour a clockwork relay rather than the induction type described in the paper, and without in any way doubting the possibility of using clockwork devices for protective purposes we feel strongly that the induction movement provides not only an accurate relay but also a very simple solution to what in the past has been a difficult problem, i.e. not the exact measurement of small differences of time but accurate discrimination by means of small differences between intervals of time. There is practically no possibility of the permanent magnets changing in strength sufficiently to endanger this discrimination. The permanent magnet used on this type of relay is mainly intended as a means of quickly bringing the movement to rest when the overcurrent subsides, and the braking during the operation period is largely provided by the a.c. flux. As an illustration of this the change in relay time with a 25 per cent change in the magnet strength is only 10 per cent, and experience with watt-hour meters has shown that permanent magnets do not vary to anything approaching this extent. The relay described is thus not dependent upon its calibration but upon design constants. The possibility of inaccurate calibration does not arise and it is remarkable how close the characteristics of the different relays are to each other before calibration.

Sensitiveness.

The term " sensitiveness," when applied to protective gear, is usually intended to mean the minimum fault current at which the gear will operate. Certain speakers during the discussion gave the impression that they considered it of extreme importance that the fault settings should be of the order of 5 per cent of the normal current of the feeder, but this is certainly not supported by experience in practice, and very few operating engineers would agree to have their gear set so low as this. Major Taylor has suggested that the limitation to sensitiveness is the relay, but of course the real limitation is stability in the case of balanced systems, and discrimination in the case of other systems of protection. Taking the stability question first, this can in no way be attributed to the relay, because, as we have pointed out in the paper, lack of stability results from effects produced in the lines or cables, pilot wires or current transformers. It has, however, been shown that relays are available which assist in overcoming such difficulties, but nevertheless we are of the opinion that it is extemely inadvisable to jeopardize the continuity of supply by setting the gear to operate at a fault current lower than necessary. The chief factor in determining the maximum setting allowable is the impedance of generators, transformers and lines, and the important point is to be sure that the minimum possible fault current is sufficient to operate all protective gear on the system. There can be no doubt that fault currents will always reach the estimated value in a very small fraction of a second, and so far it seems to be practically impossible to design a perfectly stable form of discriminating protection which will operate to break the circuit before the fault current has reached this value.

There is also the fact that many engineers consider very sensitive protection undesirable because of the difficulty it creates in locating the fault position in a cable before repairs can be effected. This important point was mentioned by Mr. Winfield and there is no doubt that the introduction of a slight time delay in the relays is an advantage from this point of view. In the case of impedance or distance protection the fault current at which the relay will trip must exceed a certain value, otherwise the voltage-drop between successive switching points will not be sufficient to allow of discriminative action of the relays and circuit breakers. Taking everything into consideration, therefore, it is difficult to see any convincing argument in favour of a lower setting than that necessary to ensure satisfactory operation of the relays at the calculated minimum fault current.

Earthing of System Neutral.

It is apparent from the discussion that most of the speakers favour the earthed system as opposed to the unearthed system. There is still, however, some difference of opinion as to whether the neutral point should be connected directly to the earth plate or through a resistance. That brings up the question of the definition of the term " earthed system," and in this connection it may be of interest to quote the following extract from the " American I.E.E. Standards ": "A circuit shall be considered directly grounded when transformer connections and characteristics are such that not less than twice the combined rated line currents from the bank or banks of transformers supplying the circuit will flow to ground when a line is grounded at a terminal of any of the transformers supplying the circuit." This establishes the difference between " earthed " and " unearthed " circuits and removes any ambiguity which may arise when reference is being made to them. Mr. Rawll suggests that it is incorrect to use the term " insulated neutral " for systems on which arc-suppression coils are installed, but if the above ruling is adopted the term is used correctly. It is of interest to read the divergent views on the subject of earthing resistance expressed during the discussion by engineers responsible for the operation of large supply systems. For instance, Mr. A. T. Scott is of the opinion that it is desirable to limit the earth current to the smallest possible value and suggests that this value should bear some relation to the electrostatic capacity to earth of the lines. It is not at all clear, however, what gain is expected from the use of this method in estimating the value of the earthing impedance, unless it be to limit any possible excess voltage of a transient nature. It is difficult to reconcile this point of view with the remarks of other speakers, particularly Messrs. Winfield, Haigh, I. Jones and E. W. M. Scott and Dr. Garrard, who all favour either solid earthing or earthing through a comparatively low resistance. We agree with Mr. Winfield that the Continental systems which are operating with insulated neutrals with or without arc-suppression coils, are usually much less complicated than the majority of networks in this country, and this difference may also explain the divergent views on the question of earthing resistances.

Mr. Gregory's suggestion for rural supply as outlined by Mr. Winfield has much to recommend it and we believe that on such installations arc-suppression coils may prove very useful, because of the importance of capital cost and the consequent necessity of economy in switching equipments.

Miscellaneous Points.

We agree with Col. Edgcumbe that the definite time-delay relay will give results equal to those obtained with the inverse definite minimum time-delay relay on simple feeder systems, but its application becomes very difficult, if not impossible, on more complex networks. This is because, with the former, discrimination depends entirely upon the grading of time settings, and no advantage is taken of the current distribution in the various feeders. Due to the distribution of fault currents in the network, some feeders will be carrying much less current than the faulty section, and if inverse and definite minimum time relays are used, advantage can be taken of this to obtain discrimination between a greater number of circuit breakers without increasing the maximum time delay. We also believe that the induction type of inverse-definite minimum time relay is less complicated than the definite time-delay relay, which is usually of the clockwork type requiring winding up periodically by an attendant.

In reply to Dr. Garrard, Figs. 6 and 7 show arrangements of directional earth-fault relays which are obviously applicable to parallel or ring feeders. We feel assured that a little further consideration will convince him that the relays described in Figs. 9 and 11 are true impedance relays. In reply to Mr. Strong, we think that multiple earthing assists in obtaining discrimination by non-pilot-wire protective systems on ring mains, owing to the concentration of neutral currents at the stations nearest to the fault. We agree with Mr. Morton that certain designs of over-current relays have many fragile parts; these are not inherent, however, in the overcurrent relay and there are designs on the market which are robust and simple.

Mr. Winfield raises the question of carrier-current protective schemes. These are very attractive, but practical difficulties arise in their application, and so far we have no knowledge of the successful use of such schemes except in the case of a simple feeder arrangement to which other types of protection could have been applied. He raises also a very important practical difficulty in the application of reactance and impedance relays to high-voltage lines, namely, that of obtaining the relay voltage from the lower-voltage side of power transformers, and compensating for the voltage-drop due to the transformer reactance. Whilst this is not an ideal arrangement, we consider that by suitable compensating means it is possible to obtain sufficient accuracy for the correct operation of impedance relays, but this sometimes entails complications which could be avoided if voltage transformers were used. There is no difficulty in obtaining correct operation of impedance relays, even when two faults occur simultaneously on a system. As regards the pilot capacity currents in the Translay system, the relay is, as stated in the paper, so designed that the leading component of the current in the pilot wires will produce a backward torque. The self-compensated system has been in successful use for some time on several large supply systems in this country.

We can assure Mr. Murphy that the relay described in Fig. 4 will withstand short-circuit conditions and is of extremely robust design. Mr. E. W. M. Scott fears difficulty with the application of the locking system in a specific instance, but gear of this type is actually in successful operation in stations similar to that which he describes.

In reply to Mr. Kapp, we have carried out some experiments with current-type phase filters applied to relay schemes, but we have had no experience with phase filters for the supply of potential to directional relays. We are of the opinion that sensitive wattmeter elements are preferable to the more complicated phase filter, and it has been our experience that if such elements are designed to operate down to 2 per cent of normal voltage, correct operation is assured.

The later communication by Messrs. Clothier and Leeson does not call for any further reply as the systems described therein appear to be merely variants of systems already fully dealt with in the paper and discussion.

DISCUSSION ON

"LOW-TEMPERATURE CARBONIZATION OF FUEL (ENGLISH PRACTICE)."*

North-Western Centre, at Manchester, 4th March, 1930.

Mr. J. Frith: I am sorry that the paper stops where it does, for although a description of a plant of this kind is interesting we knew beforehand that coal could be gasified, could be turned into coke, that the coke and the gas could be burnt under a boiler and that motor fuel, oils and creosotes could be obtained by distillation. Many of those present have no doubt been wondering whether the process is really going to pay, for no figures as to finance are given in the paper and only a few have been submitted by the authors since it was printed. These were not, however, sufficient to enable one to form an opinion as to whether this great expenditure of money, space, labour and brains will prove to be a practical proposition. I also am interested in smoke prevention, but how many power-station engineers would face this mass of complicated machinery in order to bring it about? The running of a distillation plant, a chemical factory and all the equipment shown in the diagrams, as adjuncts to the generation of electricity, is no light task. I am afraid that people will not enter upon it until figures showing how it will work out financially are available. It is gratifying to think that 15 shillings' worth of by-products can be produced from a ton of coal and that this still leaves 75 per cent of the original heat value in it. If plants dealing with 5 000 tons per week were installed, however, what would happen to the markets for the by-products? Is there an unlimited market for creosotes and fuel oils? They will be difficult commodities to dispose of. If the process were taken up in our large power stations, would there be any guarantee that the market would remain open for the by-products or that the selling price would not drop to a very low figure? The paper describes an interesting experiment, but the first thing to be done now is to produce a balance sheet.

Mr. R. M. L. Evans: At the joint meeting with the Institute of Fuel the descriptions of American and Continental practice, by Mr. McEwen and Prof. Rosin respectively, laid great stress on the vital importance to the economic stability of low-temperature carbonization of fuel of the preparation of a gas suitable for town supply. While this seems a poor policy, as the fundamental aim of the more economical combustion of fuel in the generation of electricity is to cheapen the latter and hence by competition to destroy the market for its own by-product gas, it is significant that the authors of the present paper lay no such stress on this point; in fact they consume the gas produced by the Dunston plant, after stripping it of its volatiles, in the carbonizing plant and beneath the boilers. How do they explain this apparent discrepancy, and are we to assume that they regard the stripped tar oils as of greater economic value than a town-supply gas of suitable calorific value and density? With regard to the much-discussed nuisance of the sulphur content of flue gases, this appears to be actually increased by the process described. In order, therefore, that this nuisance may not become aggravated, and also to remove a possible deterrent to the installation of low-temperature carbonizing plant, may it not become necessary to attack the problem at this point and to remove the ammonium sulphate, even though this plan may be uneconomical? In connection with the quenching of the coke after it leaves the retort, a great deal of heat seems always to be lost here in every method of carbonization of coal, but this is notoriously so in the ordinary coking process. In their chain-grate stoker type of retort the authors seem to have eliminated this loss, yet they interpose quenching apparatus, although they state that the quenching is only partial. Could not this quenching be omitted altogether, and the coke be supplied direct to the stoker at the temperature at which it leaves the retort?

Mr. J. D. Paton: Incipient combustion by the return of supposed inert gases is in all probability the cause of the sulphur increment in the coke above normal bulk ratio, on the conversion basis only. Quenching steam and flue gases carry in sulphur fumes that increase the sulphur content. I wish to point out the authors' appreciation of the words "distillation" and "phase of action" when they work on the basis of getting the maximum of contents value by the introduction of distilling gas at a temperature of 600° C. I was originally a low-temperature carbonization enthusiast, but I now regard carbonization by itself as a failure as far as maximum extraction of value is concerned, and I believe in it only where coke and gas production is necessary. The maximum values in coal exist in three constituents, namely the petrol, cresol and benzol sections. I should like to project on the screen a coloured section of a piece of coal which gives 20 per cent of volatile matter by standard carbonization procedure, and if it is examined with a view to extraction as distinct from carbonization the percentage of oil-yielding constituents is much higher. [The speaker here exhibited on the screen a lantern slide of a piece of Durham coal the constituents of which he defined, estimated and explained.] My basis for the estimation of the liquid return from any coal is the amount of transparency and the extent and nature of the colour halations of the three shades, white to yellow, yellow to brown and brown to red. These indicate the petrol, cresol and benzol fractional components, respectively. The opaque zones are either fixed carbon or inert ash infusions, and whilst I admit the necessity for carbonization where coke is desired or fixed gas is needed I do not accept the modern belief that the proposed high-pressure, high-temperature hydrogenation procedure is the best means for maximum recovery of the constituents of coal which it is possible to liquefy. Why produce fixed carbon by carbonization if oil can be recovered by contact distillation and transference or eventually by direct extraction, under normal industrial pressures and temperatures? Coal is an organic substance and its phases and stages of growth or oxidation (i.e. carbonization) are defined by the transparency or colour-index or on any other basis which one may care to adopt for the halations described above. Bergius is attempting to obtain total liquid recovery at enormous pressures and high temperatures, and I forecast a probable liquor recovery of 50 to 60 per cent from the sample shown, without the use of high pressures, high temperatures, or catalysts in the near future. This is the reason for my interest in attempts at distillation, or, more correctly, at extraction. Mention is made of pioneers, and in this connection I remember forecasting some of these results as far back as 1912, when the process advocated by the authors was partly suggested in a paper read before the Institute of Mining Engineers. My conception of future progress and my present personal procedure are along the lines of the extraction of maximum liquid values of the oil constituents in the coal. It would be an advantage if the gas undertakings would develop along the lines followed by the authors, for in conjunction with electric power production we might then have gas at a reasonable price. In a city like Manchester, which is dependent upon its industrial activities, why should we pay 3s. 4d. per 1 000 cub. ft. for industrial gas? In my business I have to use gas for production purposes, at a cost of between 3s. and 4s. per 1 000 cub. ft., and although the calorific value is given as 500 or 600 B.Th.U. I am doubtful whether it exceeds 450 B.Th.U. per cub. ft. I congratulate the authors on being located in an area where statesmanship has visualized the possibility of coal, steam, gas and electrical power being the foundations of industrial prosperity. I only wish that this city had sufficient vision to recognize the possibilities of its own canal area for this purpose. My last lantern slide gives the details of an industrial grouping which included all the features described by the authors, as far back as 1917–18, when M. Frith and I submitted a paper on fuel economics to this Institution.

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* Paper by Messrs. E. H. Smythe and E. G. Weeks (see page 219).

Mr. A. L. Lunn: I noted with disappointment the sulphur content of the coke (page 220), because I was hoping that the problems associated with this undesirable constituent had been successfully solved. The analysis of the moisture-free coke obtained by treatment of this coal gives the total sulphur content as 1·61 per cent, whereas in the analysis of the Northumberland coal which is being treated at this coal distillation plant the figure is given as 1·26 per cent. Consumers of fuel in Northumberland are fortunate in having at hand coal with a lower sulphur content than is the case in Lancashire and Yorkshire, and more particularly in the former county. I should like to have some information with regard to the plant installed for firing this semi-coke, and particularly as to the type of boiler—its arch and the size of its combustion chamber and the class of stoker employed. What thickness of fire can be used, is any difficulty experienced in maintaining combustion, and can the maximum evaporation be obtained from the boiler? In other words, is it necessary to incur expenditure on additional boiler plant in order to compensate for the effect of distilling the coal? The work described by the authors is very valuable, and it would be interesting to know whether it is proposed to extend the system to other power stations consuming thousands of tons of coal per week, where the experiment could be carried out on a large scale. At a recent smoke abatement exhibition I was interested in a certain type of fuel shown which was claimed to be smokeless, as well as clean to handle and use. I decided to try this fuel at home in an ordinary kitchen grate, but it compared very unfavourably with coal. In the first place, it was expensive. Secondly, it was very dirty, and contained an abnormal percentage of ash. It was decided to give the fuel a further test, this time in the dining-room. It was found necessary to switch on the radiators in this room to keep it comfortably warm. Approximately every hour the fire had to be attended to, as it was found to take about 40 minutes to reach the maximum heat value and then it gradually died down. In addition to these disadvantages, a large quantity of dust was deposited all over the room. It was observed that on each occasion when fresh fuel was added to the fire a quantity of light-coloured smoke ascended the chimney; this was not so black and dense as that obtained when using raw coal—thus the outside atmosphere was kept much cleaner—but much more work was involved in keeping the house clean. I am particularly interested in the use of semi-coke at the power station, and although the authors referred to the burning of this fuel in pulverized form they did not make it quite clear whether they have actually accomplished this or whether it is only contemplated. If they are already doing this, I should like to know whether they have had any trouble with the pulverizing plant. It has been stated that screw conveyors are used. There is, perhaps, a difference between the hardness of semi-coke and that of coke breeze, but in my experience the abrasion caused by the latter has resulted in this type of conveyor having a very limited life. The development of a process such as that described by the authors, of installing low-temperature coal-distillation plant at a power station, savours of the introduction of a gasworks into the electricity supply industry. Would not the ideal be to establish gasworks and power stations together, for their mutual advantage, the two being worked as a combined unit?

Messrs. E. H. Smythe and **E. G. Weeks** (*in reply*): The questions raised by Mr. Frith are of such a general nature that it would be somewhat difficult to answer them in detail within the limits of space available for this discussion. We should like to point out again that the scope of the paper is purposely confined to a description of the process and the results obtained from this process as worked at Dunston. We have shown that raw coal can be treated to produce certain solid and liquid by-products, but we have purposely kept the paper free from considerations of a commercial nature, complete with balance sheets, etc. There is, however, no difficulty in preparing a proposition of this kind, provided suitable data are submitted concerning the class of coal to be treated and the type and market prices of the by-products it is desired to produce. If Mr. Frith is interested, we suggest that he should submit an inquiry to the manufacturers of the plant who, we are sure, will be only too pleased to go into this aspect of the proposition and give him all the information he requires. As regards the other points mentioned, we do not agree that it was known that satisfactory means were available for converting large quantities of coal into semi-coke, or that coke can be burned under a boiler with satisfactory results. It would, in any case, necessitate considerable alterations to existing draught arrangements and furnace design. Semi-coke, as produced by the process described, is, on the other hand, an entirely suitable fuel for this purpose, and this was not known to be the case until we had proved it by practical working at Dunston. As regards co-operation at the power station, it is quite possible to operate low-temperature plant independently, so that the power station merely takes fuel from the plant while the liquid by-products are dealt with by a separate organization, thus relieving the power station of any responsibility in this respect. We agree that if the installation of low-temperature plant became general the supply of certain liquid by-products might be greater than the demand, but this possibility is very far distant, and long before it is reached the liquid by-products would most probably be dealt with in other ways, e.g. by "cracking" for the production of motor spirit.

In reply to Mr. Evans, the process described produces only low-grade gas having a calorific value of about 100 B.Th.U., and this gas is of no use to the gas companies except as a diluting medium. We certainly do not regard this stripped gas as being of greater economic value than town gas, and, in fact, if burned under the boilers it is only credited to the plant at the same price per therm as that paid for the coal. We do not claim to reduce the sulphur contents in the flue gases, though they are actually reduced when certain coals are treated. In any case, we do not think that the removal of the ammonium sulphate is worth while. As regards the quenching of the coke, Mr. Evans does not seem to have appreciated the fact that the object in quenching the coke as it leaves the retort is to recover some 60 per cent of the low-pressure steam required in the operation of the process, so that actually no heat is lost by quenching. We do not think it advisable to omit this quenching as, if hot coke is supplied direct to the stoker, difficulties will arise in storing the coke in the event of the boiler being out of action, and it is, on the whole, preferable to supply quenched coke to the bunkers rather than direct to the stoker.

With regard to Mr. Paton's opinion that in all probability the cause of the increment of sulphur in the coke is the sulphur derived from the distilling gases, we would say that in the event of the whole of the sulphur present in the distilling gases being transferred to the coke the increase in the sulphur content of the coke would only be of the order of 0·06 per cent. What actually happens is that the bulk of the sulphur in the raw coal appears in the coke, and as the weight of coke is less than that of the coal it follows that the percentage of sulphur in the coke is higher than in the original coal. With certain coals the percentage of sulphur in the coke is less than in the coal, but this does not apply to the coals normally used at Dunston. We were much interested in Mr. Paton's lantern slides and we are thoroughly in agreement with his view that it would be an advantage if gas undertakings were to take an interest in low-temperature carbonization with a view to the production of suitable smokeless fuel for household purposes, and also with a view to still further cheapening the cost of gas by diluting town gas and supplying gas of lower calorific value than is at present the case. The use of gas from the Babcock process as a diluent for town gas is advantageous as it can be supplied at a cheap rate, but in addition, owing to the low content of carbon monoxide in the gas, its admixture with town gas does not increase the percentage of carbon monoxide in the gas to be distributed to the consumers, as is the case when town gas is diluted with water gas.

In reply to Mr. Lunn, the design of furnace used for burning semi-coke differs in only minor respects from that used for burning coal; in fact a shorter arch may, with advantage, be used, thus reducing the cost of construction. Otherwise, the type of stoker and size of combustion chamber are the same as those normally employed. The thickness of the fuel bed on a chain-grate stoker using semi-coke is approximately twice that normally used with coal. No difficulty whatever is experienced in maintaining combustion, as the coke is very free-burning and maximum evaporation is obtained. We are sorry to hear that Mr. Lunn has had such an unsatisfactory experience with smokeless fuel and we can only conclude that it was not a very good example of its kind and was made from inferior coal. Our own experiences with Dunston semi-coke have not shown any disadvantages in connection with dust or ash, though it is certainly the case that the fire has to be attended to more often than when coal is used. On the other hand, an intense fire is reached very rapidly, which is an advantage, and the fuel is light and clean to handle and certainly very economical, taking into account the quantity received, ton for ton, as compared with coal. We have so far not experienced any difficulty with pulverizing semi-coke. As the semi-coke is comparatively soft it is easy to pulverize and does not possess the same abrasive qualities as high-temperature coke.

SOME DEVELOPMENTS OF THE PIEZO-ELECTRIC CRYSTAL AS A FREQUENCY STANDARD.

By H. J. LUCAS, Associate Member.

(*Paper first received* 16*th December*, 1929, *and in final form* 31*st January*, 1930; *read before the* WIRELESS SECTION 5*th March*, 1930.)

SUMMARY.

Part (1) deals with some observed errors in quartz piezo-electric resonators employed as frequency standards. It is shown that these are due to (*a*) frictional loading, and (*b*) losses arising from atmospheric humidity. The methods adopted to eliminate these are discussed, and the development of calibration apparatus employing the resonators as reference standards is dealt with.

Part (2) is in the main concerned with the use of the improved quartz crystal as a control element in a valve-maintained source of oscillations. The frequency-stability characteristic of such a system is investigated, the errors are found to be largely due to the valve system, and methods designed to eliminate these are discussed.

Finally a complete calibration equipment consisting of a multivibrator system with a range of 1–6 000 kilocycles per sec. in steps of 1 kilocycle per sec., centrally controlled by a quartz crystal, is shown.

INTRODUCTION.

Up to and including the War period the author was interested in the maintenance of a sub-standard wavemeter for the calibration of wavemeters in bulk. An accuracy of 1 per cent was found sufficient for all needs at that time. In the years immediately following the War accuracies up to 1 part in 1 000 were called for, while at present the sub-standard has to be correct to within 1 part in 10 000.

The first phase calls for no comment. The requirements of the second were met by the use of a wavemeter employing an oscillating triode. The accuracy of this was maintained by reference to a calibrated low-decrement closed oscillatory circuit. The latter has since become known as an " absorption wavemeter " and the reference was carried out by means of the phenomenon known as the " Ziehen " effect.

The third phase is met by similar methods, but the reference standards are in this case quartz resonators. The first part of the paper deals with the development and applications of these reference standards.

PART (1).

SUMMARY OF THE RELEVANT POINTS IN THE MODERN THEORY OF COUPLED CIRCUITS.

In practice it is found that the application of the " Ziehen " effect in the second phase and the various applications of quartz oscillators and resonators in the third phase are governed by the same fundamental principles. Nearly the whole of the practical applications of quartz crystals conform to the laws of coupled circuits. With suitable adjustment of the circuit these, in common with magneto-striction devices and valve-maintained tuning forks, exhibit the characteristic frequency-discontinuities of a system consisting of a low-decrement circuit tightly coupled to a source of free oscillations.

In certain instances the control member is used to obtain retroaction over a narrow frequency band and simultaneously to stabilize the resulting oscillations, but in no sense does it act as a generator.

The equivalent coupled-circuit conditions for the quartz crystal have been deduced by D. W. Dye[*] and other writers. The following relevant points in the theory of coupled circuits have been taken from papers by J. S. Townsend[†] and H. G. Möller.[‡] A coupled circuit with a fixed primary impedance and a secondary capable of being tuned to resonance with the frequency of the applied e.m.f. is fed by a valve or other source of free oscillations. Provided that the coupling is greater than the value defined by Möller as the " critical " value, continuous variation of frequency with secondary tuning cannot be obtained. Abrupt frequency discontinuities appear on either side of the resonant points —Möller's " Ziehen " effect. Fig. 1 illustrates this point.

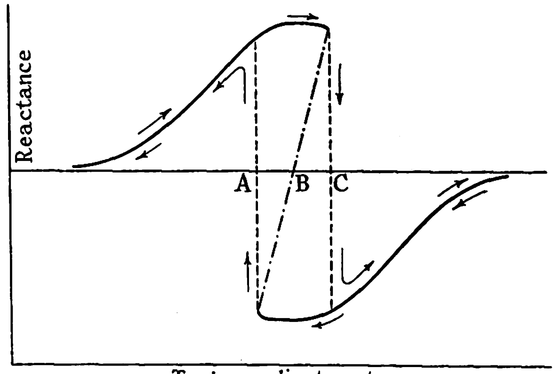

FIG. 1.

It will be noted that the portions of the operating curves bounding the hysteresis area show a very marked frequency stability, a comparatively large change of tuning producing but a small frequency change. A mathematical analysis of the simple coupled-circuit as described shows that there are three possible modes of oscillation, f_1, f_0, f_2, where f_0 is the frequency of the applied e.m.f. with the secondary removed. An examination of Fig. 1 shows that in the vicinity of resonance (B) the mathematically possible oscillation, f_0, cannot in practice be obtained, whereas f_1 and f_2 can be obtained at will. Möller gives a reasoned case as to why these conditions obtain.

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[*] " The Piezo-Electric Quartz Resonator and its Equivalent Electrical Circuit," *Proceedings of the Physical Society of London*, 1926, vol. 38, p. 399.

[†] " Oscillations obtained by Coupling a Secondary Circuit with a Continuous Wave Valve Oscillator," *Radio Review*, 1920, vol. 1, p. 369.

[‡] " Zur Theorie des Ziehens," *Jahrbuch der Drahtlosen Telegraphie*, 1920, vol. 16, p. 402.

The deductions from these observations are as follows:—

(1) All mechanical vibrator-valve combinations which obey the laws of coupled circuits produce frequency-stabilized oscillations.

(2) Such combinations have two possible modes of oscillation. In the case of quartz either may be obtained by connecting the crystal to (*a*) grid-filament, or (*b*) grid-anode.

(3) The combination cannot oscillate at the natural free period of the mechanical vibrator.

The complete argument may not be strictly true in all cases of quartz-valve combination, as the frequency break, while invariably present, is displaced, and f_1 and f_2 are higher in frequency than f_0. A very close approximation to f_0 may be obtained by the Cady crevasse method, but in this case the crystal is not used as a "control" member.

A further point may be made at this juncture. The cases referred to above are in general for free oscillations, but the outputs from such combinations behave as forced oscillations, and they may be used to control other free oscillations of approximately the same periodicity and certain far-removed periodicities, as will be discussed later.

FIRST APPLICATION OF THE QUARTZ RESONATOR.

In view of the lack of uniformity in the nomenclature used in the literature on the subject of quartz crystals, in accordance with Dye's practice the following conventions have been adopted:—

(1) Longitudinal vibrations—the mode of oscillation employing the longest dimension of the crystal. The cut for this may vary, but for the purposes of definition a cut normal to any two parallel faces of the natural crystal may be accepted.

(2) Transverse vibrations. This mode of oscillation employs the thickness of the crystal, i.e. it is at right angles to the longitudinal mode.

(3) Resonator—a crystal used non-retroactively. In general the longitudinal mode is employed.

(4) Oscillator—a crystal used retroactively or to control a retroactive circuit. The transverse mode is usually the more effective in this connection.

Practically the whole of the investigation which follows is concerned with the longitudinal mode of vibration. Considered purely from the precision standpoint, the longitudinal mode presents great advantages over the transverse. As an instance, the temperature coefficient of the former is only about one-twentieth of that of the latter. This important fact was first pointed out by Dye.

The introduction of the quartz resonator by W. G. Cady * was welcomed by the author with considerable relief. It was appreciated that the closed-circuit reference standards then in use were not to be relied upon for the accuracies demanded, and quartz appeared to offer a completely reliable alternative. Its inherent nature suggested absolute permanence and stability, its natural period could be determined with a high degree of accuracy and its reactions on the oscillating circuit were sharp and positive. An ideal solution appeared to have been arrived at, and for a time it was accepted without question. However, certain variations, apparently of the sub-standard wavemeter, were observed and these (of the order of 1 part in 3 000) could not be definitely traced to the wavemeter. It was decided, therefore, that an investigation into the behaviour of the quartz resonator was necessary.

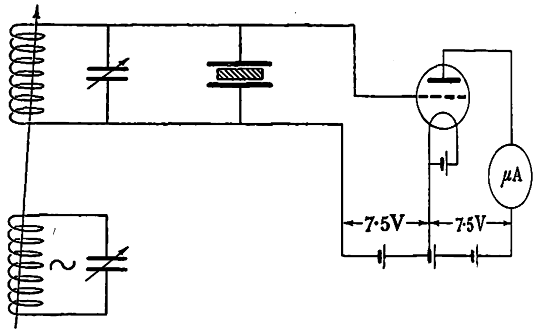

FIG. 2.

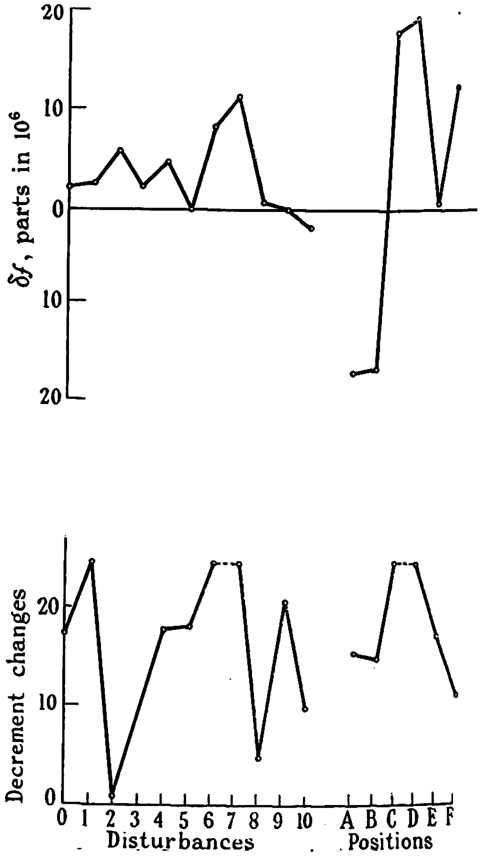

FIG. 3.

Reference to a multivibrator confirmed the opinion that the resonator or its mount was responsible for the variations. Suspicion naturally fell on the mount and a full investigation was undertaken to determine the cause of the variations.

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* "The Piezo-Electric Resonator," *Proceedings of the Institute of Radio Engineers*, 1922, vol. 10, p. 83.

The method of observation was that of the Cady crevasse, the only difference from the then standard practice being the use of a heavily biased valve voltmeter instead of the more usual thermo-junction and galvanometer. The circuit is shown in Fig. 2. This enabled less power to be used in the oscillator and gave a more sensitive record of the minute variations of potential in the operating region at the bottom of the crevasse. Fig. 3 shows a typical series of observations. The logarithmic-decrement variations shown are only relative, as they were disclosed partly by changes in the depth of the crevasse and partly by the sharpness of what is, in effect, the crest of the resonance curve of the resonator. It was evident that within the limits of 1 part in 3 000 the crystal was very unstable. In fact the slightest disturbance in the laboratory, such as closing a door, altered the readings. It was known that the frequency variations could, in part, be accounted for by changes in the small air-gap, but this would not account for the decrement changes.

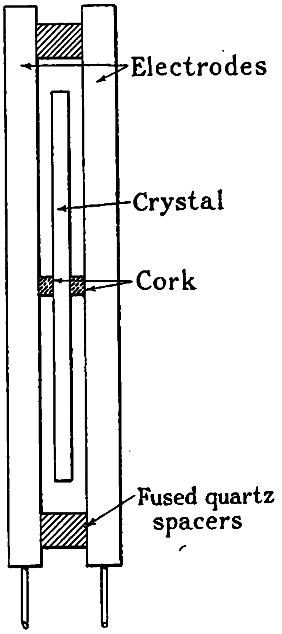

FIG. 4.

To investigate this point the resonator was supported centrally in a large air-gap (1 mm each side). The variations were found to be worse, and the decrement was also increased. This gave the clue to the trouble, as the supports for centring the crystal were obviously adding to the existing sources of error. These were finally traced to the effect of frictional loading between the crystal and its supports, which was altering both the period and the damping factor of the resonator.

The solution was simple. The resonator was firmly gripped at a nodal point of mechanical displacement for the fundamental longitudinal mode (in the centre of its length), so as to leave it free to vibrate without friction. Fig. 4 is a plan view of a resonator mounted in accordance with this method. The whole of the short-period variations shown in Fig. 3 had now vanished and the resonator could be placed in any position or could be jarred without alteration of frequency or decrement, and readings could be reproduced with a high degree of accuracy. For the first time a really consistent plot of the Cady crevasse could be obtained, enabling the numerical value of the logarithmic decrement to be computed.

This specially-mounted resonator was kept under observation for some time and long-period variations of frequency, of the order of 1 part in 10 000, as well as decrement changes were noted. These were eventually associated with changes in atmospheric humidity and the relation between the cause and its effect was soon confirmed by tests in:—

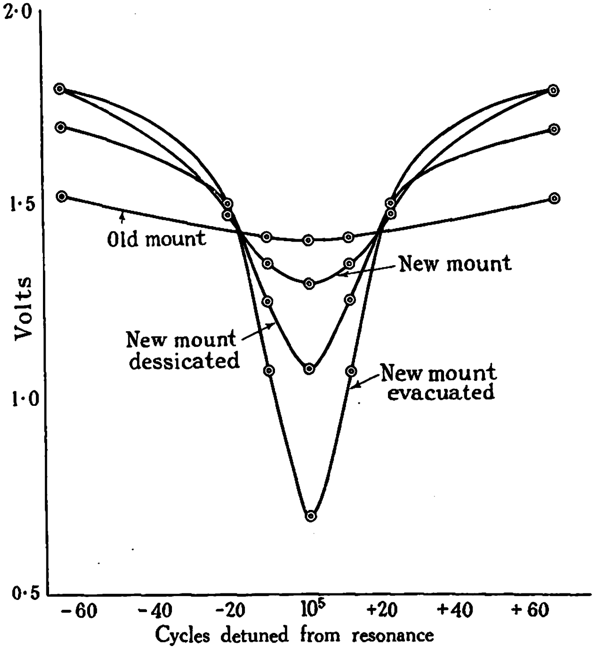

FIG. 5.

(1) a saturated atmosphere (when the piezo-electric effect disappeared), and
(2) a sealed test-tube, with a desiccating agent.

In the latter case definite stability was obtained, after a period of slow drift during which the moisture was absorbed, together with an improvement in the decrement. An increase in the frequency of approximately 1 part in 10 000 was also noted; this point will be further discussed in Part (2). The frequency change may be partly due to the removal of the loading effect of the film of moisture on the surface of the crystal, while the improvement in decrement may result from the elimination of the hysteresis loss in this film. Dye has shown that the equivalent capacity of a similar resonator is of the order of $0 \cdot 08\,\mu\mu F$. As the logarithmic decrement is a function of the capacity as well as of the resistance, it will be realized that a small loss in such a minute capacity will have a marked effect upon the decrement. Dye comments upon the probable effect of humidity on frequency and has also adopted a form of nodal-support mounting.*

The obvious step of evacuating the enclosure which contained the resonator was now taken, and the anticipated further improvement in the decrement due to the removal of the air-loading was obtained. It is doubtful whether evacuation or even desiccation without the mounting precautions would be of much value. The frequency variations and decrement depreciation due to frictional loading would to a large extent mask the improvement due to the removal of air loading. Fig. 9 shows the improvements in decrement as indicated by the depth and sharpness of the crevasse, produced as a result of the successive stages of development. The frequencies have been reduced to a common value for convenience—in practice these differ to the extent of 1 part in 5 000 for the extreme cases.

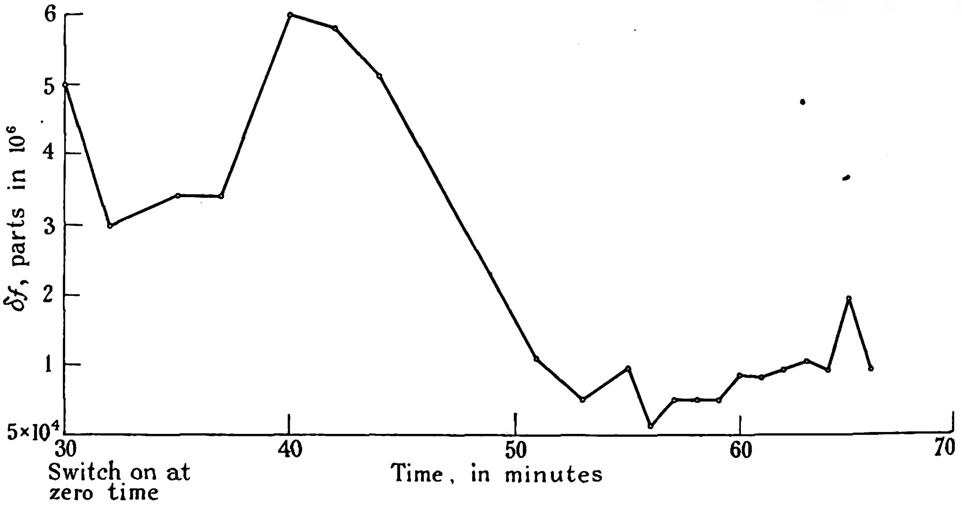

Fig. 6.

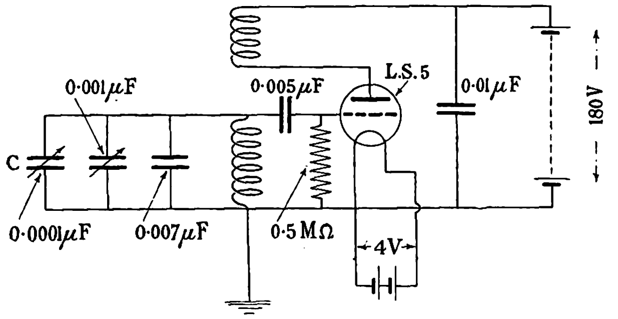

Fig. 7.

The "figure of merit" of a resonator or similar system is the degree of accuracy to which the true resonant frequency can be determined. This in turn is related to the logarithmic decrement. In the case of the mounted and evacuated crystal, Fig. 10, an open-scale plot of the bottom of the crevasse, shows that this determination can be made to an accuracy of 1 part in 200 000, whilst the normally-mounted crystal gives a value of the order of 1 part in 5 000 which is not at all constant. During the investigations described in the foregoing it was found possible to design and build valve-maintained oscillators which would remain constant in frequency for reasonable periods to within 1 part in 100 000. A typical time/frequency curve for such an oscillator is shown in Fig. 6.

It was found that the principal causes of the variations which are usually attributed to this system were changes in the capacity of the variable condenser for any given setting, together with alterations in the valve characteristic. The inconsistencies of the variable condenser could be reduced by careful design of that component, and the residual effect could be diminished to negligible proportions by the use of a fixed shunting-capacity, which should be as large as is consistent with the provision of the necessary tuning-range. Variations of valve characteristic and of anode and filament-supply potentials were all shown as changes in the equivalent capacity of the valve. As this capacity was in parallel with the tuned circuit its effect was reduced by the provision of a shunt capacity in the latter. The circuit and values used are shown in Fig. 7. This circuit could be checked back to the quartz resonator when necessary by using it as the variable source in the Cady crevasse method, and it was found desirable to distort its output to produce the requisite number of harmonics for use in calibrating other oscillators. Further development of this method produced the equipment of which the circuit is shown in Fig. 8.

The 10-kilocycle oscillator was built on the principles set out above, while the power amplifier followed normal practice. The 10th harmonic of the distorting circuit was selected by a tuned circuit and referred to the 100-kilocycle quartz resonator by the Cady crevasse method. The adjustment was carried out by means of the fine tuning condenser C (Fig. 7), while the output from the coupling coil L gave a full range of harmonics from 10 to 2 000 kilocycles per sec. in steps of 10 kilocycles. As the adjustment of the oscillator frequency was carried out by referring the distorted output to the resonator, any errors due to coupling were allowed for. The rectifying valve was found to be the most convenient method of producing the requisite number of harmonics.

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* Pp. 417 and 447, *ibid.*

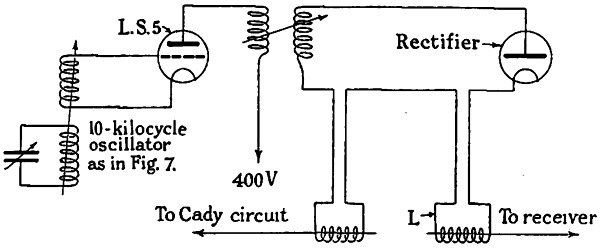

FIG. 8.

The fine-tuning condenser was calibrated in terms of the number of cycles per second by which it departed from the resonator frequency.

At the time when this equipment was developed, the B.B.C. stations were all, with the exception of 5 XX, working on a frequency which was a multiple of 10 kilocycles. Hence each station was nominally on a harmonic of the 10-kilocycle oscillator and any departure could be noted by the difference between the 10-kilocycle adjustment of the fine-tuning condenser and that obtained by referring the appropriate harmonic to the frequency of the station's carrier wave by the double-beat method; this difference was multiplied by the harmonic order of the station relative to the oscillator. Some interesting observations were made on the accuracies and stability of these stations and it was particularly noticed that 5 GB, whilst seriously departing from its nominal frequency, showed remarkable constancy. This was subsequently confirmed by Captain Eckersley's paper.* The result of a series of observations on 2 LO is shown in Fig. 9, in which the curve commences at the instant at which the station begins to radiate.

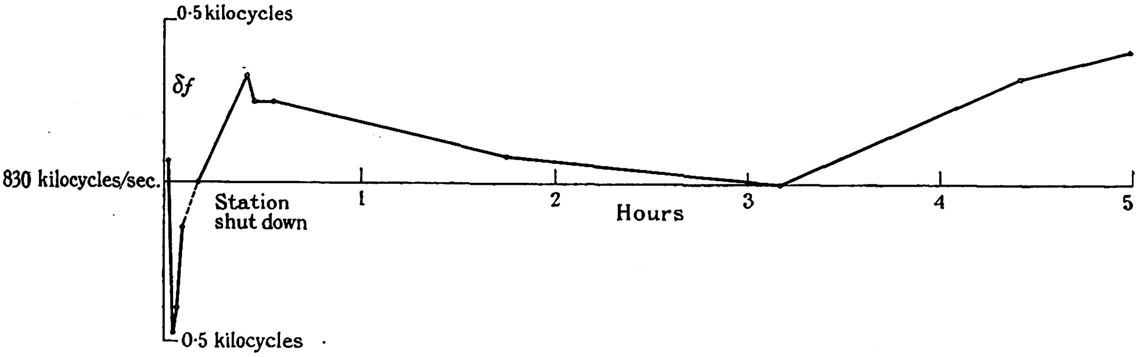

FIG. 9.

This equipment was found of very great use in the calibration of sub-standard wavemeters to the required degree of accuracy. It was also used for the measurement of inductance and capacity at various high frequencies. Further, it was and still is considered that the ideal use of a frequency standard is as a means of adjusting the frequency of a separate oscillating system and not as a " drive " or " control." The analogy to the pendulum is the employment of a free undriven pendulum as a check on a driven system, by some means which does not cause the free pendulum to deviate from its true period. It is believed that modern methods of high-precision horological determination have developed in this direction.

Briefly, the advantages of a system employing a resonator as a reference standard are:—

(1) The resonator is not doing any work—it is fed with just sufficient energy to enable the determination to be made, and the load applied by the indicating device (valve voltmeter) is practically one of potential.

(2) Provided that the " Cady crevasse " closed circuit is accurately tuned, the true period of the crystal-mount assemblage is obtained.

(3) Any variation in the electrical circuit is immediately made manifest and is under complete control.

The principal disadvantage of the system is a slight uncertainty in the value of the true resonant-period due to the approximately straight line which exists at the bottom of the crevasse and which at present limits the accuracy of adjustment to about 1 part in 200 000 (Fig. 10). It is considered, however, that this could be

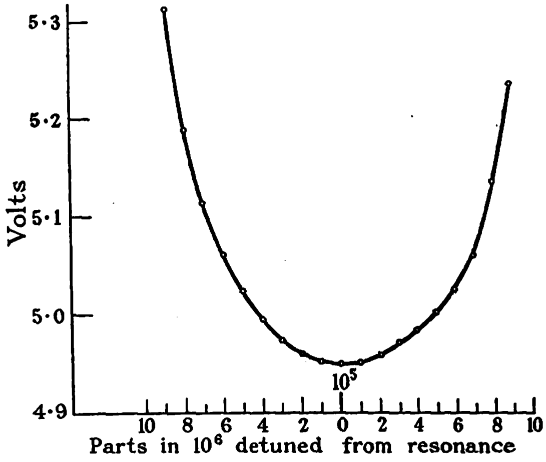

FIG. 10.

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[*] "The Design and Distribution of Wireless Broadcasting Stations for a National Service," *Journal I.E.E.*, 1928, vol. 66, p. 501.

greatly improved by further research, one suggestion being the employment of a high-frequency amplifier between the resonator circuit and the valve voltmeters. It has been found necessary to postpone these experiments owing to the need for the developments discussed in Part (2).

The fork-driven multivibrator had proved to be such a useful piece of apparatus that the possibility of applying the quartz standard to a similar scheme presented an irresistible attraction. Also a source of precise forced oscillations was required for general investigational work. It appeared that a great deal of research work would be needed to enable the resonator system to be used with the accuracy which, it was felt, would be called for in the near future. A wide-range low-frequency oscillator was also necessary for interpolation between the 10-kilocycle harmonics.

Further consideration of the resonator was therefore postponed and the work which is discussed below was undertaken, with the intention of returning to the reference standard in the near future.

PART (2).

DESIDERATA OF THE DRIVE CIRCUIT.

(1) Experience has shown that any attempt to introduce retroaction produces a tendency to frequency instability, therefore the circuit should be capable of oscillating with no retroaction with the exception of that inherent in it.

(2) The controlling member should have a low temperature-coefficient.

(3) The coefficient of coupling between the mechanical component and the valve system should be of as low a value as possible.

In applying these principles, (1) is met by a tuned anode circuit with the crystal connected between the grid and the filament. Oscillations are more readily produced by the grid-anode connection but they are feebler and less stable than those produced by the alternative connection. (2) is ensured by the use of bars employing the longitudinal mode of vibration. This gives a temperature coefficient of the order of 2 or 3 parts in 10^6 per degree C. The transverse modes give values of the order of 40 to 70 parts in 10^6. The reason why these latter modes are frequently used is that serviceable oscillators are more easily produced from them than from the longitudinal mode. (3) is met by the use of air-gaps of the order of 1 mm between the crystal and its electrodes. In any case the electrostatic coupling of the crystal is much less than that of magneto-striction, fork, and other such electromagnetically-driven devices.

DEVELOPMENT OF THE DRIVE CIRCUIT.

Preliminary work showed that very good samples of this type of crystal would produce oscillations under the stipulated conditions provided that no air-gap was used, but that they failed to function when nodally mounted with an air-gap. Utilizing the experience gained on the resonators, some of these crystals were mounted in a desiccating chamber and the best of them were found to oscillate. One of these was used in a sealed tube for the preliminary development work, and the only drawbacks noted in its behaviour were a failure to oscillate below 10° C. and the fact that it would not operate with a grid-leak and had perforce to be used under free grid conditions. At a later stage the evacuated type was employed and these limitations disappeared. To eliminate the possibility of frequency variation due to grid contact-potential, bombarded, non-"gettered" valves of the L.S.5 class have been used in all the later stages of the work. The drive circuit is given in Fig. 11 and presents no novel features.

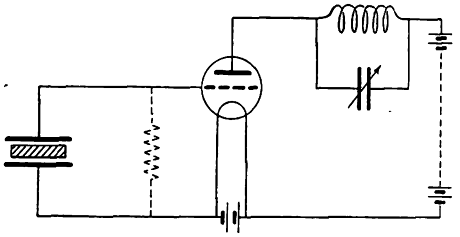

FIG. 11.

FREQUENCY STABILITY OF THE DRIVE SYSTEM.

The reference standard used for the majority of the work is a valve-maintained tuning fork. An N.P.L. Certificate gives its period, 1 kilocycle per sec., to the seventh figure, the last being "dropped," and a zero temperature-coefficient over the working range of temperature. It is considered that the former can be relied upon to 3 parts in 10^6, and such accuracy met the needs of the preliminary investigations. The method adopted for referring the drive output to the reference standard was as follows:—

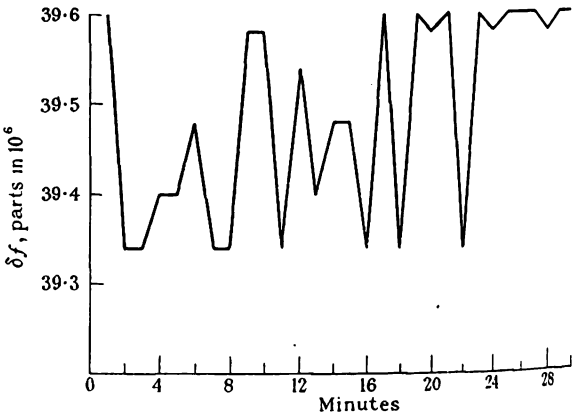

FIG. 12.

The fork was used to drive a 1-kilocycle multivibrator circuit through a biased coupling-valve. The 50th harmonic of this was beat against the drive circuit and the resultant beats were counted over a definite period of time.

Determinations of the period of such systems as these are usually effected by reference to a time standard by means of some form of synchronous motor. The method has the advantage that the comparison may be made with a fundamental time standard, but it suffers from two disabilities:—(*a*) the intervention of the synchronous motor has the effect of masking any short-period variations which may be present, and (*b*) a run covering a number of hours, and in some cases several days, is necessary to obtain a determination to within 1 part in 10^6. The method outlined above enables a determination to 1 part in 10^6 to be obtained in time periods of the order of 1 minute, for in this time (3×10^6) cycles are completed and any difference between the crystal circuit and the 50th harmonic of the fork appears as beats. Extended experience has shown that observations to 1 in (3×10^6) of beats of the order 3 per second are easily possible by taking counts over periods of 1 minute. To produce an error of this order requires an uncertainty in the chronometer reading of 0·4 sec. in 1 minute. In general, 200 beats are timed.

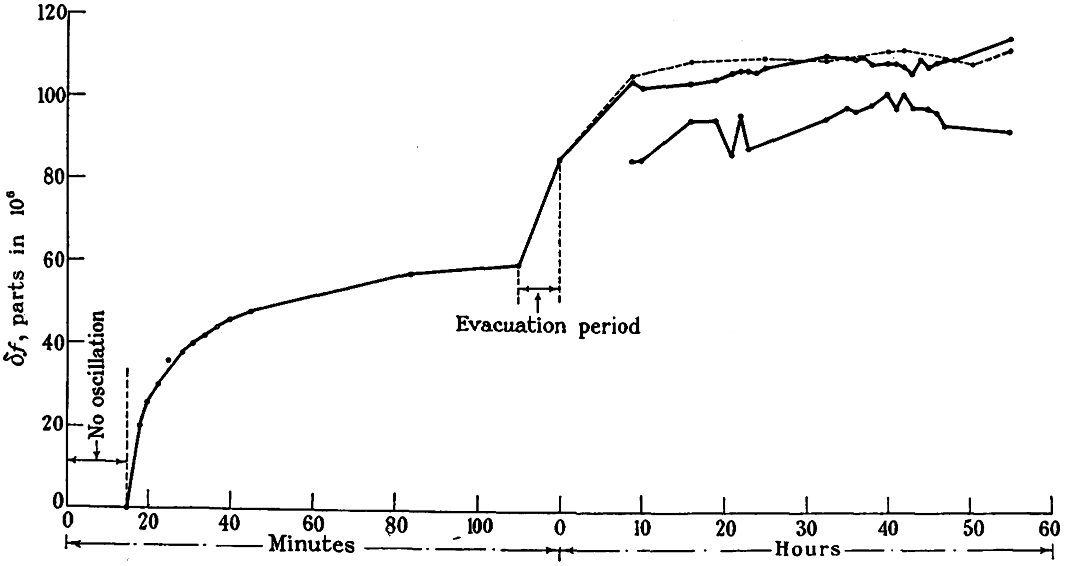

FIG. 13.

This method also permits observation of short-period variation, and the author believes that these are the first records of this nature. The crystal oscillator is adjusted by means of the anode condenser and other controllable variables so as to obtain a round number of beats in 1 minute, say 100. The count is carried on continuously and it is only necessary to note and record the variation of the chronometer seconds-hand from the 60-second mark on the completion of each hundred beats. Here again, possible errors introduced by slight inaccuracies of the chronometer reading are much less than the uncertainties due to the reference standard. An instance of an observation of this character is given in Fig. 12.

The method suffers from two defects:—(*a*) the reference is not direct to a fundamental time-standard, and (*b*) it is only applicable where the system under observation is sufficiently close to the standard to produce beats of the order 4 per second, or less. This latter condition has in all cases been easily met in these investigations.

The first observations were carried out on the non-evacuated crystal, using a free grid circuit. It was promptly found that the frequency was varying in an erratic manner and no consistent readings could be obtained. This condition was explained by reference to some work * carried out by the author's colleagues on the operation of valves under free grid conditions. The remedy consisted in bonding and earthing all free metal parts in the vicinity of the grid circuit. A permanent frequency-change of about 25 parts in 10^6 was noted and the system was quite stable.

This system was in use for some weeks and no frequency change greater than 5 parts in 10^6 was noted. Indeed, when a biased-grid system was adopted later it was found to be a most difficult matter to obtain an accuracy of this order. The reason is not far to seek. The free-grid system operates in such a manner that no grid current is flowing and there is a very close relation between grid current and frequency change. It is

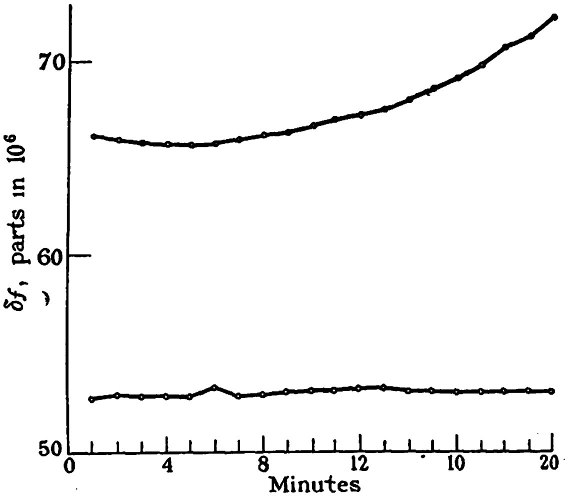

FIG. 14.

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* P. L. WOSTEAR and R. H. BILLINGSLEY: "Improvements Relating to Thermionic Valve Circuits," British Patent No. 12880—1926.

considered that such a system, properly screened, would be suitable for further investigation. It was felt, however, that the conventional biased-grid would prove more generally acceptable. In the meantime the system had been sufficiently improved to operate with grid bias.

The lower curve of Fig. 13 and the upper curve of Fig. 14 show some observations on this biased system. Fig. 13 shows a number of intermittent readings taken over 50 hours. The general upward drift is largely accounted for by temperature. Rapid fluctuations, however, are present. Fig. 14, upper curve, shows the results of a 20-minute run under continuous observation, and one of the larger excursions from the mean value shown in Fig. 13 is evidently taking place. The magnitude of these changes caused surprise and the system seemed definitely inferior to the free-grid system in previous use. As at the time no plausible reason could be offered for these fluctuations, an investigation of all the variables under control was undertaken.

FREQUENCY-CHANGES DUE TO THE CONTROLLABLE VARIABLES.

(*a*) *Anode Variable-Condenser.*—Fig. 15, top curve, gives a typical example; the other two curves show grid and anode currents. This demonstrates that while the frequency is by no means independent of the condenser setting, it is practically independent of any small fortuitous capacity-variation for a given setting. An appreciable range of capacity gives $df/dC = 0$, but unfortunately this coincides with minimum output conditions. Maximum output occurs, just before oscillations cease, at 400 $\mu\mu$F. The form of the curve obtained agrees very well with that which might be deduced from the theory outlined in Part (1), this curve being a part of one of the boundary curves in the region of instability in Fig. 1. In this instance, if a similar crystal were also connected to the grid and anode, on the extinction of the oscillation f_1 at the point of maximum capacity a new frequency f_2 would develop. These points, however, have no bearing on the question of frequency stability.

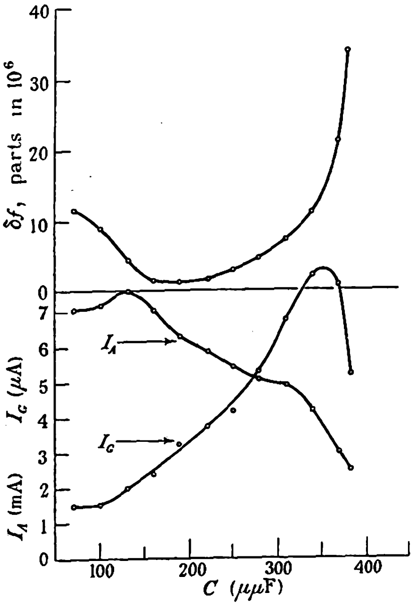

FIG. 15.

(*b*) *Anode-Inductance Variation.*—Table 1 shows that the system is independent of any possible normal variation of this nominally fixed component.

TABLE 1.

Inductance	Time for 100 beats	Variation of frequency from 5×10^4 cycles per sec.
μH	secs.	parts in 10^6
27 000	33·4	59·9
12 400	30·0	66·6
35 000	33·8	59·2

(*c*) *Anode-Potential Variation.*—In Fig. 16 a working range of 2·1 to 1·8 volts per cell has been assumed as the possible maximum voltage-variation. This gives a variation of 105 to 90 volts for a nominal 100-volt accumulator battery, and the frequency variation for this is 7 parts in 10^7. Fig. 17 is a similar curve for the standard fork which shows a frequency variation of 1 in 10^5, a ratio of 1: 14 in favour of the crystal.

(*d*) *Filament-Potential Variation.*—Figs. 18 and 19 show the variation of frequency with E_f for the crystal and fork respectively. In this case the comparison is even more in favour of the crystal, the ratio being 1: 70. Over the working range of voltage the frequency change for the quartz is 1 part in 10^7, and for all practical purposes this is negligible.

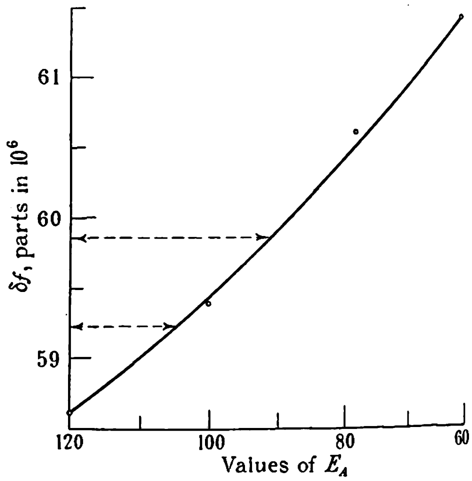

FIG. 16.

(*e*) *Grid-Potential Variation.*—This was effected by changing the value of the grid-leak, or by connecting a cell in series with it. Table 2 gives the frequency values obtained. In practice, such changes in the grid conditions are unlikely to develop.

An analysis of these results, while illuminating in themselves, gave no clear guidance as to the cause of the variation shown in the lower curve of Fig. 13.

General observation, however, gave rise to the following considerations:—

Whilst no definite proof was forthcoming that the changes were not due to the crystal or its mount, it was felt, particularly as the resonators which had been under observation for nearly three years showed no sign of this condition, that the valve circuit was more likely to be the seat of the trouble. This conclusion may appear somewhat weak when it has been shown that the fork, which is presumably free from these variations, is much more susceptible to circuital variations. The inference is that the transfer of the frequency of operation from 1 to 50 kilocycles per sec. is responsible for the greater frequency instability. Also, occasional variations of greater magnitude than those shown had been noted. These were accompanied by an increase of the anode current and were associated with extreme values of atmospheric humidity. The deduction made from this was that the stray capacity-resistances such as the valve holder and cap, the two-pin connector of the crystal mount, and the grid-leak mount were varying with atmospheric conditions. These were in shunt with, and affected, the valve input-impedance and, in turn, the resultant frequency.

TABLE 2.

Conditions	Time for 100 beats	Variation of frequency from 5×10^4 cycles per sec.
	secs.	parts in 10^6
Grid-leak A = 3MΩ; no bias ..	33·4	59·9
Grid-leak A = 3MΩ; − 1·5 V bias	32·5	61·6
Grid-leak A = 3MΩ; + 1·5 V bias	32·2	62·1
Grid-leak B = 2MΩ; + 1·5 V bias	31·0	64·5
Grid-leak B = 2MΩ; − 1·5 V bias	32·4	61·8
Free grid	34·0	58·9
Grid-leak C = 1MΩ; no bias ..	34·5	58·0

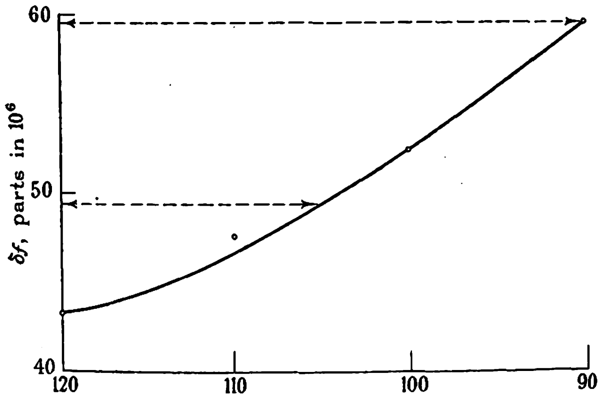

FIG. 17.

This deduction was confirmed during the development of the laboratory standard to be described later. In this instance the circuit was as described. A second circuit had the crystal and grid-leak in a desiccating chamber at normal air-pressure. Steps had been taken to reduce to a minimum the amount of dielectric in the remainder of the grid circuit. The circuits in other respects were identical and were exposed to normal atmospheric conditions. The evacuated crystal was, however, much the better oscillator. On one occasion during a spell of extreme humidity the evacuated crystal refused to oscillate, while the inferior one in the desiccator oscillated normally. After drying the mount of the evacuated crystal oscillations were obtained with a very high value of anode current and a large frequency change. As conditions improved, the input current and the frequency gradually returned to normal. The other circuit remained constant throughout. This experience was checked by reproducing the conditions artificially. The grid-leak and valve holder, etc., were breathed upon so as to produce a film of moisture and the resultant changes in frequency and anode current were noted. Two tests are recorded in Table 3. The frequency-changes of 30 and 36 parts in 10^6, due to this

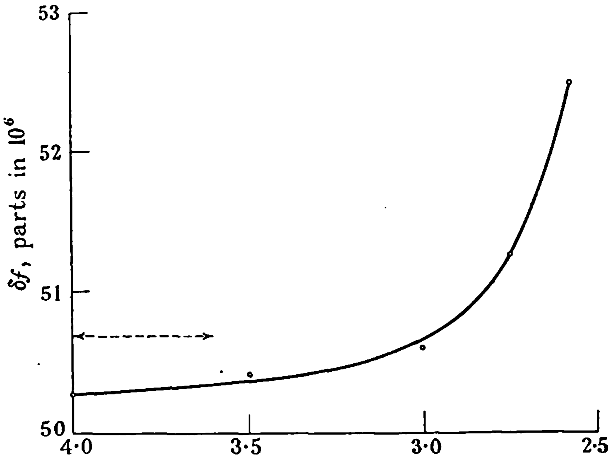

FIG. 18.

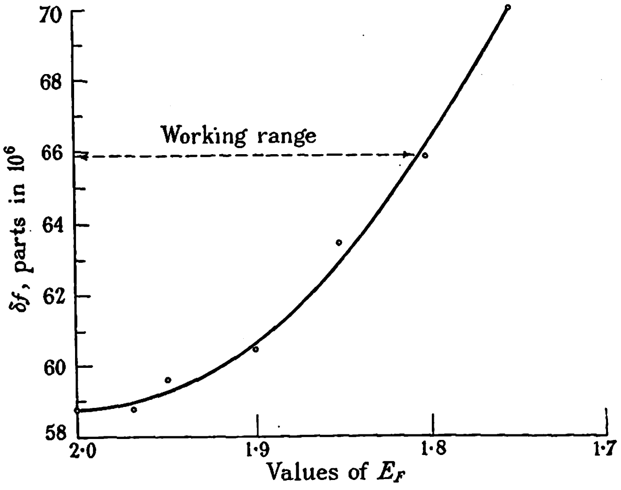

FIG. 19.

cause, are more than sufficient to account for those previously noted. As the deposited moisture was insufficient to stop oscillations and, indeed, to cause the anode current to reach values which had been observed, it can be stated that this treatment is not drastic and does not exceed the conditions produced by normal atmospheric variations. It must also be pointed out that this phenomenon is quite distinct from that produced by humidity on the crystal itself. It is purely a circuital reaction. It is proposed to investigate the matter quantitatively under controlled humidity conditions, paying particular attention to the grid-current variations. Meanwhile, it was clear that definite precautions would have to be taken in the design, lay-out and mounting of the grid circuit of the valve. Alternatively it would be essential to control the degree of humidity of the whole circuit.

The first condition was partly met by the employment of a new design of L.S.5-type valve, the L.S.5.D. This has the grid connection made to a terminal on the glass envelope, thus eliminating the valve holder and cap from the grid circuit. Also, advantage was taken of some features in the design of the laboratory standard which will now be described.

TABLE 3.

Conditions	Capacity	I_g	I_a	Time for 200 beats	Variation of frequency from 5×10^4 cycles per sec.	Difference
	μμF	mA	mA	secs.	parts in 10^6	parts in 10^6
Normal values for damp weather	145	2·75	7·0	68·4	58·6	0
After breathing on grid circuit	145	3·25	8·5	45	88·8	+30·2
10 minutes later	145	2·5	7·0	66	60·4	+ 1·8
Normal values for damp weather	200	3·5	6·0	65	61·6	0
After breathing on grid circuit	200	2·5	8·2	41	97·6	+36·0
After fanning grid circuit for 2 minutes ..	200	3·5	6·0	64	62·4	+ 0·8

THE LABORATORY STANDARD.

The limit of accuracy to which a crystal, mounted as described, can be adjusted has been found in practice to be of the order of 1 part in 10^4. Also, when once the envelope has been evacuated no further adjustment is possible. The small adjustment of frequency available in the controllable variables is of the order of 1 part in 10^5 and power considerations limit the full use of this. This is satisfactory enough for the purpose for which the instrument was designed—that of a portable standard. It is, however, desirable to eliminate the correction factor for departure from its nominal value when the standard is capable of being adjusted to an accuracy better than 1 in 10^6. To meet this condition, the following controls are available for final adjustment of the frequency:—(*a*) air pressure, (*b*) electrode air-gap, (*c*) anode condenser, (*d*) temperature, (*e*) anode and filament potentials, (*f*) humidity. It was decided to provide for the use of all these.

The design includes a bell jar and desiccator with Fleuss pump, vacuum gauges and an ether-type thermostat. The crystal is mounted directly on the fused-quartz insulating washer of the bell jar with the grid-leak connected to the same terminal inside. The lead from this terminal goes direct to the grid connection on the glass envelope of the L.S.5.D valve. The only dielectric materials in the grid circuit are the valve envelope, the fused-quartz insulating washer, the glass mounting of the grid-leak and the fused-quartz distance pieces of the crystal mount. Of these, the outside of the insulating quartz washer and the valve envelope are the only dielectrics which are subject to normal atmospheric conditions.

The first run on this equipment is shown in Fig. 13 (upper curve). The curve clearly illustrates the effect of humidity upon the frequency of the crystal itself. No oscillations were obtained until 15 minutes after closing the bell jar, and this was not evacuated until the frequency was approaching a steady value. The observed change due to the action of the desiccator is 60 parts in 10^6; to this must be added the change which took place during the period when there were no oscillations. From previous experience on resonators it can be stated that the total change is usually greater than 100 parts in 10^6. It is desired to emphasize this point as the changes due to this variable are, apart from the effects of frictional resistance, greater than those from any other single source. Most current literature makes no reference to this, and it is not understood how the accuracies quoted have been obtained. The change due to the reduction of air pressure to 0·25 in. of mercury is 10 parts in 10^6.

The continuation of this curve gives the readings for the subsequent 60 hours. The large drift of the first 10 hours is due to the further absorption of residual water-vapour by the desiccator. The early runs were taken primarily to investigate the short-period variables, and the thermostatic control was not employed. The remainder of the readings have therefore to be corrected for temperature. The dotted curve shows the corrected readings, and it will be seen that the departure from the mean value is of the order of 2 parts in 10^6. With thermostatic control this figure would be improved, as the room temperatures were used for correction and the crystal lags considerably on these.

The lower curve gives similar readings for the portable-type standard. Also, Fig. 14 gives a continuous-count 20-minute run in the two cases, with observations at intervals of 1 minute. The upper curve is interesting as it is apparent that it coincides with a point of maximum departure from the mean, the early portion of the curve just indicating the change from a fall to a rise. The lower curve shows the laboratory standard run and Fig. 12 shows a further run of the same type plotted to a very open scale to permit an appreciation of the observational errors. The data are supplied in Table 4, where, under col. 2, the readings of the chronometer seconds-hand for 120 beats are found, each series being taken consecutively. Col. 3 gives the time in seconds for each of these, col. 4 gives the difference in frequency from 5×10^4 cycles per second, and col. 5 shows the same difference expressed as the number of parts in 10^6.

It is estimated that the maximum probable error in reading the chronometer is 0·4 sec. From the table it is seen that this will introduce an error of 0·2 in 10^6. Fig. 12 shows that the maximum departure from the mean value is 0·13 in 10^6. These deviations are, therefore, probably chiefly observational errors. Over the 30 minutes shown, and dismissing the improbable contingency that they are varying at the same rate and in the same direction, the fork and crystal are constant to a value of the order of 1 part in 10^7.

TABLE 4.

Time 1	Reading of chronometer for 120 beats 2	Time for 120 beats 3	Variation of frequency from 5×10^4 cycles per sec. 4	Variation of frequency from 5×10^4 cycles per sec. 5
minutes	secs.	secs.	cycles per sec.	parts in 10^6
1	60·6	60·6	1·98	39·6
2	61·6	61·0	1·967	39·34
3	62·6	61·0	1·967	39·34
4	63·5	60·9	1·97	39·4
5	64·4	60·9	1·97	39·4
6	65·2	60·8	1·974	39·48
7	66·2	61·0	1·967	39·34
8	67·2	61·0	1·967	39·34
9	68·0	60·8	1·974	39·48
10	68·8	60·8	1·974	39·48
11	69·8	61·0	1·967	39·34
12	70·5	60·7	1·977	39·54
13	71·4	60·9	1·97	39·4
14	72·0	60·6	1·98	39·6
15	72·8	60·8	1·974	39·48
16	73·8	61·0	1·967	39·34
17	74·4	60·6	1·98	39·6
18	75·4	61·0	1·967	39·34
19	76·0	60·6	1·98	39·6
20	76·8	60·8	1·974	39·48
21	77·4	60·6	1·98	39·6
22	78·4	61·0	1·967	39·34
23	79·0	60·6	1·98	39·6
24	79·8	60·8	1·974	39·48
25	80·4	60·6	1·98	39·6
26	81·0	60·6	1·98	39·6
27	81·6	60·6	1·98	39·6
28	82·4	60·8	1·974	39·48
29	83·0	60·6	1·98	39·6
30	83·6	60·6	1·98	39·6

From these curves it may safely be assumed that the frequency instability characteristic of the portable type is absent in the laboratory type. A number of observations on the latter, covering some 6 weeks, gave variations of the order of 3 parts in 10^6. This is the degree of uncertainty of the reference standard; thus it appeared that the accuracy aimed at (of the order of 1 in 10^6) was probably attained. Also the data were available for the precautions to be taken to obtain a stability of the same order for the portable type. The work of developing the subsidiary apparatus was therefore undertaken.

THE CRYSTAL-CONTROLLED HIGH-FREQUENCY MULTIVIBRATOR.

The features of the well-tried Dye fork-driven multivibrator * indicated the general lines of development. In the first place, the transfer of the operating frequency from 1 to 50 kilocycles per sec. permits the production of the higher frequencies in one step. A multivibrator for 50 kilocycles per sec. was designed and built, the only differences from the Dye type being the different value of anode impedances necessary to give 50 kilocycles per sec. and the use of a commercial-type filament rheostat. This is possible because there is ample power in the drive to exercise a wide range of control. There is no need to tune this circuit by an accurate adjustment of the filament potential. The circuit used is as in Fig. 20. For accuracies of 1 in 10 000 the coupling valve may be omitted, but for higher accuracy it should be included. The range of this circuit has not been fully explored at the high-frequency end, but no difficulty has been experienced in working down to the 120th harmonic, i.e. 6 000 kilocycles per sec. A well-constructed open-scale calibrated oscillator is used for harmonic identification. This controlled high-frequency multivibrator was put into service and it proved to be quite satisfactory, but the need for a low-frequency controlled source for interpolation and other purposes was felt.

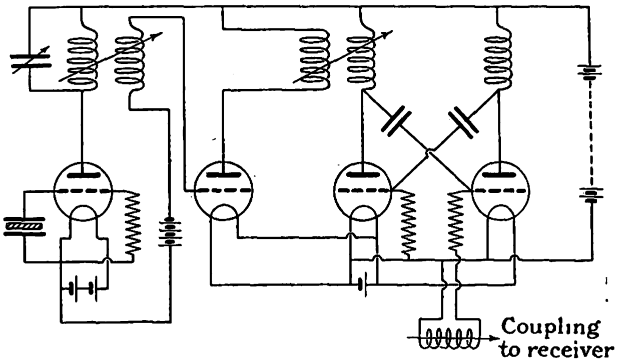

FIG. 20.

A further development of this high-frequency multivibrator, however, is needed. Transmission engineers are faced with the fact that current practice of control

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* "A Self-contained Standard Harmonic Wave-meter," *Philosophical Transactions of the Royal Society*, 1924, vol. 224, p. 259.

by transverse oscillators and stable master-drive circuits is not meeting the present needs in the matter of precision and frequency stability. Under ideal circumstances it is possible to produce short-wave transverse oscillators of a frequency within 1 part in 10 000 of the nominal value, provided that temperature, circuital conditions and the crystal mount are all strictly specified. To reproduce the frequency within these limits in a power circuit has proved to be an exceedingly difficult matter. It appears that it will be necessary to employ something in the nature of a standard for the frequency control. This has actually been put into practice at the long-wave G.P.O. station at Rugby. It is becoming an urgent necessity to develop the drive of the multivibrator so that it can be utilized in the higher-frequency bands, of the order of 3×10^5, with its present accuracy when used at 5×10^4 cycles per sec. This will permit the harmonics at extremely high frequencies to be used as " drives " of high precision and stability.

THE QUARTZ-CONTROLLED LOW-FREQUENCY MULTIVIBRATOR.

The idea was conceived of controlling a source of relaxation oscillations of the type produced by the Abraham-Bloch multivibrator circuit by impulsing a harmonic with a forced oscillation. This was tried by injecting an e.m.f. from the crystal-controlled circuit (frequency 50 kilocycles per sec.) into a multivibrator of frequency 1 kilocycle per sec., i.e. impulsing the 50th harmonic. This experiment was undertaken somewhat casually and, to the author's surprise, evidence of perfect control was obvious from the first. No difficulty was experienced in combining this with the high-frequency multivibrator with the drive exercising simultaneous controls. The circuit for this is given in Fig. 21.

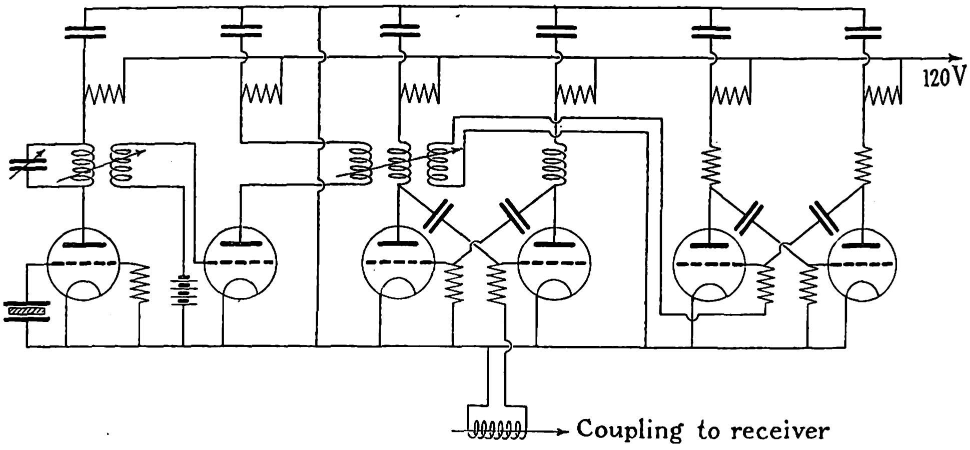

FIG. 21.

This circuit has all the essential features of the standard multivibrator, i.e. a range of 1 to 6 000 kilocycles per second in steps of 1 kilocycle per second, with the addition of the characteristic partial harmonic effects. A minor property is, however, not present. The power to use the 19th, 20th and 21st harmonics of the low-frequency side to control the high frequencies is not available. This property, however, reappears in a more useful form in the centre-drive development. Apart from the 1 kilocycle per sec. of the fundamental of the low-frequency side a number of others on either side of this value are obtainable by adjustment of the coupling, or of the variable condenser. These are the fundamentals obtained by impulsing successive harmonics. Thirteen of these are available in steps as shown in Table 5. These are

$$\frac{f}{n-6}\cdots\frac{f}{n-1}\cdots\frac{f}{n},\ \frac{f}{n+1}\cdots\frac{f}{n+6}$$

where f is the control frequency and n the normal impulsed harmonic frequency, in this case 5×10^4 and 50 cycles per sec. respectively.

TABLE 5.

Harmonic order	Output frequency
	kilocycles per sec.
44	1·135
45	1·111
46	1·086
47	1·063
48	1·041
49	1·02
50	1·0
51	0·981
52	0·962
53	0·943
54	0·926
55	0·909
56	0·983

An interesting proposal to take advantage of this property has been made by Mr. Williams of the Air Ministry Research Establishment at South Farnborough. He suggests the use of a quartz drive at 50 000 cycles per sec. controlling two multivibrators at frequencies of f/n and $f/(n \pm 1)$, where $n = 100$. The outputs of these multivibrators will appear as 500 and 495 or 505 cycles per sec., respectively. These are combined and the resultant beats of the order of 5 per sec. are counted electrically over a period of time by taking photographic records at definite time-intervals. A simple and direct reference to the time standard is thus effected without the intervention of the usual phonic motor or similar device.

This application of the principle of frequency division was made independently and had been in use some weeks when a paper describing a similar application arrived in this country.* This paper describes the control of a multivibrator of frequency 1 kilocycle per sec. by a crystal drive (frequency 50 kilocycles per sec.). The authors state that, although it is possible to exercise control in one step, they actually use two stages. In the present case this has not been found necessary. Four complete sets are in operation, one of which has been in continuous service for over a year, and in all cases complete control has been obtained. The abovementioned paper gives full evidence of the accuracy of control provided.

The development of this system of controlled precision low-frequency oscillations offers considerable possibilities. No reason is seen why oscillations of a frequency approaching 1 cycle per sec. may not be produced. A direct reference to the ultimate time standard would thus be possible. Indeed, venturing into the debatable realm of prophecy, this may be the germ of the time standard of the future.

Another variant of this method of control is under investigation. It has been found possible to exercise effective control by injecting into a multivibrator forced oscillations having a frequency of $1/n$ times the approximate period of the multivibrator. Thus a 1 kilocycle-per-sec. fork was used to control a 10 kilocycle-per-sec. multivibrator. It is hoped to utilize this principle to refer back to the time standard by impulsing a neon-tube circuit of, say, 10 cycles per sec. from a standard clock and using this in turn to control a 1 kilocycle-per-sec. multivibrator.

It is possible that in the case quoted above the 10th harmonic of the fork is the controlling factor.

TREND OF FUTURE DEVELOPMENTS.

While the equipment thus described more than meets the requirements originally laid down, i.e. the calibration and maintenance of a sub-standard wavemeter to 1 part in 10^4, it is fully realized that this is not the time to call a halt. The question of the behaviour of the quartz standard over relatively long periods of time and, in particular, the question of ageing will require years of observation with equipment of the highest precision. This will necessitate the development of improved methods of reference to the time standards. Also the question of the adequacy of the time standard as the final arbiter of frequency may at any time be questioned.

The experience gained as to the behaviour of the valve and its tendency to develop frequency instability at medium frequencies calls for further investigation, and this is actively proceeding. In this direction it is proposed to lower the frequency to 25 kilocycles per sec.; this represents the limit to which the natural quartz crystal can be obtained and worked. It is to be hoped that the production of large synthetic quartz crystals will not prove such a difficult proposition as the somewhat similar case of the artificial diamond. It is, however, felt that the true solution and urgent need is the development of the resonator reference-standard and its associated equipment to accuracies of the order 1 in 10^6 or, if possible, 1 in 10^7.

The author's thanks are due to the Air Ministry for permission to publish this paper. He also desires to express indebtedness to the inspiration of Dr. Dye's classic work already referred to. Part (1) of the paper is obviously a direct practical development of this work. Acknowledgments are due to Messrs. H. W. Sullivan for the loan of the standard valve-maintained fork. Valuable advice has been received from the author's colleagues; in particular from Mr. B. Williams, B.Sc., of the Air Ministry research staff at South Farnborough, and from Mr. R. H. Billingsley, without whose help in checking the experimental work and in the preparation of the paper and drawings a private research of this nature could not have been undertaken in the limited time available.

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* L. M. HULL and J. K. CLAPP: "A Convenient Method for Referring Secondary Frequency Standards to a Standard Time Interval," *Proceedings of the Institute of Radio Engineers*, 1929, vol. 17, p. 252.

DISCUSSION BEFORE THE WIRELESS SECTION ON THE PAPERS BY MR. LUCAS (SEE PAGE 855) AND MR. J. E. P. VIGOUREUX (SEE PAGE 265), 5TH MARCH, 1930.

Air Commodore A. D. Warrington-Morris: With regard to the paper by Mr. Lucas, there is no doubt that, with the great increase in wireless communication and the consequent necessity for as many wave channels as possible, the two most important problems which concern wireless engineers at the present time are those of the maintenance of a constant frequency and the improvement of frequency standards. The author has been responsible for inspecting wavemeters for the Royal Air Force, and as a result of those duties he has realized the desirability of a high standard of accuracy. The work described in the paper has been done without the use of laboratory facilities. Table 3, for instance, shows that humidity was varied by the simple expedient of breathing on the grid circuit. Some quantitative measurements of humidity would probably be useful in a paper of this sort. So far as aircraft signalling is concerned, the degree of accuracy referred to by the author is not yet so essential as to warrant the provision in an aeroplane of the additional weight, space and complicated apparatus which it necessitates. For point-to-point services, however, especially on the wave-bands settled for fixed stations by the Washington Convention, the greatest possible accuracy is required. The author appears to view with disfavour the use of a quartz control employing a transverse mode, on account of the high temperature-coefficient. I should like to know whether he has any further objections, and whether he can give some information as to the direct use of the longitudinal mode on short waves without frequency multiplication.

Dr. D. W. Dye: Mr. Lucas has produced a frequency standard of a type superior to any other so far designed in this country for frequencies of the order concerned. The problem of transferring them to lower frequencies has been successfully solved in the system devised by Mr. Williams, whereby two neighbouring harmonics are selected and controlled by a multivibrator. That is, in my opinion, a very ingenious arrangement; it is the first of its kind, so far as I know, to be employed in stepping down. It would be somewhat difficult, I think, to keep these systems in step with the crystal over the long periods of time which would be essential in checking absolute frequency measurements against some other time standard, but the system is evidently worthy of further investigation and development. With regard to the mounting of the crystal, in my own work on the subject I soon found that humidity had a considerable effect upon the oscillations, particularly in making the damping large when there was much moisture in the atmosphere. I did not find it difficult to get satisfactory behaviour, without using special precautions. It was found that a bell-jar and desiccating agent in the enclosure was sufficient to keep the specimens in a dry condition while being investigated, and to ensure that the results could be reproduced from time to time. With regard to mounting, I also have supported the crystal at a nodal point of the longitudinal mode of vibration, but not in quite the same way as that adopted by Mr. Lucas; mine was balanced as on a knife-edge on the narrow edge of the crystal. Fig. 5 led me to think that there was something unusual in the values given, but the author's explanation of the errors in scaling explains the apparently remarkable results. Concerning the use of crevasses, this method is most valuable for determining the damping and elucidating the equivalent networks for oscillators or resonators, but it is not the most suitable for determining or setting a source to the precise frequency of resonance. If the resonator is connected to a small condenser (of, say, 300 $\mu\mu$F) and a practically constant e.m.f. is applied to the combination by the use of a coil of small inductance connected to the condenser, the current in the inductance as a function of frequency is as shown in Fig. A. As the frequency is increased, the current rises to a maximum, turns sharply and steeply downwards to a minimum and then slowly approaches its original value. The frequency of resonance lies on the steeply falling, nearly straight portion, but is not at the point of intersection of this curve with the datum current for frequencies near, but outside, the region of resonance. The graphical construction corre-

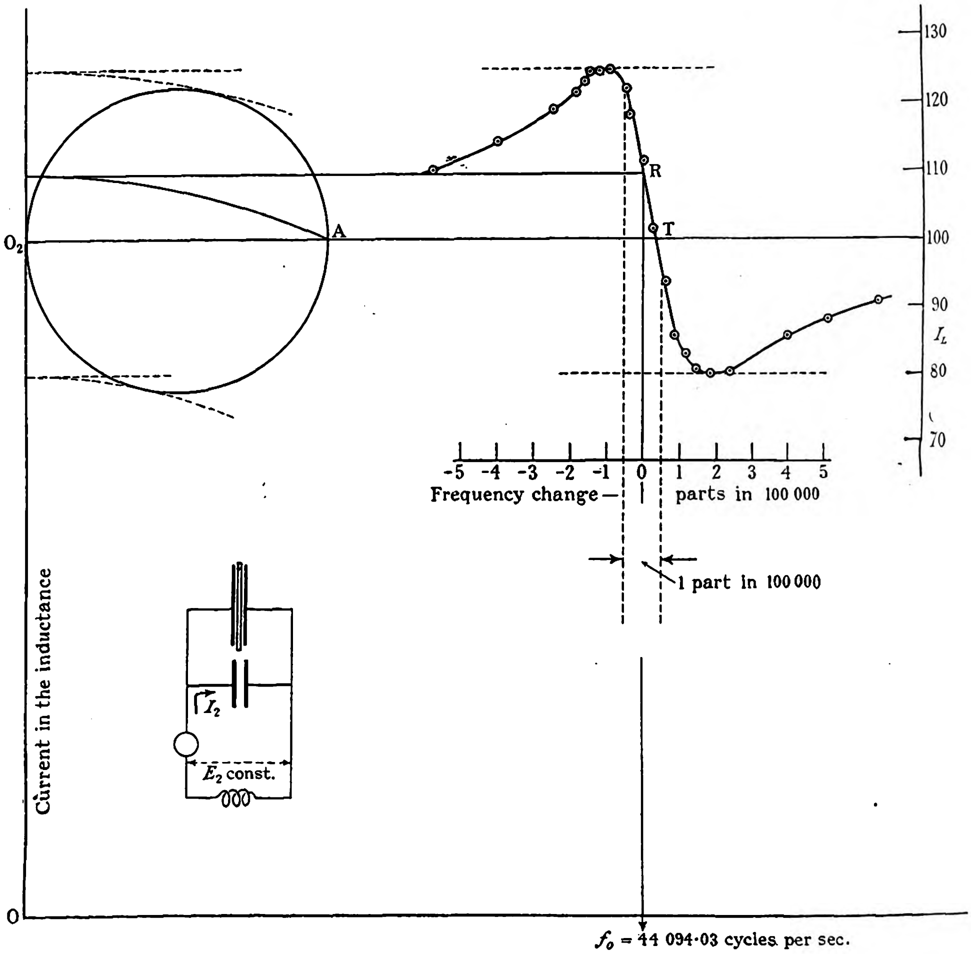

Fig. A.

sponding to this case is very simple and is shown on the left of the curve. A circle is drawn of diameter equal to $(\theta_1 - \theta_2)$, where θ_1 and θ_2 are the maximum and minimum currents respectively. This circle has its centre at the height of the current value just outside resonance. The vertical tangent OO_2 is drawn intersecting the abscissa scale at 0. Any point on the curve of current is transferred to the circle by drawing an arc, of radius equal to the current at the point in question, from the centre O. The intersection of this arc on the circle gives the corresponding point on it. The resonance point on the circle is at A and the converse process of transferring this to the current curve is obvious as shown, giving the point R on the curve. The above construction assumes that the air condenser used has no losses. For the mere purpose of setting a frequency, it is not necessary to carry out the graphical construction. If θ_1 and θ_2 are the maximum and minimum currents, the current at which resonance occurs is given by $\theta_r^2 = \theta_1^2 + \theta_2^2 - \theta_1\theta_2$. The resonant frequency may then be found directly by adjusting it until this current is obtained. It is convenient to have a square-law scale on the galvanometer for the purpose. The two vertical dotted lines show a belt of frequency of width equal to 10 parts in a million. A change of deflection of about 30 cm on a galvanometer scale is given for this change. A setting to about 1 part in 10 million can be made if such extreme accuracy is desired. With regard to the frequency changes given in Mr. Lucas's paper, it would be desirable to indicate on the curves the direction in which the change in frequency occurred; this can only be inferred from the text. I think that in Fig. 9 there must be an error either in the scale of frequency changes observed on the broadcast station 2LO, or in the frequency assigned to the base line. The latter is marked as 10 kilocycles per sec., but the range of frequency is from $+ 0{\cdot}5$ to $- 0{\cdot}5$ kilocycle per sec. This means that the variations were of the order of 2 or 3 per cent, which is very unlikely. I wish now to refer to the frequency-changes dealt with in Part (2) of the paper. Mr. Lucas states, when giving the desiderata of the drive circuit, that experience has shown that any attempt to introduce retroaction produces a tendency to frequency instability; and that the circuit should therefore be capable of oscillating without any retroaction apart from that inherent in it. This seems to me to make a distinction without a difference and, although the meaning is clear, I am not certain that the right conclusion has been drawn. It might be advantageous to make use of the good-quality screen-grid valves now available, and then to introduce the retroaction independently, but that is a matter of opinion. I agree with the other two desiderata given, although the statement that the electrostatic coupling of the crystal is much less than that of magneto-striction, fork, and other such electromagnetically driven devices, may require modification. As a general statement it is probably true, but it must not be supposed that finality has been reached in regard to other forms of oscillator and that these could not be designed to have a coupling as small as, or smaller than, that of the quartz oscillator. The question of the small magnitudes of the damping and of the necessary coupling determines the variability of the whole system with regard to the external conditions applied. In Fig. 3 it would be interesting if another curve, starting at the instant of switching on, could be given. My experience with the transverse form of oscillator shows that the energy absorbed in the oscillator itself, although very small, does raise the temperature by 2 degrees or more above that of the electrodes, in the course of half an hour. This causes a drift in frequency which cannot be overcome by any temperature control, because it occurs inside the oscillator itself. As a result of the use of the thin longitudinal bars, the effect might be worse, but the temperature coefficient would be smaller. Thus, if an anode battery or other external factor varies, besides the possibility of a small instantaneous change, there will inevitably be a drift due to the change in the energy in the oscillations of the crystal. It would be interesting to have some figures on this point. Measurements of the variation of frequency due to a small condenser placed across either the grid-anode or grid-filament of the valve would also be welcome. Considerable variations do occur from these causes and, as Mr. Vigoureux's paper shows, frequency variations of 25 to 30 parts in a million are produced by changes in capacity of a few micro-microfarads. These figures apply to higher frequencies, and I assume that the variations would be smaller for a low-frequency oscillator. Mr. Lucas criticizes somewhat adversely the tuning fork which he employed, in which large frequency variations occurred with changes in the circuit conditions, notably in the filament voltage. These variations are much larger than those of the forks which I have used. I have not investigated the forks manufactured by Messrs. H. W. Sullivan, although they were manufactured more or less to one of my own designs. By means of a new magnetic system on the forks I have been able to reduce all these errors to such a small magnitude that a variation of 30 per cent in the anode voltage produces a frequency change of less than 1 part in a million. A change of 10 per cent in filament voltage also produces a frequency change of less than 1 part in a million.

Mr. C. O. Browne: I notice that Mr. Lucas mounts his quartz resonator by means of two pieces of cork situated at the centre of the crystal, presumably at the ends of the electric axis. Can he give any information as to the effect of mounting the crystal in the same way but with the cork at the sides of the crystal? As described in his paper, the resonator is certainly held at a nodal point of mechanical displacement for the fundamental longitudinal mode, but it is also supported at an antinode for vibrations due to the inverse piezo-electric effect. With reference to the curves in Fig. 15, I notice that changes in the anode-condenser setting have been plotted against the resultant changes in frequency. I would suggest that such errors might perhaps be eliminated by substituting a pure resistance for the inductance-capacity circuit connected to the anode of the valve. It is well known that a crystal can be made to oscillate with a resistance only in the anode circuit. If Mr. Lucas has already tried this arrangement, will he state whether the errors due to the resistance are greater than those due to the inductance and condenser combined?

Mr. B. Williams: The need for deriving the fundamental frequency of the crystal from two successive harmonics arose from a necessity for checking certain claims in connection with this apparatus. As there was no equipment of the required accuracy available, this method suggested itself to me as a means of measuring the absolute frequency. As Dr. Dye has pointed out, although this is theoretically a simple process it presents difficulties in practice. The problem of the control of low-frequency multivibrators from high-frequency crystals involves a considerable number of variables, some of which have already been tracked down. It necessitates the maintenance of a constant output from the drive, and of steady anode and filament values in the multivibrators. I am chiefly concerned with the practical side of Mr. Vigoureux's paper and regard it as most useful from the point of view of the production of sub-standard quartz oscillators, to accuracies of the order of 1 in 10 000. From this standpoint, the variables associated with the quartz and the valve which can be utilized for the production of minute changes of frequency without going to the ultimate limit of grinding, are of importance. They are especially so in connection with the design of quartz oscillators *in vacuo* from the corresponding quartz resonators. In connection with the difference between the range of capacities for the two methods of using the crystal (i.e. the plate-grid and grid-filament modes), Mr. Vigoureux gives, in equation (73), an expression for this range in terms of the anode-grid capacity, and states that for the other mode of vibration the two ranges of capacity are in direct proportion to the inter-electrode capacities. By noting the values of these changes of capacity, therefore, it should be possible to measure the grid-anode capacity of a screen-grid valve. For instance, if Mr. Vigoureux's constants for the quartz and the valve are used in equation (73), but instead of $2 \cdot 4\ \mu\mu$F a value of $0 \cdot 005\ \mu\mu$F is substituted for the grid-anode capacity, the actual change of capacity is found to be $2\ \mu\mu$F. Such a quantity is difficult to measure, but it can be measured. On testing this in practice with a screen-grid valve I obtained values at 50 000 cycles per sec. which were considerably larger than this. I should like to ask Mr. Vigoureux whether the equations would hold for very small values of the inter-electrode capacities. Would the method which I have outlined be suitable for checking the capacities of the screen-grid valve?

Mr. J. E. P. Vigoureux: In Mr. Lucas's paper there is a remark about the accuracy to which the response frequency of a quartz resonator can be determined from the crevasse curve. It may be worth mentioning that there is a certain ratio of minimum to maximum ordinate of the curves for which the accuracy of the frequency determination is greatest. The curves are obtained by measuring either the voltage across the tuning circuit or the current in the inductance of the latter, and if the deflection of the recording instrument is plotted against the frequency a curve similar to that shown in Fig. 10 of the paper results. Dr. Dye has pointed out that if the curvature at its lowest point were a maximum, the location of the response frequency would be as accurate as possible. The minimum can always be altered by changing the ratio of capacity to inductance, or by adding to or reducing the resistance of the tuned circuit. If the deflection of the recording instrument be proportional to the square of the current or voltage measured, best conditions for frequency measurement are obtained when the minimum ordinate is half the maximum ordinate.

Mr. H. J. Lucas: I have been unable to do more than concentrate on those portions of Mr. Vigoureux's paper immediately bearing upon the frequency instabilities which I have been investigating. The conclusion at which I arrived—that these were caused by variations of the valve-input impedance with atmospheric humidity—receives certain confirmation. The frequency changes produced by variations in grid conductance and grid-filament capacity, as shown by Mr. Vigoureux, are in the same sense as those produced by humidity variations. The magnitude of the g_2 variations is, however, too small to account for the observed departures and the C_2 variations only partially account for them. I do not find Mr. Vigoureux's argument in favour of the grid-anode connection very convincing. I submit that the question of frequency stability is of more importance than any consideration of power output. The majority of the curves for this connection show that any given change of circuit constants produces a larger frequency change than in the grid-filament connection. It is of interest to note that the crystal used for this investigation has two well-defined response frequencies and is capable of generating these frequencies simultaneously. This is a common phenomenon of transverse oscillators and is a serious handicap to the production of good crystals for control purposes. A very able paper by F. R. Lack* discusses the point and arrives at the conclusion that it is a characteristic of the "parallel" cut crystal. From the values given by Mr. Vigoureux I deduce that his crystal is a "perpendicular" cut. My own experience also confirms the fact that the latter cut suffers from this disability. Mr. Vigoureux's paper is already proving very useful in solving current problems, and I have no doubt that it will prove invaluable as a standard work of reference for a considerable period to workers in this field.

Mr. W. H. F. Griffiths (*communicated*): I wish to congratulate Mr. Lucas on a paper that conveys no real idea of the vast amount of work which he must have carried out. Only those directly interested in the standardization of electrical quantities can have any idea of the difficulties which are encountered in such work and which can only be overcome by much patience and resource. For this reason one must be careful not to speak lightly of accuracies higher than, say, 1 part in 10 000. As an admirer of Dr. Dye's past work on the development of a valve-maintained tuning fork as a frequency standard, I am naturally at present in favour of the fork-controlled multivibrator system as a standard of radio frequencies, more especially in view of the present improvements which he is effecting both in the fork itself and in the associated equipment for checking and watching the variation of its frequency. The portable crystal standard described in the paper, however, undoubtedly fills effectively the gap immediately below this standard. When viewed as a very precise sub-standard, second only to the fork, its temperature coefficient is entirely negligible while the fault inherent in the portable standard—the inability to adjust the frequency more closely to its nominal value than 1 part in 10 000—is rendered less important, as corrections for accuracies higher than this will only be needed occasionally. The stability appears to be excellent for such a purpose. Very precise sub-standards are absolutely necessary if full use is to be made of standards having accuracies of a few parts in 10^6. Realizing this, I have been working upon the problem in a different way by endeavouring to rely upon the calibration permanence of inductance and capacity in a simple resonant circuit, and the value of sub-standards of this kind would be increased if an occasional check of capacity "drift" were made with the portable crystal reference standard described by the author. By designing special fixed inductances and variable condensers I have found it possible to produce a wide-range wavemeter (it is a comparatively simple matter to obtain accuracy in sub-standard wavemeters of limited range) with a temperature coefficient of the order 1 part in 10^5 per degree C. and with a degree of calibration permanence of the order 1 part in 10^4 over considerable periods of time. The comparatively negligible temperature-coefficient is due to a thermal compensation principle employed in the construction of the inductances, and the high degree of calibration permanence is due to a dimensional compensation principle employed in the construction of the variable condenser which renders it as permanent as a fixed air condenser of first quality. Because of its simplicity and rapidity of operation I feel that this type of continuously variable sub-standard will have a useful field of application, especially if an accurate quartz resonator is used at periods of a few months to give an indication of the ageing of the variable condenser at its maximum capacity setting. At this setting the variable condenser approximates to a fixed air condenser of minimum dielectric gap and maximum plate area, and the greatest percentage capacity change is therefore expected in this position. I should be glad to have the author's views and suggestions upon this application of the reference standard. I should perhaps add that for frequencies lower than 3 000 kilocycles per sec. I have found it possible to increase the utility of this sub-standard by converting it into a generator. This is done by associating its simple resonant circuit with a negative resistance device (i.e. without reaction, in the manner suggested by Dr. N. W. McLachlan) in the shape of a 4-electrode valve in which the inter-electrode capacity is reduced to a value such that a slight relative displacement of the electrodes will not affect the accuracy of the wavemeter. To suit the purpose, a valve has been produced by collaboration between Dr. McLachlan and the General Electric Co., Hammersmith. Used in this manner the wavemeter is practically independent of quite large changes in the potentials of the electrodes of its valve and of the filament current of the latter. Its stability over short periods is such that the frequency has remained constant to 2 or 3 parts in 10^6 for 12 hours in a room of varying temperature, the check being made by short-period comparisons against the 220-kilocycle harmonic of a multivibrator controlled by the fork standard used by Mr. Lucas and in a manner similar to that described on page 861.

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* "Observations on Modes of Vibration of Quartz Crystal Plates," *Proceedings of the Institute of Radio Engineers*, 1929, vol. 17, p. 1123.

Mr. H. J. Lucas (*in reply*): I wish to thank Dr. Dye for his suggestion of a method of adjusting the frequency of an oscillator to that of a resonator. I consider it doubtful whether any normal oscillating circuit will be sufficiently stable to enable full advantage to be taken of the accuracy of adjustment which the method allows, but I hope to use a quartz-controlled oscillator checked at intervals by comparison with a resonator, using the controllable variables for adjustment. I agree that it would have been better to have indicated the direction of the various changes in frequency, but this can be deduced from the text and the fact that both crystals were approximately 2 cycles per sec. below their nominal frequency. The scale errors in Figs. 5 and 9 have been corrected for the *Journal.* It is interesting to note that desideratum (3) is receiving confirmation in recent improvements in the valve-maintained fork. In view of the improvements indicated by Dr. Dye the advent of the new standard tuning fork will be received with great interest.

With regard to the question of the employment of retroaction, it was considered that the feed-back by the valve inter-electrode capacity, besides being sufficient for all normal purposes, should be a stable quantity inasmuch as it could only vary by movement of the valve electrodes, which would naturally be guarded against. A screen-grid valve was not employed, no bombarded valve of this type then being available, and it was anticipated that variations in grid contact potential would be troublesome in a "gettered" valve.

I regret that time does not permit of experiments being conducted on the rise of temperature of a crystal under oscillatory conditions.

I made no criticisms of the tuning fork during my work and I accepted it as my frequency standard without question. No evidence appeared to suggest that the fork had any inaccuracy greater than that anticipated, that is, 2 or 3 parts in a million under operating conditions when the supply voltages were maintained at their correct values.

I fully concur that quantitative measurements of humidity would have proved valuable, but the conditions under which the work was carried out precluded this. The point raised by Air Commodore Warrington-Morris regarding the use of the transverse mode of vibration for control purposes is interesting, but the objections are (1) the indicated reason-high temperature coefficient, (2) the production of spurious frequencies in the neighbourhood of the fundamental due to the coupling of this and other modes of vibration, and (3), as Dr. Dye has shown, the impossibility of obtaining nodal support for a transverse oscillator. It has not been found possible to make satisfactory longitudinal crystals having a frequency above 300 kilocycles per sec.

An instance of the use of a resistive load referred to by Mr. Browne has been given by Hull and Clapp.* I considered that either method of supporting the crystal, i.e. at the ends of or at right angles to the electric axis, introduces a definite amount of damping by operating on the reciprocal vibration, and this would probably account for the decrement of my best evacuated crystal being no better than that of Dr. Dye's crystal in air.

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* See reference on page 867.

It is hoped to employ the information provided by Mr. Vigoureux in future work on resonators.

Mr. J. E. P. Vigoureux (*in reply*): Replying to Mr. Williams's inquiry as to the validity of formulæ (42) and (73) for very small values of the inter-electrode capacities, these formulæ are obtained, as pointed out on page 270, on the assumption that the range of capacity in the plate circuit, over which oscillations can be maintained, namely $C \sim C_0$, is fairly large. If the plate-grid capacity is very small, this range will also be small, and formula (73) is not applicable. It is then no longer true to say that " the total range of capacity C over which oscillations are possible with the filament-to-grid connection is to the corresponding range in the plate-to-grid connection as C_3 is to C_2." But an idea of the range can be obtained from formula (71) by assuming usual values for the various constants of the valve. I find that with $C_3 = 8$ $\mu\mu$F, $m = 100$, $g_0 = 10^{-5}$ mho, and the other variables approximately the same as those given in Table 1 of the paper, the range for the plate-grid connection is just over 4 000 $\mu\mu$F. With the filament-grid connection and values of 0·1, 0·08 and 0·07 $\mu\mu$F respectively for the plate-grid capacity, the ranges would be 41, 24 and 12 $\mu\mu$F. When the plate-grid capacity is 0·06 $\mu\mu$F or less, oscillations cannot be maintained. If those figures represent anything like the actual state of things, it would seem that the oscillations observed by Mr. Williams were due to imperfect elimination of capacity between the plate and the grid leads, outside the valve.

A few experiments were carried out to check the theoretical results obtained above. The quartz disc the constants of which are given in the paper was used again, with an air-gap of 0·012 cm. The amplification factor of the valve was 180, its plate resistance was 240 000 ohms, and the plate and screen-grid voltages were 115 and 84 respectively. A 1·2-megohm grid leak was used. At first the oscillatory circuit was made up of a shielded variable air condenser, a 1-ohm vacuo-junction and an ordinary cylindrical 160-μH coil. When no particular precautions were taken to eliminate capacity between the plate circuit and that electrode of the resonator connected to the grid, oscillations took place fairly strongly. By merely screening the lead connecting the plate to the insulated terminal of the condenser, the amplitude of the oscillations and the range of capacity over which they could be maintained were considerably decreased.

A toroidal coil of inductance 100 μH was next wound and enclosed in a copper box; the leads connecting it to the vacuo-junction and to the insulated terminal of the condenser were also screened, and all the screens were maintained at filament potential, either by direct connection or by large condensers. With this arrangement it was impossible to obtain any oscillations. One end of a screened lead was then connected to the plate terminal. To the other end was soldered a thin brass plate 3 × 7 cm, the distance of which from the resonator electrode joined to the grid could be adjusted at will. It was thus possible to add a small capacity between the plate and the grid, although the actual value added could not be estimated in these preliminary experiments. It was then possible to obtain oscillations, provided the added capacity exceeded a certain value. For the limiting value, and for two larger values of this capacity, the ranges were 20, 30 and 47 $\mu\mu$F, and the amplitude of the maximum difference of potential across the toroidal coil was less than 3 volts in the first case; it was 7 in the second and 17 in the third. A 5-$\mu\mu$F shielded condenser between the grid and the plate increased the range to 430 $\mu\mu$F and the amplitude to 35 volts.

These results show that the plate-grid capacity is too small to maintain oscillations, and it seems that the method cannot be employed, without modifications, to measure the plate-grid capacities of screen-grid valves.

On page 270 of the paper, second line above equation (42), F should be replaced by E, and the ordinates of Fig. 6 should be multiplied by 10 000.

A NEW NULL METHOD OF TESTING INSTRUMENT TRANSFORMERS, AND ITS APPLICATION.

By G. F. SHOTTER, Associate Member.

(*Paper first received* 18*th November*, 1929, *and in final form* 13*th January*, 1930; *read before the* METER AND INSTRUMENT SECTION 7*th February*, 1930.)

SUMMARY.

The paper describes some of the common methods and the author's new null method of testing instrument transformers.

The technical points of the method are discussed and examples are given illustrating the simple derivation of ratio and phase-angle error of current and potential transformers.

The accuracy of the method is dealt with, tests on a hole-type current transformer are described, and the number of standard transformers required is discussed.

In conclusion the author sums up the advantages of the method and describes some interesting applications of it in connection with the testing of power transformers, etc.

In the Appendix is given the proof of the method.

INTRODUCTION.

Since the importance of a high degree of accuracy in metering is now recognized, it is becoming more and more essential to obtain a quick and accurate method of determining the characteristics of instrument transformers.

Although it may be claimed that a knowledge of such characteristics is unnecessary when meters are tested with their instrument transformers, it should be realized that no secondary tests can be accurately carried out either *in situ* or in the laboratory when the characteristics are unknown.

Before describing the method which is the subject of the paper, it might be of interest briefly to outline a few of the methods which are available for routine testing and which should be treated separately from the precision methods used by the standardizing institutions.

Perhaps the most obvious method of testing the ratio of instrument transformers is to connect ammeters or voltmeters (as the case may be) in the primary and secondary circuits. An extension of this method is the addition of standard current transformers or potential transformers in the primary circuits.

The disadvantages of this method are: (1) the inherent errors of the instruments themselves, and (2) the difficulty of obtaining accurate simultaneous readings. Both these errors are especially pronounced, particularly when testing current transformers, since in a.c. ammeters the scale closes up rapidly below two-thirds of full-scale deflection. For any reasonable degree of accuracy to be obtained, several sizes of ammeters or multi-range instruments would be required.

Either of these alternatives is objectionable because, since a 1-ampere instrument would be required to obtain accurate readings at the lower range, its burden would cause an additional error which, in some cases, would be as much as 2 per cent, depending upon the type of transformer tested.

Another method involves the use of two wattmeters, the potential circuits of which are connected to a common source of e.m.f. in phase with the current in the primary circuit of the current transformers (in the case of current-transformer testing). Here, also, the use of a multi-range group of instruments is desirable.

The small error introduced by the angle of the transformer when being tested at unity power factor is negligible, and, consequently, the above two methods have so far been used for the testing of ratio only, although it is possible to measure the phase angle if the wattmeters have negligible reactances in their pressure circuits or have identical time-constants.

The scaling difficulties of the wattmeter method are not nearly so prominent as in the ammeter method; the scale is more open and the volt-ampere burden imposed by the wattmeters is less. From a practical point of view the use of two instruments, which have to be read simultaneously by two persons, is unsatisfactory, especially when a variation occurs in the load.

A third method, proposed by Dr. P. G. Agnew of the American Bureau of Standards, consists in the use of two watt-hour meters the discs of which are marked into 100 equal divisions and which are adjusted to run at nearly the same rate. The method of testing is to compare the speeds of the two instruments when connected to the secondaries of a standard and an unknown transformer respectively.

The meters are interchanged with respect to the transformers in order to eliminate the errors of the instruments. This method, with care, gives good results, but one objection is the time taken in carrying out the tests and in working out the calculations. Another objection is the lack of sensitivity at low loads.

A fourth method, developed by S. Silsbee of the American Bureau of Standards, consists in comparing a known standard transformer against the unknown transformer by means of a compensating circuit which balances out the vector difference between the two transformers.

In a modification of this method, also devised by Silsbee, a dynamometer wattmeter is substituted for the detector and compensating circuit. This modification greatly reduces the cost of the apparatus as compared with the null method. Using a suitable wattmeter, such as that described by R. S. J. Spilsbury of the National Physical Laboratory, in the *Journal of Scientific Instruments* for June 1924, an accuracy of about 0·1 per cent in ratio and 5 minutes in phase angle is obtainable at low loads.

With regard to the two-wattmeter method of testing, some of the difficulties of simultaneous readings can obviously be overcome by the use of a double-element wattmeter, and by connecting the known and unknown transformers to it in such a manner as to cause opposition of the two elements, thus enabling the difference between the two secondary currents to be measured.

Although this method may be satisfactory at high loads, it is far from satisfactory at lower loads, even if a specially sensitive wattmeter (whose burden would, incidentally, be prohibitive) were used.

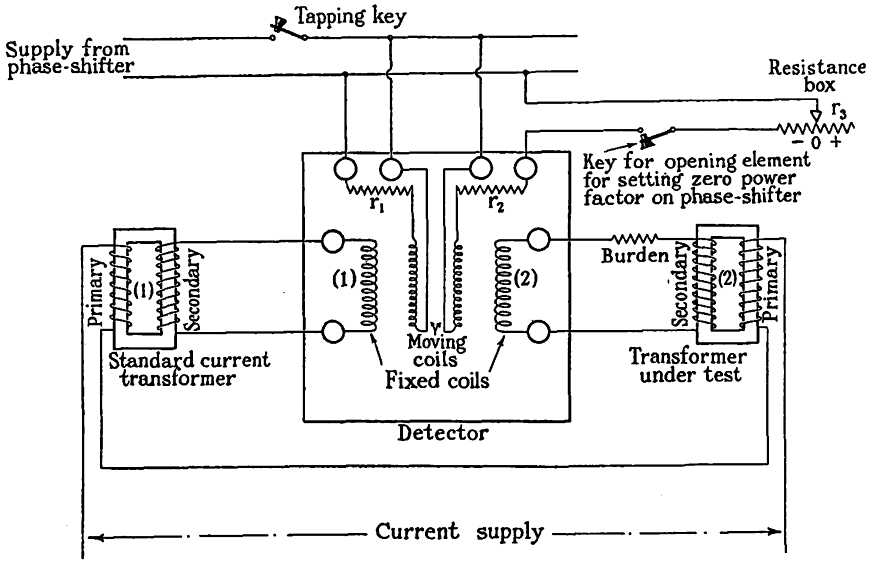

Tapping key
Supply from phase-shifter
Resistance box
r_3
− 0 +
Key for opening element for setting zero power factor on phase-shifter
r_1
r_2
Burden
Primary
(1)
Secondary
(1)
(2)
Secondary
(2)
Primary
Standard current transformer
Moving coils
Fixed coils
Transformer under test
Detector
Current supply

FIG. 1.

The author's method, which is the subject of this paper, is based on the double-wattmeter method just described, but with important modifications which eliminate all the disadvantages cited above. Instead of reading the difference directly from the instrument, the potential circuit of one of the elements is so arranged that resistance can be added to or subtracted from this circuit until balance (shown by null deflection of the pointer) is obtained on the instrument. When the final point of balance is obtained, this fact is apprehended by means of a tapping key inserted to make or break the common potential circuit to the instrument (see Figs. 1 and 2).

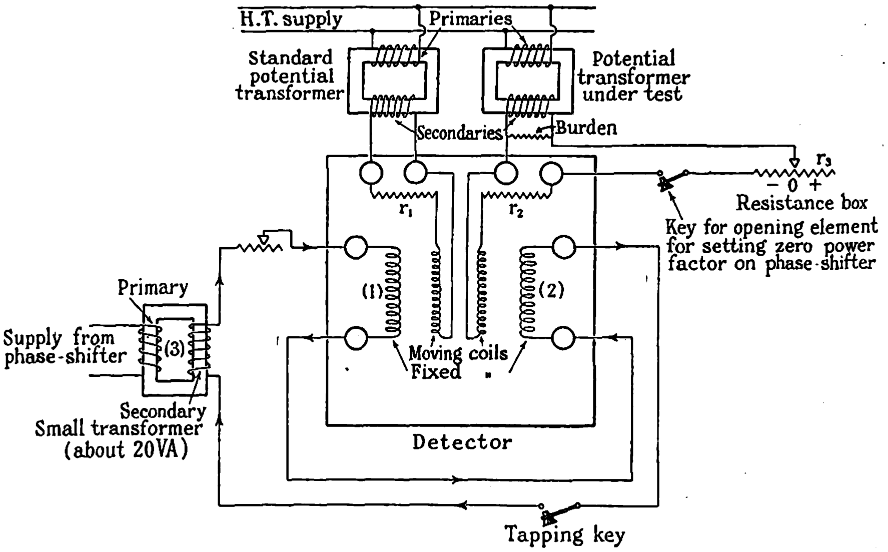

H.T. supply
Primaries
Standard potential transformer
Potential transformer under test
Secondaries
Burden
r_3
− 0 +
Resistance box
Key for opening element for setting zero power factor on phase-shifter
r_1
r_2
Primary
Supply from phase-shifter
(3)
Secondary
Small transformer (about 20VA)
(1)
(2)
Moving coils
Fixed
Detector
Tapping key

FIG. 2.

It was found, when using an ordinary standard wattmeter (2½ A, 100 V) with this modification, that the sensitivity was increased 10 times; with a specially constructed wattmeter such as that described by Mr. Spilsbury and mentioned above, the sensitivity can be increased 50 times, i.e. a sensitivity of 1 part in 25 000 can be obtained at full load, giving a sensitivity of 1 part in 1 250 at 1/20th full load and unity power factor, against 1 part in 250 when using a standard wattmeter.

If the common potential circuit to the wattmeter is excited from a source of e.m.f. which is in phase with the current in the common primary circuit of the current transformers, it can be proved that the resistance added to or subtracted from the potential circuit is a measure of the difference of ratio between the known and unknown transformers (see Appendix).

There still remains the difficulty of obtaining the angle error of a transformer; this, however, can be obtained if a second test is carried out with the source of e.m.f. to the common circuit of the wattmeter displaced 60° from the current in the common primary circuit and values of r_3 are obtained under these conditions.

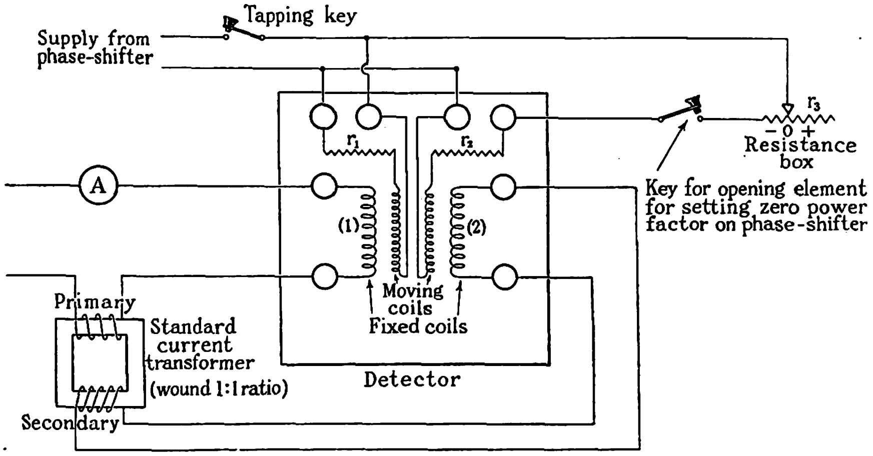
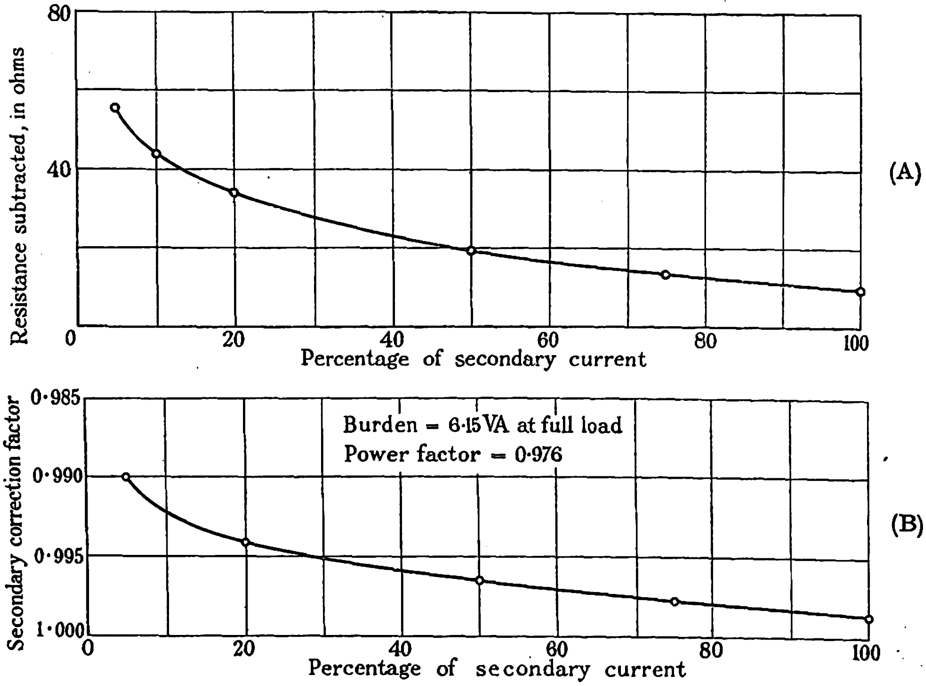

Tapping key
Supply from phase-shifter
r_1
r_3
r_3
− 0 +
Resistance box
Key for opening element for setting zero power factor on phase-shifter
A
(1)
(2)
Moving coils
Fixed coils
Primary
Standard current transformer (wound 1:1 ratio)
Secondary
Detector

FIG. 3.



FIGS. 4A and 4B.

Two values of resistance will now have been obtained, one at 0° and the other at 60° phase difference, and assuming that the test is being carried out on a current transformer and that the 60° phase-difference test is carried out with the source of e.m.f. in the common potential circuit leading the current in the primary windings of the current transformers, then a little consideration will show that whereas the resistance added or subtracted in the 0° test is a measure of the difference in ratio between the two current transformers, in the 60° test it is a measure of the difference between the combined ratio and phase-angle errors of the two current transformers.

Assuming, for a moment, that the standard current transformer has no phase angle or ratio error, then the above values expressed as a percentage are proportional to the ratio error and to the combined ratio and phase-angle error respectively of the unknown transformer, and it can be proved that the algebraic difference between the combined ratio error and phase-angle value at 60°

test and the ratio error value at 0° test, is proportional to the angle error of the unknown transformer (see Appendix).

As an example, supposing that the secondary current of the unknown transformer is 1·0 per cent low at the load under consideration (i.e. = 4·95 amps.) and that it has a leading phase angle of 40 minutes, then the value of r_3 obtained in the test at 0° would be equivalent to 1·0 per cent subtracted from the resistance of the right-hand potential element, and the value at the 60° test would be equivalent to 1·0 per cent subtracted and 2·0 per cent added (since a phase angle of 40 minutes means an error of 2·0 per cent at 60° phase difference).

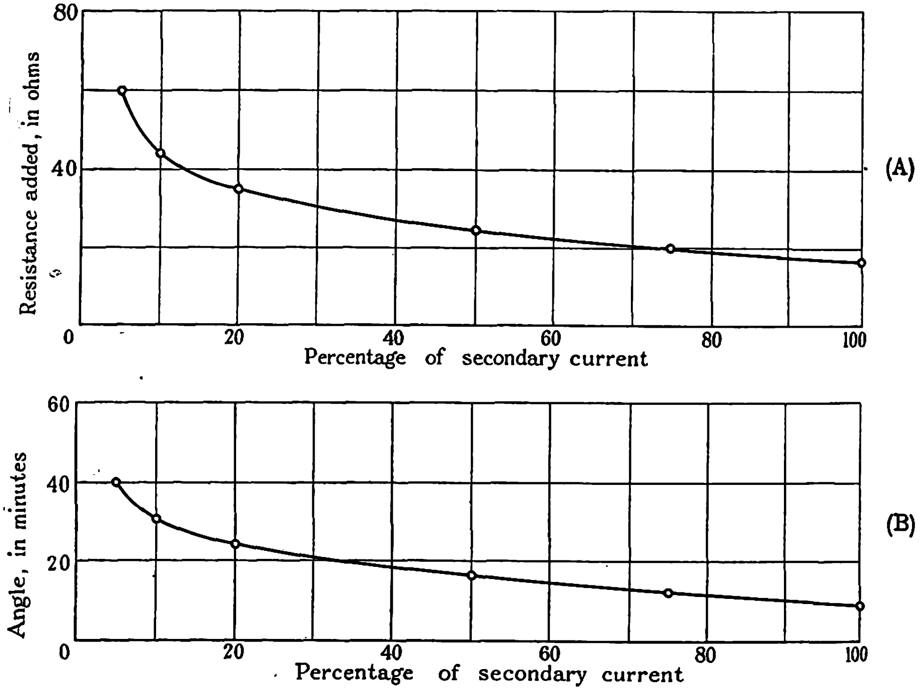
The method can be well illustrated by describing a test carried out on a "hole" type transformer wound to a ratio of 1: 1. It is seen from Fig. 3 that the primary winding of the transformer is connected in series with the left-hand current coil (1) of the detector, and its secondary is connected to the right-hand current coil (2), the two potential circuits of the detector being connected to the supply from the phase-shifter and a tapping key being interposed in this circuit. Another key is interposed in the right-hand element potential circuit to enable the quadrature point (indicated by zero deflection on the detector) to be set on the phase-shifter. r_3 represents the adjustable resistance box, which is suitably marked.

Fig. 4A shows the curve of values of r_3 in the 0° test for various values of secondary current plotted against secondary current, while Fig. 5A shows the curve of values of r_3 obtained in the 60° test for various values of secondary current plotted against secondary current.

Fig. 4B shows the values of secondary current correction factor, deduced from Fig. 4A, plotted against secondary current, while Fig. 5B shows the values of the phase-angle error of the transformer deduced from the algebraic difference of the values obtained in Figs. 4A and 5A, plotted against secondary current.

It will be observed that a test of this character is extremely simple, and it is obviously only one step forward to make the resistance box in such a manner as to give, for any given wattmeter, direct indication of the percentage error. A case of this kind, i.e. a test on a transformer wound for a 1 : 1 ratio, is obviously an ideal one, as no calculation has to be made in allowing for the standard-transformer errors. In any comparison method this is, in the author's opinion, an objectionable feature, since mistakes can easily creep in, especially in regard to signs when calculating; and to obviate this difficulty the following further extension was made to the idea. Another similar resistance box, with suitable dials, is incorporated in series with r_3. If now, for every load, a set of values in terms of percentage ratio error and combined ratio and phase-angle error of the standard transformer (which are tabulated in a suitable form) are dialled on the second resistance box correctly as regards sign, then the same relative conditions can be obtained as in the ideal 1 : 1 ratio case previously cited, i.e. the torque in the left-hand element can be made to correspond, for every load and power factor tested, to the primary current of the standard transformer. It will now be seen that the method reduces itself to one of extreme simplicity and minimizes any possibility of errors.

So far, the illustrations of tests and the above deductions have been applied to current transformers, but the same scheme and modifications can be applied, with the same facilities, to potential transformers. Figs. 6 and 7 illustrate the completed method as applied to the



FIGS. 5A and 5B.

routine testing of current and potential transformers respectively. It will be seen from Figs. 6 and 7 that the adjustable resistances are incorporated in the potential circuit of the right-hand element in one unit consisting of six variable resistances, three for the standard corrections and three for the errors of the unknown transformer.

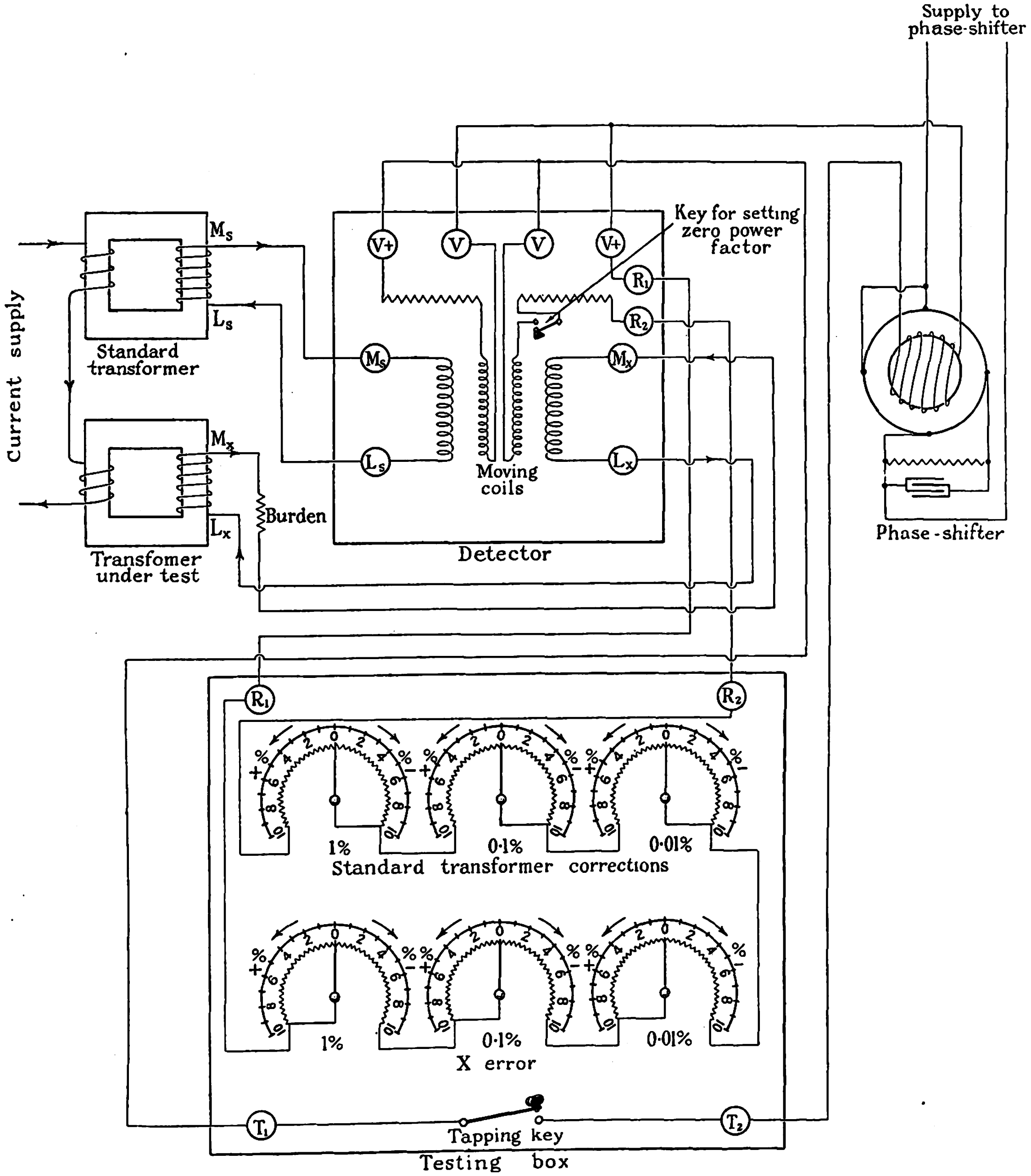

Supply to phase-shifter
Key for setting zero power factor
Current supply
M_s
L_s
Standard transformer
M_x
L_x
Burden
Transfomer under test
V+
V
V
V+
R_1
R_2
M_s
M_x
L_s
L_x
Moving coils
Detector
Phase-shifter
R_1
R_2
1%
0·1%
0·01%
Standard transformer corrections
1%
0·1%
0·01%
X error
T_1
T_2
Tapping key
Testing box

FIG. 6.

These dials are arranged to give steps of 0·01 per cent from 0·0 to 11·1 per cent, which should more than cover the worst error met with in practice.

Fig. 6 requires no further explanation, since this has been given previously when dealing with current-transformer testing; but with reference to Fig. 7, which illustrates the apparatus applied to the testing of potential transformers, further exposition is required. It will be observed that on the right-hand side of Fig. 7 a small step-down transformer is shown connected to the supply from the phase-shifter. This is required to supply the requisite current (about 5 amperes) to the two fixed coils of the detector connected in series. Apart from the connections and the fact that the potential coils are excited from the standard and unknown transformer secondaries, the arrangement is identical with that of Fig. 6.

Fig. 8 gives an illustration of a plan of the testing box and illustrates the inclusion of charts giving typical standard-transformer corrections.

TECHNICAL POINTS RELATING TO THE METHOD.

(1) *Detector.*—The detector as at present constructed is a double-element instrument of similar construction and sensitivity to that described by R. S. J. Spilsbury and previously mentioned in the Introduction, with the exception that it has a central zero. In addition, the moving-coil systems are arranged to be at right angles to the fixed-coil systems so that the mutual inductance between the fixed and moving coils is zero at the balance point, and so that no error can occur due to an e.m.f. induced from one circuit to another.

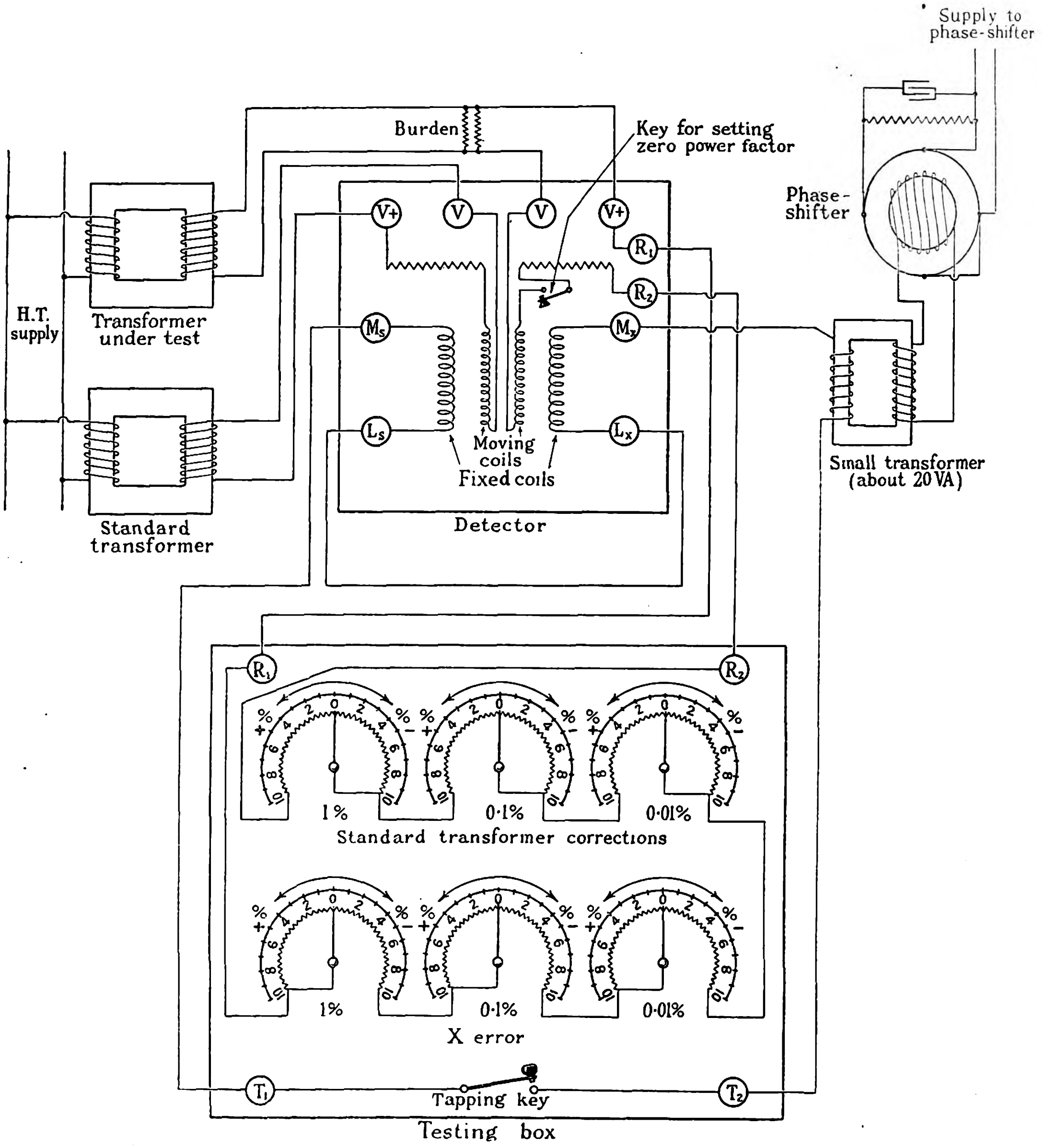

Supply to phase-shifter
Burden
Key for setting zero power factor
Phase-shifter
H.T. supply
Transformer under test
Standard transformer
V+
V
V
V+
R₁
R₂
Ms
Mx
Ls
Lx
Moving coils
Fixed coils
Detector
Small transformer (about 20VA)
R₁
R₂
% + 10 8 6 4 2 0 2 4 6 8 10 − %
1%
0·1%
0·01%
Standard transformer corrections
1%
0·1%
0·01%
X error
T₁
Tapping key
T₂
Testing box

FIG. 7.

(2) *Balance of Elements of the Detector.*—The verification of the balance of the elements of the detector can be readily made by setting all the dials of the testing box to zero and connecting the fixed coils of the detector in opposition and the potential coils in parallel to sources of current and e.m.f. respectively. Any difference which may exist can be compensated for by adjusting suitably the dials of the testing box, preferably on the standard correction dials; or, if necessary, a small variable resistance can be incorporated for balance purposes if preferred.

(3) *Effect of Reactance in the Potential Circuits of the Detector.*—With regard to this error, since both elements of the detector are identical in construction it can be proved that so long as the angle error of the two elements is identical no error can occur, due to this cause, in the final result; consequently, this allows for some latitude in the design of the detector.

(4) *Burden of the Detector.*—With regard to the burden of each of the fixed coils of the detector, this is at

the present time a comparatively low figure, of the order of 4 VA, and, since it is seldom that a metering equipment imposes less burden than this in practice, it is not an objectionable feature. If, however, it is necessary at any time to obtain the characteristics of a current transformer at zero burden, this can easily be obtained by testing at different burdens and afterwards extrapolating the curves for zero burden figures.

The burden imposed by the potential coils of the detector is of the order of 10 VA, which is, of course, comparatively small, considering that the volt-ampere rating of the smallest potential transformer is about 50 VA; but where necessary, if the zero burden is required, extrapolation can be resorted to, as above.

(5) *Sensitivity of the Detector.*—At full load and unity power factor this is approximately 1 part in 25 000 when using the tapping key for the final adjustment, which is equivalent to 1 part in 600 at the lowest testing point, viz. 1/20th full load and 0·5 power factor. It will consequently be seen that the method leaves little to be desired with regard to sensitivity for routine testing.

In the case of current-transformer testing, where high sensitivity is really required at low loads, an increase in sensitivity can be obtained by increasing the pressure applied to the potential elements. This is due to the fact that the pressure is only applied to the potential coils when detecting the movement of the pointer of the detector by the tapping key; care, however, has obviously to be exercised in this direction.

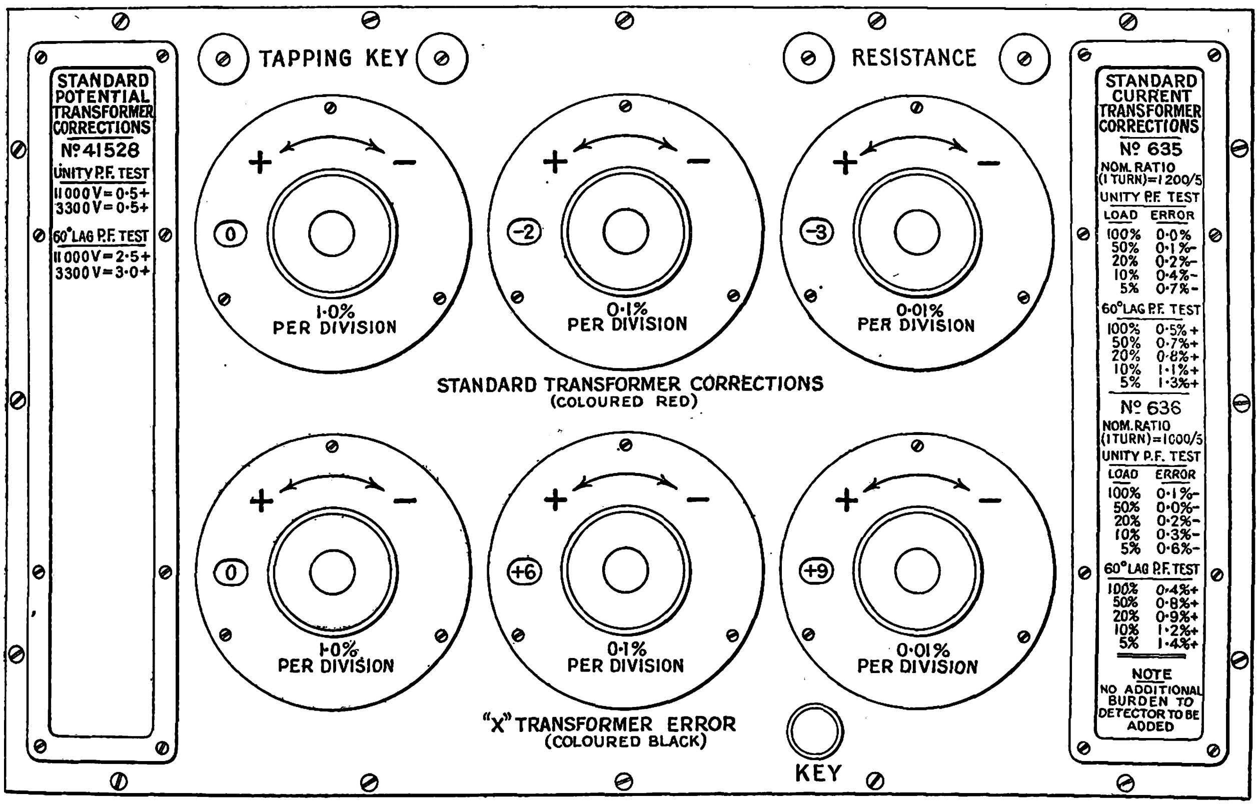

TAPPING KEY
RESISTANCE
STANDARD POTENTIAL TRANSFORMER CORRECTIONS
Nº41528
UNITY P.F. TEST
11000V=0·5+
3300V=0·5+
60°LAG P.F. TEST
11000V=2·5+
3300V=3·0+
+
−
0
1·0% PER DIVISION
+
−
−2
0·1% PER DIVISION
+
−
−3
0·01% PER DIVISION
STANDARD TRANSFORMER CORRECTIONS
(COLOURED RED)
+
−
0
1·0% PER DIVISION
+
−
+6
0·1% PER DIVISION
+
−
+9
0·01% PER DIVISION
"X" TRANSFORMER ERROR
(COLOURED BLACK)
KEY
STANDARD CURRENT TRANSFORMER CORRECTIONS
Nº 635
NOM. RATIO (1 TURN)=1200/5
UNITY P.F. TEST
LOAD ERROR
100% 0·0%
50% 0·1%−
20% 0·2%−
10% 0·4%−
5% 0·7%−
60°LAG P.F. TEST
100% 0·5%+
50% 0·7%+
20% 0·8%+
10% 1·1%+
5% 1·3%+
Nº 636
NOM. RATIO (1 TURN)=1000/5
UNITY P.F. TEST
LOAD ERROR
100% 0·1%−
50% 0·0%−
20% 0·2%−
10% 0·3%−
5% 0·6%−
60°LAG P.F. TEST
100% 0·4%+
50% 0·8%+
20% 0·9%+
10% 1·2%+
5% 1·4%+
NOTE
NO ADDITIONAL BURDEN TO DETECTOR TO BE ADDED

FIG. 8.—Plan of testing box.

(6) Error introduced by setting the phase-shifter for quadrature with reference to the secondary instead of to the primary of the standard transformer is generally negligible, and can be eliminated by allowance on the phase-shifter setting (see Appendix, section 4).

SIGNIFICANCE OF SIGNS ON THE TESTING-BOX DIALS.

(a) *Ratio Testing.*

It will be noted from Fig. 6 that the measuring resistances on the testing box are inserted in the right-hand potential element of the detector, and this right-hand element is always shown connected to the transformer under test. Although this is arbitrary, it involves simplified connections.

It will be realized that, assuming for simplicity that the standard transformer secondary current is 1·0 per cent low at the load under consideration and that a correction is to be made for this error, then, in order to make the equivalent torque on the left-hand element proportional to that of the primary current, it would be necessary to subtract 1·0 per cent resistance from the potential circuit of this element. But it will be seen that this can be obtained by adding resistance to the right-hand element, and, consequently, although the corrections for the standard transformer are made by adding or subtracting resistance on the right-hand element, the signs on the dials are made to correspond to correct notation.

The author has found that the best way of expressing the ratio error of an instrument transformer is as a secondary correction factor, i.e. the value by which the nominal secondary current has to be multiplied to give the actual secondary current, or, if preferred, as a percentage increase or decrease in the secondary current. For example, a current transformer the nominal ratio of which is 100/5 A and which has a true ratio of 100/4·95 A would have a secondary correction factor of 0·99, or an error of secondary current of 1·0 per cent low.

In Figs. 6 and 7 the positive sign denotes that the secondary current is high, and a negative sign that it is low.

The same remarks apply to the error of the unknown transformer.

(b) Phase-Angle Testing.

A little explanation is required to show the sequence of stages compensating for the phase-angle error of the standard transformer and obtaining the angle error of the unknown transformer.

Case (1).—*Current-Transformer Testing.*—The effect of a leading angle (i.e. where the reversed secondary vector leads the primary vector), which is the normal characteristic of a current transformer, upon the detector at lagging power factor (i.e. when the current supply to the primaries of the transformers lags behind the potential-coil supply) is to increase the torque of the element to which it is connected, and, consequently, assuming that a correction has to be made for a leading phase-angle error of the standard current transformer, resistance would, in effect, have to be added to the left-hand element of the potential circuit of the detector in order to make it appear that the standard transformer had no phase-angle error. This, however, is effected by subtracting resistance from the right-hand element. For a lagging angle the reverse procedure is, of course, adopted.

It will, of course, be realized that in the 60° test both ratio and phase-angle errors have to be compensated for on the standard transformer, therefore the setting on the dials of the testing box would have to be set for the algebraic sum of the percentage error of the standard current transformer and the percentage error due to its angle error at 60°.

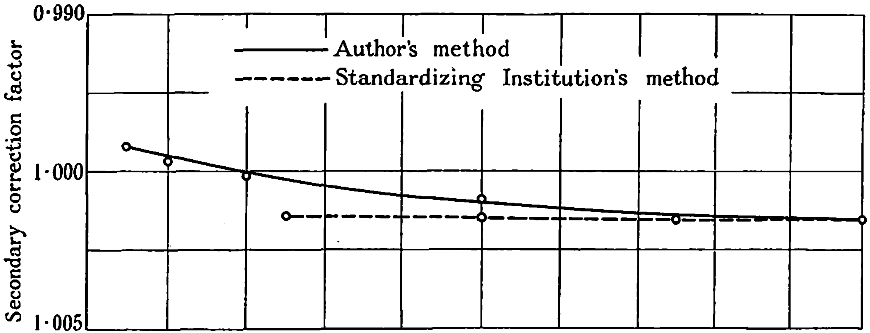


FIG. 9.

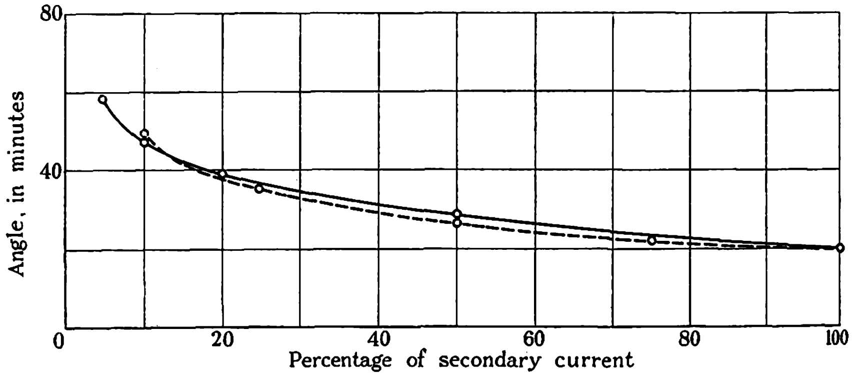


FIG. 10.

As an example, take the case of a standard transformer the secondary current of which is 1·0 per cent low at the load under consideration, with a phase-angle error of 40 minutes leading.

In the 0° test, the standard correction-dials will be set at — 1·0 per cent, which is equivalent to subtracting resistance of this amount from the left-hand element, thereby making the torque of this element equivalent to the primary current.

At the 60° test the dialling, as stated before, will have to be arranged to give a torque on the left-hand element which is equivalent to the primary current and the phase difference between the primary current and the potential-coil supply, i.e. 60°. To procure this result, from the error assumed (40 minutes), resistance would have to be added to the left-hand element of an amount equal to 2·0 per cent (since 40 minutes phase-angle error = an error of 2·0 per cent at 60°) for the angle error, and 1 per cent would have to be subtracted for the ratio error, making an effective alteration of 1·0 per cent added resistance, which is the algebraic sum of the two errors. This is effected on the right-hand element by subtracting resistance equivalent to 1·0 per cent.

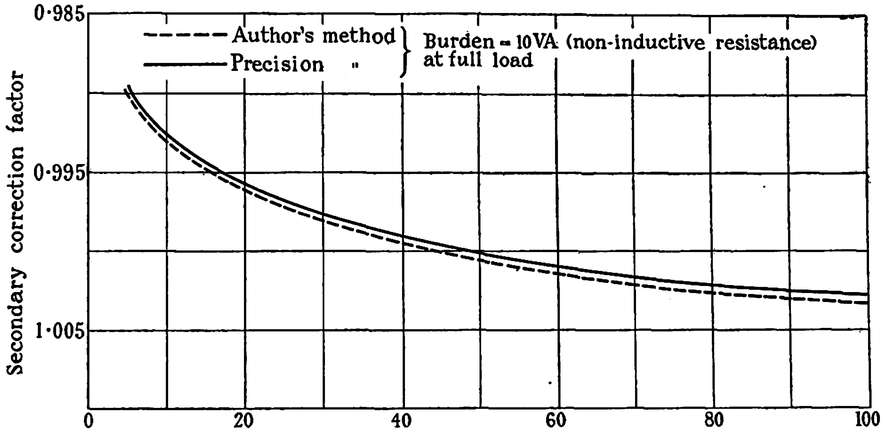


FIG. 11.

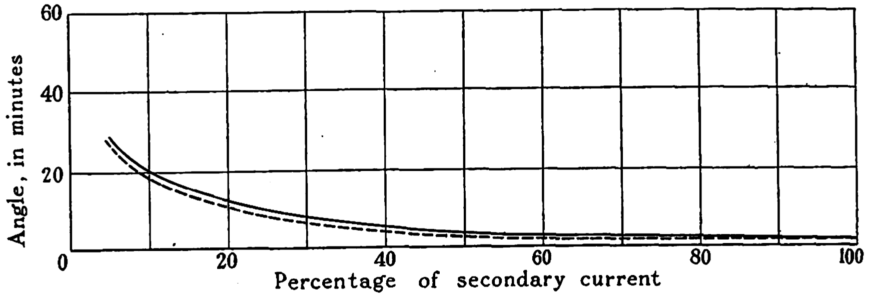


FIG. 12.

In the case of deriving the angle of the unknown transformer the same reasoning holds good, except that the reverse procedure is made, since the indication on the dials at the 60° test gives the combined ratio and phase-angle error, the percentage error due to angle being then the algebraic difference between the combined ratio and phase-angle error and the ratio error at the 0° test, from which value the phase angle is derived as follows:—

Phase angle, in minutes = (Percentage algebraic difference at 60°) × 20 (since 20 minutes = 1·0 per cent error at 60° phase angle).

The following examples are given, illustrating the extraction of ratio and phase angles for current transformers with various characteristics, from dial readings taken at the two tests:—

(1) Test (1) Ratio error = + 0·5 per cent.
Test (2) Combined ratio and phase-angle error = + 3·0 per cent.
Algebraic difference = (Test 2) — (Test 1)
= (+ 3·0 per cent) — (+ 0·5 per cent)
= + 2·5 per cent.
Angle = + 2·5 per cent × 20 = + 50 minutes.

(2) Test (1) Ratio error = — 0·5 per cent.
Test (2) Combined ratio and phase-angle error = + 3·0 per cent.
Algebraic difference = (Test 2) — (Test 1)
= (+ 3·0 per cent) — (— 0·5 per cent)
= + 3·5 per cent.
Angle = + 3·5 per cent × 20 = + 70 minutes.

(3) Test (1) Ratio error = + 1·0 per cent.
Test (2) Combined ratio and phase-angle error = + 0·5 per cent.
Algebraic difference = (Test 2) — (Test 1)
= (+ 0·5 per cent) — (+ 1·0 per cent)
= — 0·5 per cent.
Angle = — 0·5 per cent × 20 = — 10 minutes.

(4) Test (1) Ratio error = — 0·5 per cent.
Test (2) Combined ratio and phase-angle error = — 1·0 per cent.
Algebraic difference = (Test 2) — (Test 1)
= (— 1·0 per cent) — (— 0·5 per cent)
= — 0·5 per cent.
Angle = — 0·5 per cent × 20 = — 10 minutes.

It will be noted that the method is quite simple, and if due notice is taken of the sign the rest of the calculation is only a case of simple mental arithmetic.

Case (2).—*Potential-Transformer Testing.*

(*a*) *Ratio Test.*—This is identical with current-transformer testing, and the derivation of error is the same, a positive sign of percentage error meaning that the secondary voltage is higher than nominal, and vice versa for a negative sign.

(*b*) *Angle Test.*—In order to obtain the same sign notation, viz. a positive angle means that the reversed secondary leads the primary and a negative angle means that the reversed secondary lags relatively to the primary, it is necessary to make the current in the fixed coils lead with respect to the source of e.m.f. of the potential coils.

It will be noted, consequently, that since the current supply to the fixed coils is obtained from the small step-down transformer the primary of which is connected to the phase-shifter, then the phase-shifter is always rotated in the same direction (i.e. from 0° to 60° lead) both for current- and potential-transformer testing, to obtain the same sign notation.

It will be realized that this alteration in the relative vector relationship of the fixed and moving coils is due to the fact that a positive angle on a potential transformer produces a decrease in torque in a meter on a lagging power factor, which is the reverse of that of a current-transformer angle.

Accuracy of the Method.

No mention has yet been made of the accuracy of the method in practice, and as the only proof of this, from a practical point of view, is a comparison of results obtained by this method with those obtained by precision and other similar methods, comparison tests will be mentioned.

Figs. 9 and 10 show tests taken on a low-tension silicon-steel-core current transformer, comparing results obtained by the author's method with those obtained by a British standardizing institution. It will be seen that as regards the angle-error tests there is practically no difference between the results, but as regards ratio tests there is a slight difference of about 0·2 per cent at $\frac{1}{4}$ load. Unfortunately, the lowest point available from the standardizing institution is the $\frac{1}{4}$-load value.

Figs. 11 and 12 show comparison tests taken on a silicon-steel current transformer which was tested by the non-inductive shunt precision method, the shunts of which had been calibrated by the American Bureau of Standards. As will be seen, the comparison is extremely good both on ratio and phase-angle tests, there being a maximum error of 1 part in 2 000 on ratio test and 1 minute on phase-angle test.

Figs. 13 and 14 show comparison tests taken on a mumetal-core current transformer by the author's method, against a non-inductive shunt precision method at a standardizing institution, and by a manufacturer's method. It will be observed that there is very little difference between the results, both on ratio test and phase-angle test. It should, however, be noticed that the burden imposed in the author's test was slightly different from that imposed in the other tests. The

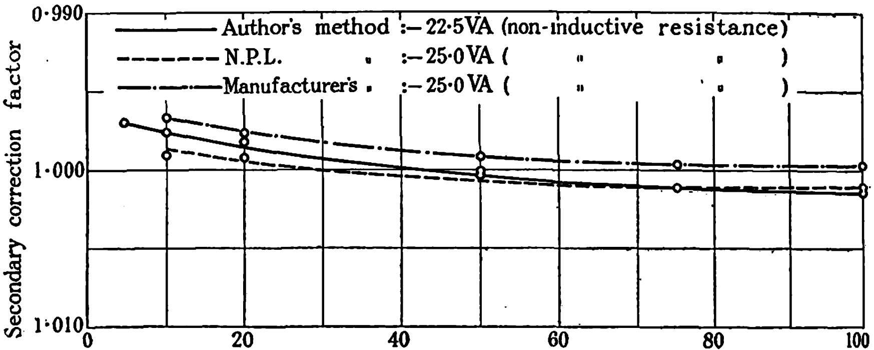


Fig. 13.

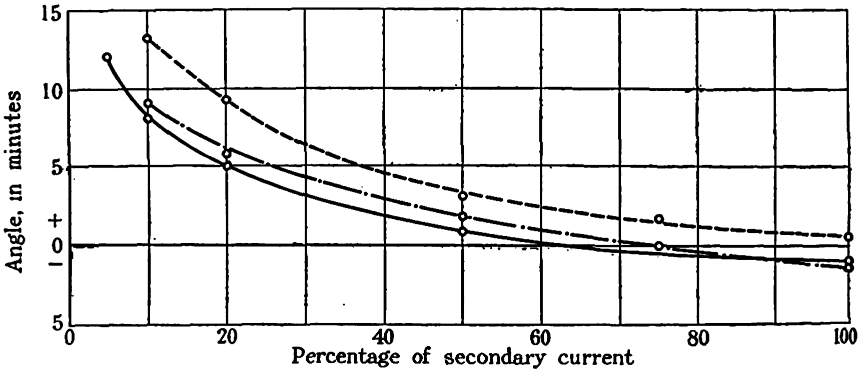


Fig. 14.

manufacturer's and the author's tests on ratio would have been brought more into line if the burden values had been equal.

STANDARD CURRENT TRANSFORMERS OF THE "HOLE" TYPE.

It is of interest to point out that all the above comparison tests were carried out by the author using a standard transformer of the "hole" type, the errors of which, ascertained by the method of calibration as a 1 : 1 ratio transformer outlined in Fig. 3, and exhibited in Figs. 4 and 5, had been compensated for by appropriate setting of the resistance values. Theoretical considerations, however, showed that it would be advisable to ensure that the same characteristics which were obtained when the transformer was wound for 1 : 1 ratio should apply for all other ratios. This involves keeping a constant radius for the primary turns and ensuring that these turns are always in the same position in the "hole."

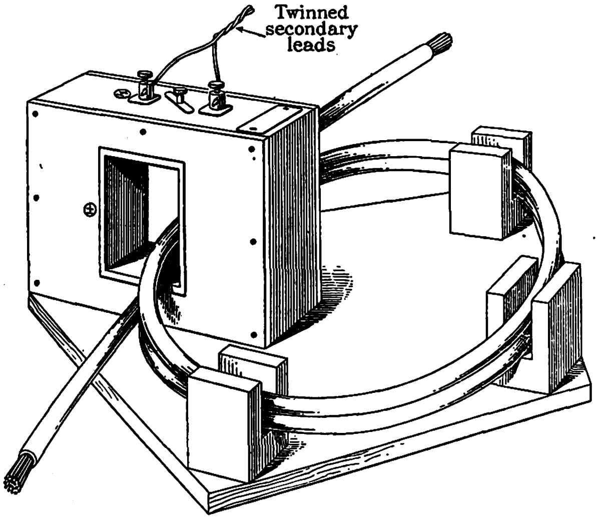


FIG. 15.

Fig. 15 illustrates a winding frame used in conjunction with one of the author's standard transformers, which ensures that the above conditions are fulfilled. Although from experiment it does not appear that this is very necessary in the type of standard transformer illustrated, which has two secondary windings on either side of the "hole," yet it is essential with transformers which have only one secondary winding.*

Incidentally, a necessary precaution which is often neglected when testing current transformers, is to use twinned wires from the transformer secondaries to the instruments.

An interesting series of tests was carried out by the author on the effect of the disposition of the primary winding on a "hole" type transformer, the results being shown in Fig. 16. The core of the transformer tested was of circular form with a distributed secondary, and the primary was wound in five different ways. From the curves it will be observed that there is very little difference between the results.

The disposition shown in (E) appears to give the best accuracy for ratio, but is the least satisfactory for angle. The maximum difference, however, between any of the results on the angle test is only approximately 5 minutes.

The explanation of the differences may be the variation of the leakage fluxes between the primary and secondary windings under the different conditions.

STANDARD TRANSFORMERS REQUIRED TO DEAL WITH ALL RATIOS OF TRANSFORMERS.

A point which often arises in connection with a comparison method is that of the multiplicity of standards which would be required to test all British standard ranges of current transformers. Consider a "hole" type standard current transformer the nominal ratio of which with one primary turn is 1 200/5 A. The ranges that can be tested by a standard of this size by suitably varying the number of primary turns are as follows:—

5/5, 10/5, 15/5, 20/5, 30/5, 40/5, 50/5, 60/5, 80/5, 100/5, 150/5, 200/5, 300/5, 400/5 and 600/5 A.

Two difficulties arise from this: (1) the tedious process of winding a large number of primary turns for the smaller ratios, and (2) that the following ratios, up to 2 000/5 A, cannot be tested:—

250/5, 500/5, 800/5, 1 000/5, 1 500/5 and 2 000/5 A.

A simple solution in the first case and one which is frequently carried out at the present day is to make use of a wound primary (in addition to the "hole" for the smaller ratios). If this is done, in the case cited, viz. 1 200/5 A ratio, it is possible to test the following ratios by winding the primary:—

60/5, 80/5, 100/5, 150/5, 200/5, 300/5, 400/5 and 600/5 A.

With the addition of a standard transformer the nominal ratio of which with one primary turn is 2 000/5 A, of the remaining British standard ranges from 5/5 to 2 000/5 A the following can be tested:—

250/5, 500/5, 1 000/5 and 2 000/5 A.

This leaves two ratios which have not yet been catered for, viz. 800/5 and 1 500/5 A. In order to include these ratios and to avoid purchasing two more standard transformers, an interesting modification of the method may be adopted. This consists of adding impedance to the potential element of the detector not incorporating the testing-dial resistances, viz. the left-hand element, which impedance must have theoretically the same time-constant as the left-hand potential element in order to produce a torque on that element equal to that which would be produced by a standard transformer having the same nominal ratio as the transformer under test, the standard transformer being wound for a ratio nearest to that of the transformer under test, i.e. to give a greater secondary current.

Considering the case of 800/5 A and 1 500/5 A ratio transformers to be tested, the standard transformer used to test the 800/5 A transformer would be the 1 200/5 A

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* H. W. PRICE and C. K. DUFF: "Current Transformers," *University of Toronto Bulletin*, 1921, No. 2, Section 4.

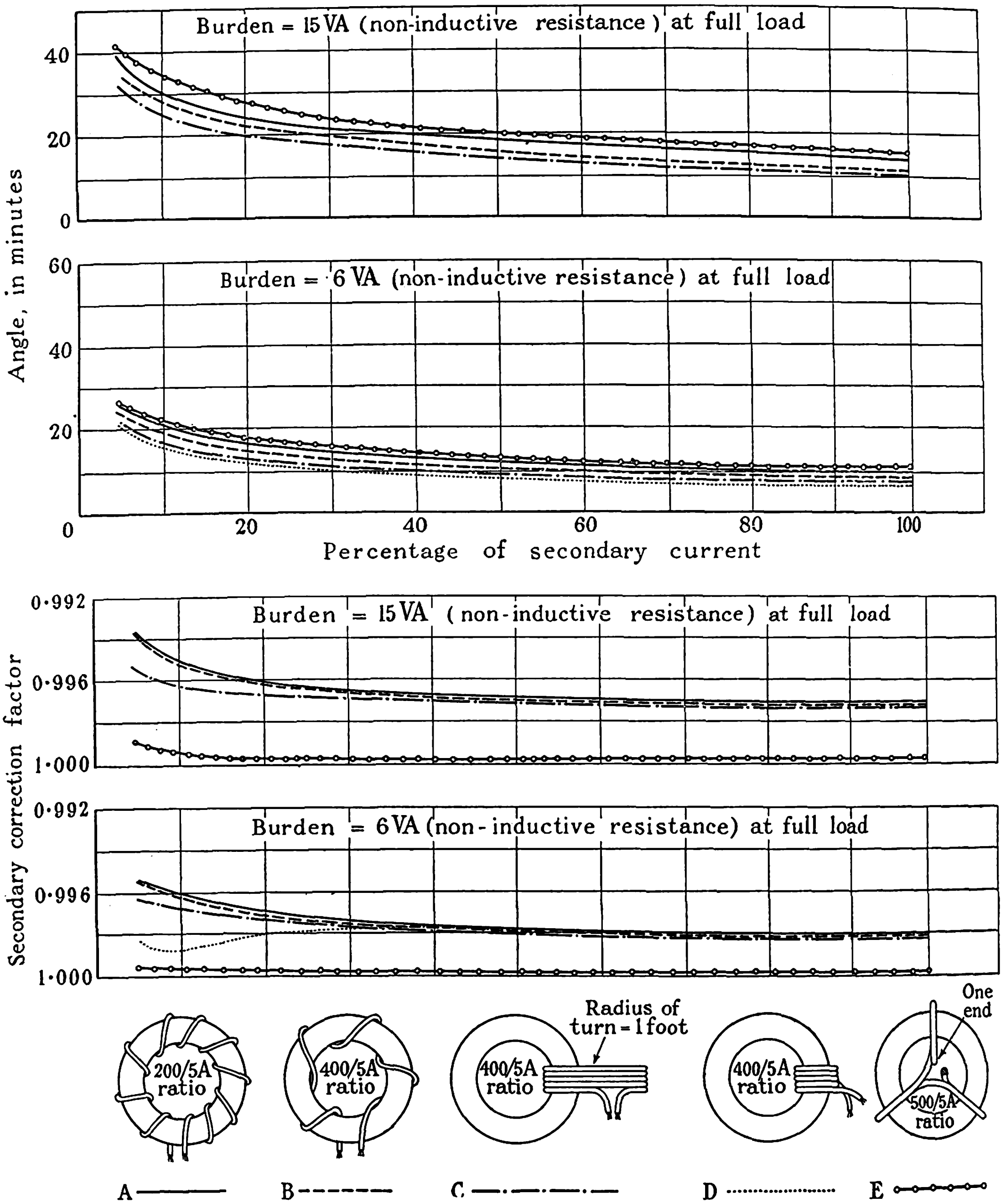

FIG. 16.—Curves showing effect of disposition of primary winding of cu rent transformer.

type wound for a ratio of 600/5 A. The impedance which would have to be added would be equal to:—

$$\frac{800}{600} \times \text{original impedance of left-hand element.}$$

In the case of the 1 500/5 A transformer, the standard transformer used would be the 1 200/5 A type wound as a 1 200/5 A instrument.

The impedance which would have to be added would be equal to:—

$$\frac{1\,500}{1\,200} \times \text{original impedance of left-hand element.}$$

As the reactance of the potential circuit of the detector is very small compared with the resistance, the impedance added can generally take the form of a resistance, with negligible error.

CONCLUSIONS.

The advantages which can be claimed for the method may be summed up as follows:—

(1) It reduces calculation to a minimum.

(2) It is a null method and can therefore be operated by non-technical testers.

(3) The error is read directly from the testing-box dials.

(4) It is accurate and sufficiently sensitive for most commercial requirements.

(5) It is the only method, so far as the author is aware, which with the same apparatus can be used for testing both current and potential transformers.

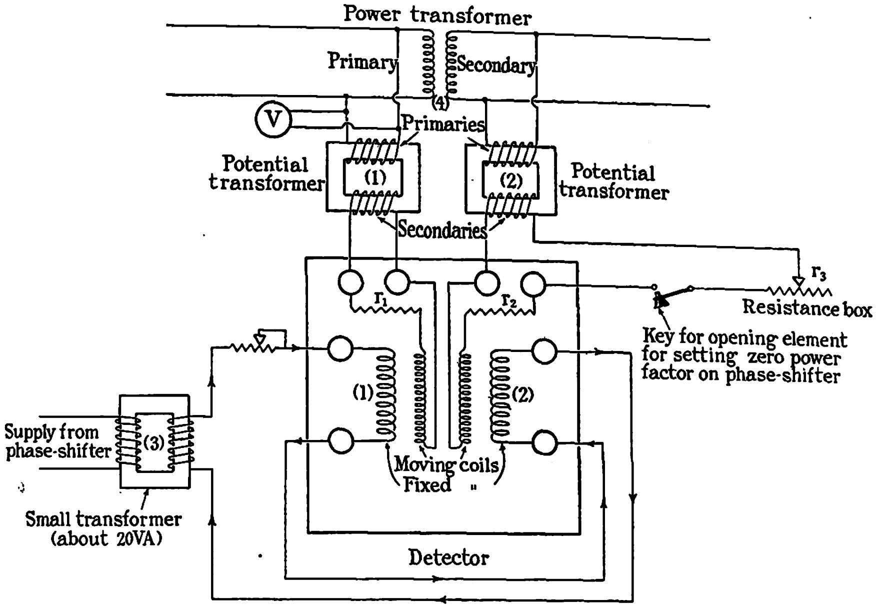
Power transformer
Primary
Secondary
(4)
V
Primaries
Potential transformer
(1)
(2)
Potential transformer
Secondaries
r3
r1
r2
Resistance box
Key for opening element for setting zero power factor on phase-shifter
(1)
(2)
Supply from phase-shifter
(3)
Moving coils
Fixed "
Small transformer (about 20VA)
Detector

FIG. 17.

(6) A minimum of apparatus is required.

(7) It allows rapid operation. The actual time taken to test six transformers for ratio and phase-angle error at one burden on four transformers, and two burdens on two transformers, is approximately 45 minutes, including load setting, but excluding the time taken in connecting the apparatus and transformers.

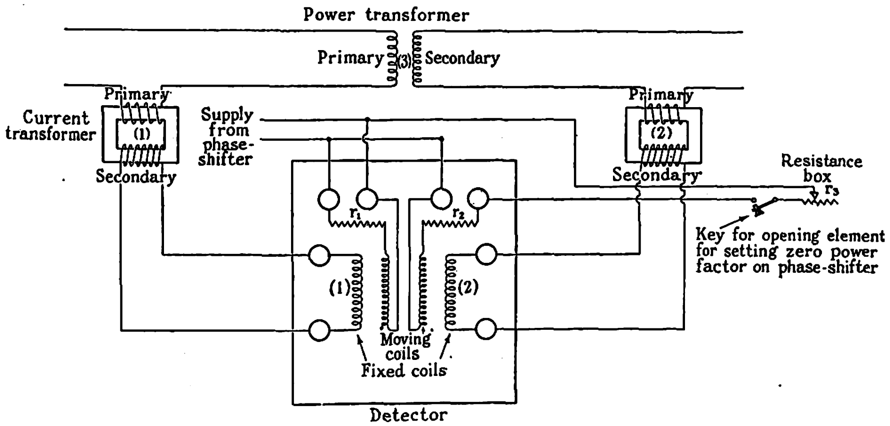
Power transformer
Primary
(3)
Secondary
Primary
Current transformer
(1)
Secondary
Supply from phase-shifter
Primary
(2)
Secondary
Resistance box
r3
r1
r2
Key for opening element for setting zero power factor on phase-shifter
(1)
(2)
Moving coils
Fixed coils
Detector

FIG. 18.

(8) It is the only British test equipment for instrument transformers.

SUGGESTED APPLICATIONS OF THE METHOD.

(1) *The Measurement of Ratio and Determination of the Regulation Curve of a Power Transformer.*—An interesting application of the method is the testing of power transformers for ratio and the determination of the regulation curve, as shown in Fig. 17. A little consideration will show that if the characteristics of the potential transformers are identical, then no allowance will have to be made for their characteristics. If there is a difference, then the algebraic difference between the characteristics of the two potential transformers can be allowed for on the testing-box dials.

In carrying out such a test, the phase angle between the current supply to the fixed and moving coils of the detector is set at 0° by means of the phase-shifter.

The error read on the testing-box dials, after balance has been obtained, is proportional to the ratio between the primary and secondary voltages of the power transformer.

By loading the secondary of the power transformer, a regulation curve can be taken at various loads and power factors, and by obtaining values on a 60° phase angle between the fixed and moving coils the angular displacement of the secondary of the power transformer with respect to its primary can be deduced.

(2) *The Measurement of Iron Losses of a Power Transformer.*—A possible application of the method is for testing the losses of power transformers. This is outlined in Fig. 18, which is a fundamental diagram of such a suggested scheme. In this case, again, if the errors of the two current transformers are identical, then no corrections for these are necessary; whilst, if there is a difference, the algebraic difference between the two characteristics must be corrected for on the testing box.

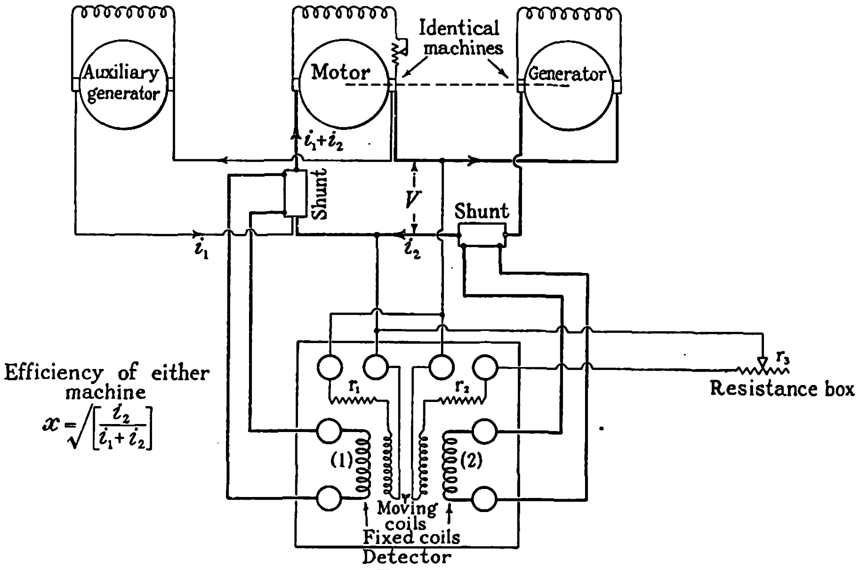

Fig. 19.

Using this method it seems possible to obtain, by means of a 0° test (i.e. 0° between the fixed and moving coils of the detector, established by means of the phase-shifter) and a 60° test (60° between the fixed and moving coils), the iron and copper losses of a power transformer by deduction from the phase angle so ascertained between the reversed secondary vector and the primary vector of the power transformer.

If several loads are taken on the power transformer, and ratio and angle tests are also taken, the complete characteristics of a power transformer can be analysed. This, however, the author leaves for further development to those interested in the testing of power transformers.

(3) *The Application of the Method to Hopkinson's Efficiency Tests on D.C. Machines.*—As a matter of interest, another suggested application of the method is its use in conjunction with the Kapp modification of the Hopkinson efficiency tests on d.c. machines, which is shown outlined in Fig. 19.

Shunts are used for the supply of current to the fixed coils of the detector, and the combined losses of the two identical machines are read directly from the testing box.

The efficiency of either machine can readily be deduced by applying the usual formula.

Other applications of the method might be developed, e.g. its use for determining the efficiency of a rotary convertor.

Finally, the author would like to thank the chief engineer of the North Metropolitan Electric Power Supply Co.—Captain J. M. Donaldson—for permission to publish results of tests taken in the company's laboratory. He is also indebted to Mr. W. Casson for assistance in the preparation of the paper and for suggestions as to other applications of the method, and to Mr. E. W. Hill for valuable suggestions.

APPENDIX.

LIST OF SYMBOLS.

I_p = primary current;
I_1 = secondary current of standard current transformer;
I_2 = secondary current of unknown current transformer;
ϕ = angle of lead or lag between I_p and V;
V = applied voltage to pressure coils of detector;
θ_1 = angle error of standard current transformer;
θ_2 = angle error of unknown current transformer;
γ_1 = angle of left-hand potential element;
γ_2 = angle of right-hand potential element;
r_1 = resistance of left-hand potential element;
r_2 = resistance of right-hand potential element;
r_3 = resistance added or subtracted on right-hand potential element in 0° test;
r_4 = resistance added or subtracted on right-hand potential element in 60° test;
L_1 = coefficient of self-induction of left-hand potential element;
L_2 = coefficient of self-induction of right-hand potential element.

CURRENT-TRANSFORMER TESTING.

(1) *Balance Test.*—Let the fixed coils be connected in opposition and in series with a source of e.m.f. so that a current I flows through the coils.

Let the potential coils be connected to a source of e.m.f., V, in phase with current I.

When balance conditions are obtained

$$I\frac{V}{\sqrt{[r_1^2 + (\omega L_1)^2]}}\cos\gamma_1 = I\frac{V}{\sqrt{[r_2^2 + (\omega L_2)^2]}}\cos\gamma_2$$

If $L_1 = L_2$ and $\gamma_1 = \gamma_2$

then $r_1 = r_2 = r$

(2) 0° *Test.*—Let the fixed coils be connected to the secondaries of the standard and unknown current transformers respectively.

Let the potential elements be connected in parallel to a source of e.m.f. in phase with the primary current.

Assume, for simplicity, that the standard current transformer has no errors.

Then $I_1\dfrac{V}{r_1}\cos\phi = I_2\dfrac{V}{(r_2 \pm r_3)}\cos(\phi \pm \theta_2)$ for balance.

Since $\phi = 0°$ and θ_2 is small, $\cos(\phi \pm \theta_2)$ can be expressed as unity.

$$\therefore \frac{I_1}{I_2} = \frac{r_1}{(r_2 \pm r_3)}$$

and, since from balance test $r_1 = r_2 = r$,

then $\dfrac{I_1}{I_2} = \dfrac{r}{(r \pm r_3)}$

(3) 60° *Test.*—Let the fixed and potential coils be connected as in the 0° test and let a phase difference of 60° between I_1 and V be imposed. Assume that the standard current transformer has no angle error. Then

$$I_1\frac{V}{r}\cos\phi = I_2\frac{V}{(r \pm r_4)}\cos(\phi \pm \theta_2) \text{ for balance}$$

Therefore $\dfrac{\cos\phi}{\cos(\phi \pm \theta_2)} = \dfrac{r}{(r \pm r_4)} \times \dfrac{I_2}{I_1}$

But from the 0° test $\dfrac{I_2}{I_1} = \dfrac{(r \pm r_3)}{r}$.

Substituting, we obtain

$$\frac{\cos\phi}{\cos(\phi \pm \theta_2)} = \frac{r}{(r \pm r_4)} \times \frac{(r \pm r_3)}{r}$$

and

$$\frac{\cos\phi}{\cos(\phi \pm \theta_2)} = \frac{(r \pm r_3)}{(r \pm r_4)} = \text{angle correction-factor}$$

Therefore the angle correction-factor equals the resistance of the potential element and the resistance added or subtracted at the 0° test, divided by the resistance of the potential element and the resistance added or subtracted at the 60° test. (The same method applies to the allowance for the errors of the standard current transformer.)

(4) *Effect of Standard Current-Transformer Angle Error.*—The phase-shifter setting for zero power factor is made on the left-hand element of the detector.

Assume that the standard current transformer has an angle error of + 1° (i.e. the reversed secondary vector leads the primary vector), then conditions are as follows:—

The left-hand element is connected to the secondary of the standard current transformer and has exactly 60° phase difference between the fixed and moving coils.

On the right-hand element, due to the standard current-transformer angle, the phase difference between the fixed and moving coils is only 60° − 1° = 59°, i.e. the angle between I_p and V; and although this has no effect on the 0° test, on the 60° test a slight error may be introduced.

The standard current-transformer angle is compensated for by adding resistance to the right-hand element potential circuit.

Hence

$$I\frac{V}{r}\cos 60° = I\frac{V}{(r + 3{\cdot}0\,\%\,r)}\cos 59° \text{ for balance,}$$

where 3 per cent is the figure which would be given as the correction for 60 minutes for the standard current transformer.

Now if the unknown transformer is connected to the right-hand potential element with an angle of, say, + 3°, then

$$I\frac{V}{r}\cos 60° = I\frac{V}{(r \times 1{\cdot}0309 \times F_c)}\cos 62° \text{ for balance,}$$

where F_c = correction factor of the percentage resistance added or subtracted for the angle error of the unknown transformer.

Therefore

$$F_c = \frac{\cos 62°}{\cos 60° \times 1{\cdot}0309} = 0{\cdot}911$$

If the standard current transformer had no angle error, then the correction factor (calculated) of the unknown transformer for an angle of + 3° would be derived as follows:—

$$I\frac{V}{r}\cos 60° = I\frac{V}{r \times F_c}\cos 63°$$

$$\therefore F_c = \frac{\cos 63°}{\cos 60°} = 0{\cdot}908$$

If the angle error of the unknown current transformer were calculated on a basis of 60°, then from the correction factor derived in the case when the standard current transformer had an error of + 1° there would be an error of 0·3 per cent; but, if necessary, the calculations for derivation of the angle could be based on 59° or (60° ∓ the standard current-transformer angle) to give absolute values.

When it is considered, however, that a good standard current-transformer angle error only varies from a few minutes at full load to 30 minutes at 1/20th full load, the calculations can be made on a basis of 60° for most commercial purposes.

The simpler method, however, is, after setting for 90° on the left-hand element between I_1 and V, to set the phase-shifter minus the standard angle error for positive angles, and vice versa for negative angles, at both the 0° and the 60° tests. This will give a setting of 0° and 60° respectively between I_p and V for the two tests.

(5) *Effect of Reactance in Potential Circuit of Detector.*—Provided the angles are identical in both elements, no error can accrue, since the angular difference between the fixed and moving-coil currents is fixed by the phase-shifter.

If there is an angular difference, this can be compensated for by adding or subtracting resistance at a 60° balance test.

The same reasoning applies to the testing of potential transformers.

[The discussion on this paper will be found on page 906.]

SOME ACCESSORY APPARATUS FOR PRECISE MEASUREMENTS OF ALTERNATING CURRENT.

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[From the National Physical Laboratory.]

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Summary.

The paper describes apparatus for obtaining for purposes of measurement a voltage proportional to, and in phase with, a given alternating current. The Introduction outlines defects in the water-cooled tube resistors which have been in use at the National Physical Laboratory for this purpose; these defects have led to the construction of air-cooled resistors for moderate currents, and current transformers with nickel-iron cores for heavy currents. Section (1) deals with the requirements for the air-cooled resistors, and with theoretical and practical points in their design; tests showing very satisfactory performance are described. Section (2) outlines the construction of the special current transformers, and deals at some length with the method of calibrating them. Finally, the effects of a number of variables on the transformer performance are investigated: the characteristics are shown to be very good, and no sign of instability is found.

Introduction.

In the measurement of alternating current and power by electrostatic methods, it is generally necessary to employ apparatus capable of providing a voltage of the order of 2 volts, proportional to, and in phase with, the current to be measured. Usually a "non-inductive" resistor is used, and the design of such resistors has been given considerable attention.

At the National Physical Laboratory air-cooled resistors have been used for currents up to 20 amperes. Beyond this value, and up to 2 000 amperes, manganin tubes, internally water-cooled and specially compensated for self-inductance, have been employed. An account of the latter type has been published in the *Journal*.*

The experience gained with the tube resistors during the last 20 years has shown that they have certain disadvantages. In the first place the resistance tends to increase, owing to cracking of the film of enamel which covers the internal surface, and subsequent corrosion by the water. This effect is only serious in the smaller sizes, but necessitates their adjustment by shunting at rather frequent intervals. A second difficulty is that the residual inductance of the larger tubes is neither as small nor as constant as is desirable. The reduction of this quantity was, of course, one of the main objects of the design, and it does not appear possible to improve much on the figures obtained, which correspond to a phase angle of about 3 minutes at 50 cycles per sec. for the 2 000-ampere size. A phase error of this magnitude could be tolerated if it were satisfactorily constant; but it has been found, using a method due to Hartshorn,* that variations of the order of 2 minutes can be made by varying the disposition of the connecting leads.

Further difficulties were introduced a few years ago by the necessity for measuring currents in excess of 2 000 amperes. It had originally been intended to build resistors of similar design for 5 000 amperes. In order to keep down the phase angle, the manganin tube for such resistors should be about 12 cm in diameter and about 1 mm thick; but it does not appear possible to procure such tubing commercially. Even if it were possible to build the resistors, the amount of power which they would dissipate would be a serious problem; a 3-phase set-up, in which three resistors are used to preserve balance, would absorb 30 kW at 5 000 amperes.

The smaller sizes of water tubes have recently been eliminated by the design and construction, at the Laboratory, of air-cooled resistors to carry currents of 50, 100 and 200 amperes. These are described in the next Section. Air-cooled resistors are, naturally, larger than water-cooled resistors of equal capacity, and it has not been thought advisable to adopt this type for currents above 200 amperes, on account of the extreme bulk entailed. While this matter was being considered, however, the remarkable properties of nickel-iron alloys of high nickel content became known, and it was at once seen that current transformers with cores of such materials might solve at one stroke all the difficulties in the design of heavy-current resistors. Assuming that transformers could be obtained with satisfactory characteristics, it would merely be necessary to connect an accurate resistor of 0·4 ohm, the construction of which presents no difficulty, in the secondary circuit of, say, a 5 000/5 transformer, when the assembly would be the equivalent of a 5 000-ampere non-inductive resistor giving a 2-volt drop, except that the power loss would be of the order of 50 watts instead of 10 kW. Everything, of course, depended on the accuracy and stability of the transformer, and it was decided to make a detailed investigation of these points; the provision of a 5 000-ampere measuring device being the most urgent problem, transformers of this range were selected for the work. For this purpose a specification was drawn up, and three 5 000/5 transformers, in accordance therewith, were obtained from Messrs. Everett, Edgcumbe and Co., Ltd. Section (2) gives an account of the results obtained with these transformers.

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* C. C. Paterson and E. H. Rayner: "Non-Inductive Water-Cooled Standard Resistances for Precision Alternating-Current Measurements," *Journal I.E.E.*, 1909, vol. 42, p. 455.

* L. Hartshorn: "The Measurement of the Inductance of Four-Terminal Resistance Standards," *Proceedings of the Physical Society of London*, 1927 vol. 39, p. 377.

(1) AIR-COOLED NON-INDUCTIVE RESISTORS.

(*a*) *Requirements*.—The purposes for which these resistors are used are:—(i) for testing ammeters; (ii) for testing wattmeters and watt-hour meters; (iii) for use with a.c. potentiometers; (iv) for testing current transformers; and (v) for standards of resistance and phase angle in a.c. bridges.

It has been found that, in order to obtain sufficient sensitivity for certain of these tests, a voltage-drop of the order of 2 volts is required. A range of resistors is therefore required, of such values that it is possible to obtain a p.d. of 1 or 2 volts for any current. Air-cooled resistors have been designed and constructed at the Laboratory to give a voltage-drop of 2 volts when carrying currents of 1, 2, 5, 10, 20, 50, 100 and 200 amperes respectively. The same general principles of design have been followed in all these resistors. The difficulties involved increase with an increase in current, and it is proposed, therefore, to describe in detail the design of the 200-ampere resistor only.

For the tests (i), (ii) and (iii) referred to above, an accuracy of 0·1 per cent is usually required; and it is desirable to be able to obtain this accuracy without the necessity for applying corrections to the nominal value of the resistance. Bearing in mind the possibility of similar errors in the determination of the voltage component in power measurements, it is probably necessary, in order to obtain an accuracy of 0·1 per cent, that the actual value of the resistance should not deviate more than 2 parts in 10 000 from its nominal value under all conditions of loading and room temperature, and that the residual phase angle should not introduce an error of more than 2 parts in 10 000. The residual phase angle will not introduce appreciable error into measurements of current or of power at unity power factor, but an error which reaches a maximum at zero power factor is introduced into the measurement of power at low power factors. Power factors under 0·5 are not often required in routine test work: at this power factor a residual phase angle of 0·4 minute causes an error of 2 parts in 10 000 in the power measurement, and this value, therefore, should not be exceeded. The residual phase angle is proportional to the frequency, which is now standardized in this country at 50 cycles per sec. For this frequency, a phase angle of 0·4 minute corresponds to a time-constant (inductance ÷ resistance) of 4×10^{-7}.

For tests (iv) and (v) above it is sometimes necessary to attain the greatest accuracy possible, and for this purpose the true value of the resistance should be used and a correction should be made for the residual phase angle. The temperature-rise of the larger sizes of these resistors is considerable, but it has been found possible, by using selected constantan wire, to keep the resistance constant to within 1 part in 10 000 for any current not exceeding rated current. The true resistance may, therefore, be determined to this limit. The residual phase angle of a resistor may be determined to within 0·05 minute at 50 cycles per sec., but, unless the resistor is carefully designed, this phase angle will be altered by stray magnetic fields produced by currents in neighbouring conductors. If large loops in the current circuit are avoided, the phase angle of the air-cooled resistors remains constant to within 0·05 minute.

(*b*) *Principles of Design*.—The main principle of the design was to construct a single non-inductive circuit of comparatively high resistance which will be referred to as a " unit." Lower-resistance circuits were then obtained by the simple multiplication of units in parallel. Resistances of this type, designed by Mr. C. C. Paterson and Dr. E. H. Rayner, have been in use at the Laboratory for many years. Provided that the mutual inductance between units is negligible, the time-constant of the whole resistor is substantially independent of the number of units. This conclusion is modified in practice by the inductance of the busbars which connect the units in parallel.

The " unit " resistance adopted was 2 ohms, with a rated current of 1 ampere.* The material of which it is made consists of 2 constantan wires which are separately double-silk-covered, and then laid flat and single-silk-covered over all. A length of about 40 in. of this bifilar wire constitutes the unit. The two individual wires are soldered at one end to a busbar, which forms the mid-point of the resistor. The free ends are connected respectively to the two main busbars, by means of which the current is led in and out of the resistor. The time-constant of this unit may be estimated very easily, and is found to be approximately 2×10^{-7}, that is, one-half the value which, in the last Section, was decided to be reasonable. In the light-current resistors the inductance of the busbars adds little to this figure, but, as the number of units in parallel is increased, the busbars increase both in length and in section, until, finally, the inductance of the busbars becomes the dominating factor.

Now, all these resistors are constructed as 4-terminal resistors; that is to say, the current is led in and out through one pair of terminals, and the voltage-drop across the resistor is measured between another pair of terminals which are connected to suitable points in the busbars. The points on the busbars to which the voltage terminals are connected will be referred to as the " voltage points." The impedance of the resistor is defined as the ratio of the voltage across the voltage terminals to the current entering and leaving the current terminals. The phase angle of the resistor is defined as the phase angle between the voltage across the voltage terminals and the current entering and leaving the current terminals. It is clear, therefore, that if the impedance of the busbars is an appreciable part of the impedance of the whole resistor, the impedance of the latter will depend on the position of the voltage points. The selection of suitable voltage points is of the greatest importance for heavy-current resistors. If the number of units connected in parallel to the busbars is large, the problem is analogous to that of determining the voltage at any point across a transmission line, with inductive leakage, and inductance and resistance in the line. The busbars constitute the line and the units connected to it constitute the leakage. Capacity effects may be neglected. The problem is solved on this basis in e Appendix, and it is there found that if the voltage points are at the opposite end of the busbars to the current terminals, the inductance of the resistor will be equal to the inductance of the units * minus one-sixth of the inductance of the busbars. If the inductance of the busbars is more than 6 times the inductance of the units, the resistor will have a leading phase angle. On the other hand, if the voltage points are at the same end of the busbars as the current terminals, the inductance of the resistor will be equal to the inductance of the units plus one-third of the inductance of the busbars. Provided, therefore, that the inductance of the busbars is greater than 6 times the inductance of the units, it is possible to select voltage points so as to make the resistor non-inductive. The results of this analysis are slightly modified in practice by the finite number of units connected to the busbars and also by the relative magnitudes of the section and length of the busbar. The selection of the correct voltage points is therefore carried out experimentally. Thus the time-constants of the light-current resistors are approximately 2×10^{-7}, and this figure can be reduced still further in the heavier-current resistors by the selection of suitable voltage points. The time-constants of these resistors will to some extent be affected by magnetic fields. It is of little use to adjust the voltage points carefully to give zero phase angle, if the magnetic fields produced by the currents in the conductors in other parts of the circuit disturb this phase angle. The magnetic fields which these resistors may encounter are proportional to the current in the circuit, and it is evident that far more attention must be given to the effect of these magnetic fields in the case of heavy-current resistors than is necessary for the smaller sizes.

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* In some of the light-current resistors constructed, a unit of 4 ohms was adopted in order to make the adjustment of the resistance to its nominal value more easy.

Magnetic fields may affect the resistor in two ways. In the first place, the effective inductance of the resistor may be altered. It may be safely assumed that magnetic fields will have little, if any, effect on the effective inductance of the units. The wires of each unit are not twisted up together, but the disposition of the wires carrying currents in reverse directions in the different units is sufficiently haphazard to ensure that any small e.m.f. induced in one unit will be offset by other e.m.f.'s in other units. On the other hand, the busbars consist of two rectangular bars side by side, and it is possible for an appreciable e.m.f. to be induced between them by a magnetic field. The solution of this problem was found in duplicating the busbars and connecting one-half of the total number of units to each pair of busbars (see Fig. 2). The four bars were arranged side by side, and the two outer bars were connected to one current terminal and the two inner bars to the other current terminal. Thus a uniform magnetic field would induce equal and opposite e.m.f.'s in each pair of busbars, and the inductance of the whole resistor would be unaffected.

Secondly, magnetic fields may induce an e.m.f. in the leads between the voltage points and the measuring instruments. Such an e.m.f. would alter the effective phase angle of the resistor. These leads are carefully twinned together so as to avoid trouble from this cause. The leads are, however, in two sections, first from the voltage points to the voltage terminals fixed to the side of the box enclosing the resistor, and, secondly, external leads, which do not form part of the resistor, from these terminals to the measuring instrument. An ordinary pair of terminals would be separated by an appreciable amount, and, in the loop thus formed, it would be possible for a magnetic field to induce an e.m.f. A special voltage connector which is free from this defect has therefore been designed, and is described later.

The temperature-rise of these resistors is a factor which requires consideration, since in the 200-ampere size the energy dissipated amounts to 400 watts. It is found experimentally that if provision is made for a natural circulation of air, the temperature-rise of the units is practically independent of the spacing between them. A natural circulation is ensured by leaving openings in the resistor box at the top and the bottom: the spacing between units varies from ½ in. for the light-current resistors to ⅙ in. in the 200-ampere size, where the spacing is reduced to the minimum practicable in order to keep the size of the whole resistor moderate. The actual temperature-rise of the units in the 200-ampere resistor is from 40 deg. C. to 50 deg. C., and it is therefore essential that the temperature coefficient of the wire employed should be very small. The temperature coefficient of commercial constantan is very variable, and samples from different melts may vary from a few parts in 100 000 per deg. C. positive to as much as 8 parts in 100 000 per deg. C. negative. The wire used in the construction of these resistors was obtained by selection, and has a temperature coefficient per deg. C. of a few parts in a million.

The adjustment of the resistances of these resistors to their nominal values is a point of importance. The resistors are wound in the first place so as to have approximately the correct resistance. Suitable voltage points are then selected, experimentally, to give the smallest phase angle attainable. The resistance is then adjusted to its nominal value by the adjustment of one or more units. Usually this final adjustment will not have an appreciable effect on the phase angle. If the resistance is higher than its nominal value, the adjustment is very easily made by short-circuiting the two wires of a unit some distance from the mid-point busbar. This lowers the resistance of this unit below 2 ohms, and, therefore, increases its temperature-rise. To avoid this each resistor, in the heavier-current sizes, has one unit with a resistance of rather more than 2 ohms, and adjustment is carried out on this unit. In the 200-ampere size there are 200 units in parallel, and a considerable alteration of the resistance of one unit will have very little effect on the value of the total resistance. It is therefore very easy to adjust the total resistance to any desired accuracy. In the lighter-current resistors, where there are fewer units in parallel, the adjustment requires more care.

A few words may be said about the mid-point of the resistor. The mid-point is used for wattmeter measurements, with a fictitious load. One terminal of the voltage circuit is connected to the mid-point of the current resistor, while the other terminal is connected to the needle of the electrostatic wattmeter. The

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* By the inductance of the units is meant their total inductance when connected in parallel; i.e. if inductance of 1 unit = L_1 and there are 200 units, combined inductance of 200 units = $L = L_1/200$, neglecting mutual inductance between units.

voltage connector on each resistor has therefore three points, one to each current busbar and the third to the mid-point busbar. It is desirable to keep all three leads twisted together to avoid trouble from magnetic fields; but, as the needle voltage of the wattmeter is 100 volts, little error is introduced by small departures of the nominal mid-point of a resistor, with 2 volts drop, from its actual mid-point.

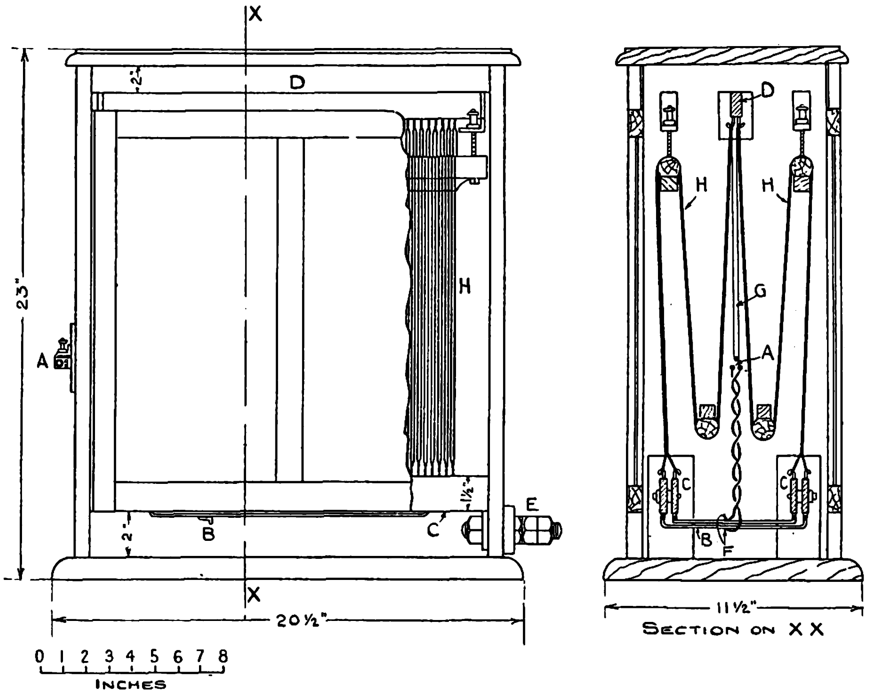

Fig. 1.—Elevation and section of 200-ampere resistor.

A = 3-point voltage connector (detail drawings shown in Figs. 3 and 4).
B = Paralleling conductors at voltage points, 0·104 in. diameter copper.
C = Current busbars.
D = Mid-point busbar.
E = Current terminals.
F = Voltage points (" twinned " copper leads of 0·048 in. diameter from these points to voltage connector A).
G = Copper lead, 0·104 in. diameter, from mid-point busbar to voltage connector A.
H = Resistance units.

Note.—Separate low-resistance voltage connections with terminals were provided for measuring the resistance with direct current on the Kelvin double bridge. These are omitted from the diagram for the sake of clearness.

(*c*) *Design Details of the 200-Ampere Resistors.*—The resistor is mounted in an oak framework, which is shown in Fig. 1. The two side-panels are removable and the top is hinged. The current busbars are fixed near the bottom of the box in a horizontal position. The current terminals are at one end of the box, and the voltage connector is at the other end. Thus the voltage leads need not be taken near the heavy-current conductors, and the danger of induced e.m.f.'s from the magnetic fields of the latter is minimized. The busbars are constructed of brass and have a cross-section of $1\frac{1}{2}$ in. × $\frac{5}{16}$ in. They are shown in plan in Fig. 2. Copper hooks are soldered into the tops of the busbars at intervals of $\frac{1}{3}$ in., and the ends of two units are soldered to each hook. The units are carried over wooden supports to the mid-point busbar, which is fixed at the top of the box. An elevation showing the arrangement of two units, one going to each pair of current busbars, is shown in Fig. 1. The units were made up in pairs: that is to say, an 80-in. length of double wire was bent over at its mid-point, and this mid-point was soldered to a hook on the mid-point busbar. The ends of this double unit were then soldered to hooks on the current busbars. Since the exact voltage points were not known until the resistor was wound, a copper wire was fixed under each busbar running along the major portion of its length, and soldered into it near either end. The voltage terminals were soldered to suitable points on these wires. Since there were duplicate busbars, the wires underneath them were paralleled at the voltage point (see Fig. 1). The diameter of these wires was 0·104 in., so that small equalizing currents could flow between the busbars without much voltage-drop.

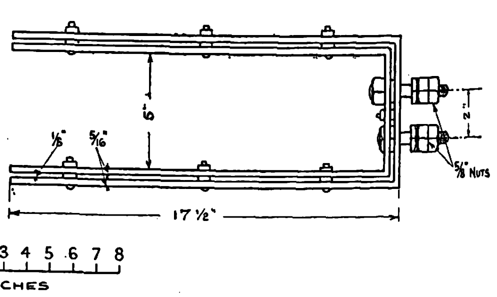

Fig. 2.—Plan of current busbars.

The design of the voltage connector is shown in Figs. 3 and 4. It may be seen from Fig. 4 that there are two loops, one in each half of the connector. Each of these loops is extremely small, and the method of cross-connecting the leads in one causes any e.m.f.'s induced in them to oppose each other. The complete connector is almost absolutely astatic to magnetic fields.

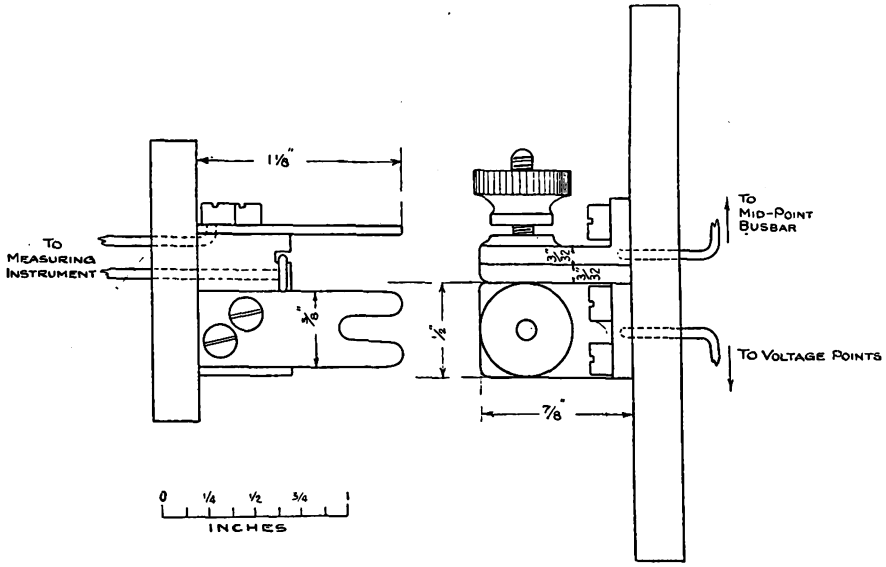
1⅛"
To Measuring Instrument
3/32
3/32
⅜"
½"
To Mid-Point Busbar
To Voltage Points
⅞"
0
¼
½
¾
1
INCHES

Fig. 3.—Elevation of 3-point voltage connector.

(*d*) *Performance of the* 200-*Ampere Resistor.*—The completed resistor was subjected to a series of tests in order to determine whether its performance reached the standard required. The change of resistance with rated current from the resistance when cold was less than **1 part in 10 000.** The change due to variation of ambient temperature was entirely negligible. The time-constant was experimentally adjusted to be less than $0 \cdot 5 \times 10^{-7}$, i.e. the phase angle at 50 cycles per sec. was less than 0·05 minute.

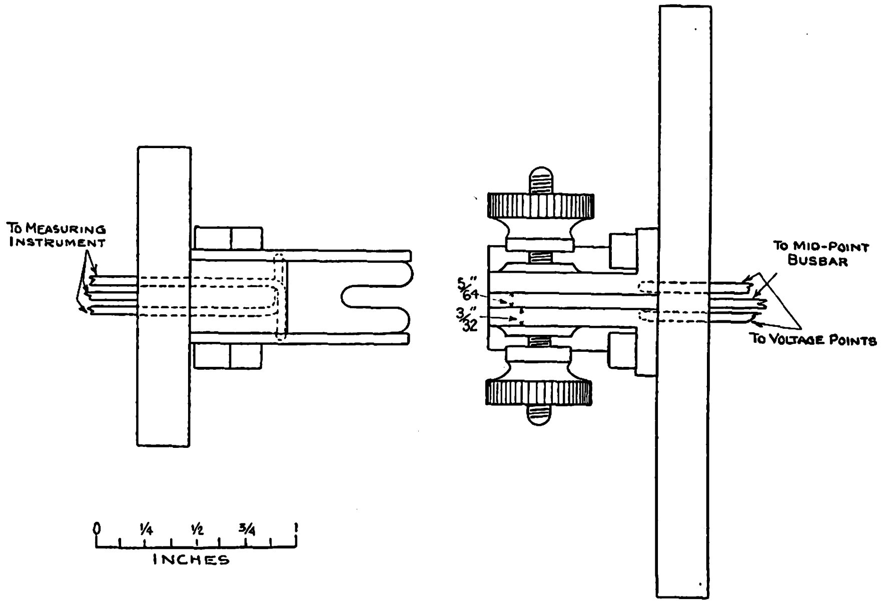
To Measuring Instrument
5/64"
3/32"
To Mid-Point Busbar
To Voltage Points
0
¼
½
¾
1
INCHES

Fig. 4.—Inverted plan view of 3-point voltage connector, showing crossed leads in one half to render the connector astatic.

The resistor was then subjected to a test for stray magnetic field. The field produced at the centre of a circle, 1 metre in diameter, by the rated current of 200 amperes flowing round the circumference is equal to 2·5 C.G.S. units. This was adopted as the basis of tests. The resistor was subjected to a uniform alternating field of 2·5 C.G.S. units in various directions while carrying rated current: no change of phase angle greater than 0·1 minute was observed. The field was in time-phase with the resistor current. To determine the effect of non-uniform fields, a conductor carrying 200 amperes was placed in close proximity to the resistor, in various positions; again no change of phase angle greater than 0·1 minute was observed.

The resistor is mounted on a trolley, and the leads to it are normally taken downwards together, and then away from the resistor. Under normal conditions of use, therefore, the resistor will not be subjected to a field as strong as 2·5 C.G.S. units, and the phase angle may be assumed to be constant to within 0·05 minute.

(2) HIGH-RATIO CURRENT TRANSFORMERS.

(*a*) *Construction.*—The core of each transformer consists of jointless rings of mumetal, and carries a secondary winding of 999 turns: in order to minimize the effect of stray magnetic fields the winding was distributed as uniformly as possible round the core. The transformer was supplied uncased, and was mounted at the Laboratory in a substantial teak housing approximately 11 in. × 11 in. × 6 in., care being taken to avoid mechanical strains on the core material. In the centre of the casing is a circular hole $3\frac{1}{2}$ in. in diameter through which cables can be passed to form the primary winding. With a single cable through this aperture the ratio of the transformer is 5 000/5 amperes, the ratio compensation obtained by the omission of one secondary turn being almost exact.

(*b*) *Calibration.*—It has been mentioned that these transformers have been developed in order to provide means of measuring currents for which resistance standards are not available; it is therefore at once obvious that the usual method of direct calibration against water-cooled manganin standards is not applicable. Experience suggested that the characteristics of the transformer were likely to be practically independent of the number of turns in the primary winding, more especially in view of the uniform distribution of the secondary winding: evidently if this proved to be the case the calibration could be made with a number of primary turns such that full ampere-turns were obtained with a relatively light current. This would allow the use of the very satisfactory 200-ampere resistance standard already described.

To determine whether the characteristics of the transformer are actually independent of the number of primary turns, measurements were first made using the 200-ampere air-cooled resistors and the 1 000- and 2 000-ampere water-cooled manganin tubes as standards. Since it was desired to push the investigation to the limit of accuracy which the transformers would allow, somewhat elaborate precautions were taken to ensure that the phase angles of the standards could be determined accurately. Long copper extensions were attached to the current terminals of the tube resistors, so as to ensure that the stray field due to the current circuit should be constant, whilst special attention was given to the disposition of the apparatus and leads. The phase angles of all the standards used were measured by a bridge method immediately after the tests.

Observations were made with 1, 2, 5, 10 and 25 primary turns. In the cases of 1- and 2-turn primaries the calibration could not, of course, be carried up to the full ampere-turns of the transformer, since the largest resistance standard carries only 2 000 amperes. The measurements showed that under any given set of conditions the characteristics of the transformer were the same for 25, 10 and 5 primary turns, within 0·01 per cent for ratio and 0·1 minute for phase angle, i.e. within the limit of accuracy of the difference measurements. The values for two turns and one turn showed a similar agreement for ratio, but differences of 0·2 minute in phase angle occurred.

These latter values were, of course, obtained with the large tube resistors, and it was not known whether they were due to genuine "turn effects" or to uncertainties in the measurements of the phase angles of the resistors. The figures for 25, 10 and 5 turns were obtained with the air-cooled standards, and are believed to be quite reliable. It was therefore decided to investigate the matter further by direct comparison of two similar transformers having different numbers of primary turns.

Two sets of tests were made. In the first set one transformer, referred to as A, had twice as many primary turns as the other transformer, referred to as B. In the second set A had 4 times as many turns as B. The results obtained are shown in Table 1, the ratio differences being given to 0·01 per cent, and the phase-angle differences to 0·05 minute.

TABLE 1.

Primary turns		Fraction of full ampere-turns		Ratio difference	Phase-angle difference
A	B	A	B	B–A	B–A
				per cent	minute
26	13	1/1	1/2	$0\cdot0_0$	$+0\cdot3_5$
8	4				$+0\cdot3_5$
4	2				$+0\cdot3_5$
2	1				$+0\cdot2_5$
26	13	2/5	1/5	$0\cdot0_0$	$+0\cdot3_5$
8	4				$+0\cdot3_0$
4	2				$+0\cdot3_5$
2	1				$+0\cdot4_0$
26	13	1/5	1/10	$0\cdot0_0$	$+0\cdot3_0$
8	4				$+0\cdot2_0$
4	2				$+0\cdot3_5$
2	1				$+0\cdot4_0$
24	6	4/5	1/5	$0\cdot0_0$	$+0\cdot5_0$
12	3				$+0\cdot3_5$
8	2				$+0\cdot4_5$
4	1				$+0\cdot5_0$
24	6	2/5	1/10	$0\cdot0_0$	$+0\cdot4_0$
12	3				$+0\cdot2_5$
8	2				$+0\cdot3_5$
4	1				$+0\cdot3_5$

It will be seen from these results that the ratio difference between the transformers is the same for any given ratio of primary turns, whatever may be the actual numbers of turns. It is already known from the comparison with resistance standards that there is no significant "turn effect" when the number of primary turns is 5 or more. The present results therefore show that no such effect occurs over the whole range of numbers of turns employed, and confirm the values obtained with the tube resistors.

For phase angle, differences up to 0·2 minute occur for a given turn-ratio. These differences are, however, not systematic, and are therefore not genuine turn effects. They are of exactly the same order as those found in the comparisons with resistance standards.

The explanation of the discrepancies was found to lie in small differences of phase angle which were produced by varying the distribution of the primary winding on the core. When only one or two primary turns are employed, there is a tendency for the primary magnetomotive force to be concentrated over a small region of the core, and under these conditions leakage of flux and slight lack of uniformity in the secondary winding produce small variations in phase angle. When the number of primary turns is large, the distribution is naturally more symmetrical and the trouble does not arise. A set of tests was made in which the distribution of a small number of primary turns was deliberately varied over a considerable range. The maximum resultant variation of phase angle was 0·2 minute.

TABLE 2.

Frequency	Burden	Fraction of full ampere-turns	True ratio* / Nominal ratio	Phase angle †
cycles/sec.	VA			minutes
50	5	1/1	$1\cdot000_0$	$+0\cdot{}_6$
		3/4		$+0\cdot{}_6$
		1/2		$+0\cdot{}_7$
		1/5		$+0\cdot{}_8$
		1/10		$+0\cdot{}_8$
50	12·5	1/1	$1\cdot000_0$	$+0\cdot{}_7$
		3/4		$+0\cdot{}_7$
		1/2		$+0\cdot{}_8$
		1/5		$+0\cdot{}_9$
		1/10		$+0\cdot{}_9$
50	25	1/1	$1\cdot000_0$	$+0\cdot{}_8$
		3/4		$+0\cdot{}_9$
		1/2		$+1\cdot{}_0$
		1/5		$+1\cdot{}_1$
		1/10		$+1\cdot{}_2$
25	12·5	1/1	$1\cdot000_0$	$+1\cdot{}_1$
		3/4		$+1\cdot{}_2$
		1/2		$+1\cdot{}_4$
		1/5		$+1\cdot{}_6$
		1/10		$+1\cdot{}_7$
100	12·5	1/1	$1\cdot000_0$	$+0\cdot{}_4$
		3/4		$+0\cdot{}_4$
		1/2		$+0\cdot{}_4$
		1/5		$+0\cdot{}_5$
		1/10		$+0\cdot{}_5$

It appears from the results discussed that the limits of accuracy which can be obtained with these transformers at maximum ratio without using very special precautions are 0·01 per cent for ratio and 0·2 minute for phase angle. Within these limits the characteristics are independent of the number of primary turns. When the number of primary turns is 5 or more, and these are reasonably well distributed, the phase angle is reproducible to 0·1 minute.

This conclusion cleared the way for the calibration of the transformers against the 200-ampere resistance standard: this was carried out at three burdens at a frequency of 50 cycles per sec., and at one burden at 25 and 100 cycles per sec., with 25 primary turns, and the results for one transformer are given in Table 2.

For the majority of the work of the Laboratory the secondary burden is 12·5 VA, consisting of a precision resistor of 0·4 ohm, giving the voltage-drop of 2 for the electrostatic instruments, and leads of 0·1 ohm resistance. (It is necessary to use long leads in order to avoid placing the resistor in the large magnetic fields produced by the 5 000-ampere circuit.)

TABLE 3.

Frequency	Burden	Fraction of full current	True ratio / Nominal ratio	Phase angle
cycles/sec.	VA			minutes
50	12·5	1/1	$1\cdot000_0$	$-0\cdot{}_1$
		3/4		$-0\cdot{}_1$
		1/2		$0\cdot{}_0$
		1/5		$+0\cdot{}_1$
		1/10		$+0\cdot{}_1$

It is possible to improve the performance of the transformer at any given burden and frequency by connecting a small condenser, which need not be of high quality or precisely known capacitance, across the secondary terminals. Such a condenser, if of suitable value, will compensate the magnetizing current of the transformer and reduce the apparent phase angle to zero. The compensation will, of course, be perfect for one value of current only, but where the variation of phase angle with current is small the results obtained are very good. Table 3 shows the characteristics obtained by connecting a condenser of 1·4 μF capacitance across the secondary of the transformer to which Table 2 refers.

(c) *Effect of Stray Fields.*—In the use of the transformers in 3-phase circuits it is hardly possible to avoid placing them in magnetic fields of considerable intensity, due to currents in other phases. Even in single-phase work stray fields due to other parts of the circuit are present, and, at 5 000 amperes, may be very strong. It has been mentioned that the phase angles of the water-tube resistors are seriously disturbed by such fields, and the effect on the transformers is therefore of special interest.

In order to investigate the point, a transformer was placed at the centre of a coil having five turns, 1 metre in diameter. A current of 1 000 amperes, of the same frequency as the transformer primary current, was passed through the coil, giving a field of approximately 63 C.G.S. units near the centre. Various orientations of the field were investigated, and it was found that the maximum effect on the transformer characteristics was produced when the axis of the coil was parallel to the axis of the transformer core. Under this condition the disturbing field caused a change of less than 0·01 per cent in ratio, and a change of 0·6 minute in phase angle. The effect was independent of the relative time-phase of the transformer and coil currents, and therefore of the sense of the disturbing field.

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* Ratio is defined as the quotient of primary current divided by secondary current. The values of (True ratio/Nominal ratio) are given to 0·0001 (0·01 per cent).

† The positive sign indicates that the vector of reversed secondary current is in advance of that of primary current. The values of phase angle are given to 0·1 minute.

The change of phase angle was in such a direction as to tend to make the transformer secondary current lag behind the primary current. As, under the normal conditions of use, the secondary current leads the primary current by about 0·8 minute, the effect of the field is to reduce the phase angle nearly to zero.

In order to obtain a comparison with the 2 000-ampere tube resistors, one of these was subjected to the same test, the field being reduced in the ratio of the current ratings, i.e. to 25 C.G.S. units. The change of phase angle of the tube due to the disturbing field was 3·0 minutes. The stray-field effect on the 5 000-ampere transformer is therefore only one-fifth of that on the 2 000-ampere resistor, which is a very satisfactory result.

(*d*) *Effect of Permanent Magnetization.*—A permanent magnetization of the core might be produced by the opening of the secondary circuit of the transformer while current was flowing, or by accidentally passing a direct current through the winding. A test of the magnitude of the effect was made by passing a direct current of 7 amperes through the secondary winding (the rate of change of flux in the core being controlled by a short-circuited primary winding) and gradually reducing the current to zero. The change of ratio due to the resultant magnetization was less than 0·01 per cent; the change of phase angle was 0·4 minute, the secondary current increasing its lead on the primary current. It was found possible to remove the effect completely by re-applying the direct current, and reducing it to zero while subjecting it to a series of reversals. This operation takes less than a minute.

It should be emphasized that it would be very dangerous to open the secondary circuit of one of these transformers while current was flowing through the primary winding, as an extremely high voltage would be produced. It is proposed to connect a neon-tube "lightning arrestor" across the secondary terminals, so as to limit the open-circuit voltage to about 300 volts.

(*e*) *Effect of Temperature.*—The transformer was allowed to remain for 24 hours in air at a temperature of 40° C., and was then re-tested. The value obtained for the ratio was the same, within 0·01 per cent, as that obtained at 15° C.: the phase angle also was the same within 0·1 minute.

(*f*) *Stability.*—Observations of the ratio and phase-angle errors of the transformer at one current and burden have been made at intervals over a period of 6 months. During this time no change of ratio larger than 0·01 per cent, and no change of phase angle larger than 0·1 minute, have been detected.

To investigate further the stability of the characteristics the following test was made. The transformer was provided with a primary winding of 10 turns, clamped in position, and its ratio and phase-angle errors were determined, using a bridge of very high sensitivity. The observation was repeated twice daily for two weeks: the transformer was then given a severe jarring by striking a number of heavy blows on its case with a mallet, and observations were then made daily for a further two weeks.

The total range of variation of phase angle during the test was ± 0·02 minute, which was of the same order as the sensitivity of the bridge; the shock test produced no detectable effect. The ratio remained constant within 0·01 per cent throughout the tests.

In view of the doubts which have been expressed with regard to the stability of mumetal, these results are of considerable interest; they suggest that a transformer with a mumetal core can be at least as stable as one in which silicon iron is used.

APPENDIX.

THE EFFECTIVE IMPEDANCE OF A 4-TERMINAL DISTRIBUTED RESISTANCE WHEN THE POSITION OF THE VOLTAGE POINTS IS VARIED.

The busbars are represented in Fig. 5 by AB and A′B′, and it is assumed that there is a continuously distributed impedance between the busbars. The current is led in and out at A and A′, and the voltage points are at C and C′.

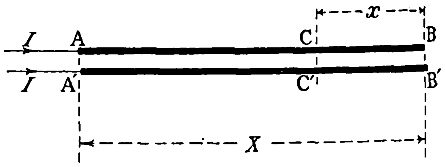

FIG. 5.

Let the length of the busbars = AB = X.

Let the length to the voltage points from the current terminals end = AC = $X - x$ or BC = x.

Let the impedance of the two busbars in series be $(r + j\omega l)$.

Let the impedance of the continuously distributed resistance between the busbars be $(R + j\omega L)$.

It will be assumed that r, ωl and ωL are small compared with R.

Let the current entering at A be I, and the voltage between C and C′ be E.

Then the effective impedance of the 4-terminal resistance = $Z = E/I$.

Impedance of busbars per unit length

$$= z = (r + j\omega l)/X$$

Admittance of continuously distributed resistance per unit length $= y = \left\{1/(R + jwL)\right\}/X$.

It is well known that the voltage (E) and current (I_x) at any point, such as C, along a pair of conductors, are given by

$$E = K_1\epsilon^{x\sqrt{(yz)}} + K_2\epsilon^{-x\sqrt{(yz)}}$$

$$I_x = \sqrt{\frac{y}{z}}\left\{K_1\epsilon^{x\sqrt{(yz)}} - K_2\epsilon^{-x\sqrt{(yz)}}\right\}$$

where K_1 and K_2 are constants.

Where $x = 0$ the current in the busbars is zero, i.e. the current at B $= 0$.

Let the voltage between busbars at B $= E_B$.

Then $E_B = (K_1 + K_2)$ and $(K_1 - K_2) = 0$.

$$\therefore K_1 = K_2 = \tfrac{1}{2}E_B$$

$$\therefore I = \tfrac{1}{2}E_B\sqrt{\frac{y}{z}}\left\{\epsilon^{X\sqrt{(yz)}} - \epsilon^{-X\sqrt{(yz)}}\right\}$$

and $$E = \tfrac{1}{2}E_B\left\{\epsilon^{x\sqrt{(yz)}} - \epsilon^{-x\sqrt{(yz)}}\right\}$$

$$\therefore Z = \frac{E}{I} = \sqrt{\frac{z}{y}}\left[\frac{\epsilon^{x\sqrt{(yz)}} + \epsilon^{-x\sqrt{(yz)}}}{\epsilon^{X\sqrt{(yz)}} - \epsilon^{-X\sqrt{(yz)}}}\right]$$

$$= \frac{1}{Xy}\left\{\frac{1 + \frac{1}{2}x^2yz}{1 + \frac{1}{6}X^2yz}\right\} \text{ approx.}$$

Let $(x/X) = a$.

Then

$$Z = \left\{R + j\omega L\right\}\left\{1 + \frac{a^2}{2R}(r + j\omega l)\right\}\left\{1 - \frac{1}{6R}(r + jwl)\right\}$$

$$= \left\{R + j\omega L\right\}\left\{1 + \frac{1}{6R}(3a^2 - 1)\,(r + j\omega l)\right\} \text{ approx.}$$

when $a = 1/\sqrt{3}$, i.e. $x = 0{\cdot}577X$

$$Z = R + j\omega L$$

Also $Z = \left\{R + \frac{1}{6}(3a^2 - 1)r\right\} + j\omega\left\{L + \frac{1}{6}(3a^2 - 1)l\right\}$

therefore Z is non-inductive when $L = \frac{1}{6}\,(1 - 3a^2)l$, i.e when $a = \sqrt{\left\{l - 6L/3l\right\}}$.

It is interesting to note the impedance when the voltage points are fixed at either end.

(i) *Voltage points at* A: $a = 1$.

$$Z = (R + \tfrac{1}{3}r) + j\omega\,(L + \tfrac{1}{3}l)$$

(ii) *Voltage points at* B: $a = 0$.

$$Z = (R - \tfrac{1}{6}r) + j\omega\,(L - \tfrac{1}{6}l)$$

From this last equation it may be seen that the resistance cannot be made non-inductive unless the inductance of the busbars is at least 6 times the inductance component of the impedance between the busbars. Since it is difficult to increase the inductance of the busbars without increasing the stray-field effect, the inductance of the resistance units should be the minimum possible.

[The discussion on this paper will be found on page 906.]

PRECISION TESTING OF CURRENT TRANSFORMERS.

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[From the National Physical Laboratory.]

(*Paper received 10th December, 1929; read before the* METER AND INSTRUMENT SECTION *7th February,* 1930.)

SUMMARY.

The paper describes in detail how the testing of current transformers may be carried out with speed and accuracy by means of a potential-divider bridge. The corrections to be made to the readings are deduced from the theory of the bridge; and it is shown that, by taking a few simple precautions, an accuracy of 0·01 per cent for ratio measurements, and of 0·1 minute for phase-angle measurements, is attainable if the transformer characteristics are stable to this limit.

A very sensitive and accurate bridge, which is not so convenient for general purposes as the potential-divider bridge, is then described. Results obtained with this bridge are compared with those obtained with the potential-divider bridge, and are found to be in close agreement.

TABLE OF CONTENTS.

(1) Introduction.
(2) The potential-divider bridge.
  (*a*) Description.
  (*b*) The effect of the residuals and the effect of the capacity shunt.
  (*c*) The determination of the constants of the circuit.
  (*d*) Stray-field effects and earthing.
(3) The "direct bridge."

LIST OF SYMBOLS.

I_1 = primary current of transformer under test.
I_2 = secondary current of transformer under test.
R_1 = resistance of primary resistor.
L_1 = inductance of primary resistor.
X_1 = reactance of primary resistor = $2\pi L_1 \times$ frequency.
R_2 = resistance of secondary resistor = $0 \cdot 1$ ohm.
L_2 = inductance of secondary resistor.
X_2 = reactance of secondary resistor.
r = resistance of potential divider = 200 ohms.
r_a = resistance of tapped portion of potential divider opposed to voltage-drop across R_2.
C = value of capacity shunt.

For circuit shown in Fig. 1:

r_c = resistance of portion of potential divider shunted by capacity $C = 136 \cdot 1$ ohms.
Z_c = combined impedance of potential divider and capacity.
Y = total admittance of primary resistor R_1 in parallel with impedance Z_c.
$\omega = 2\pi \times$ frequency.
$\theta = \omega C r_c$.
$a = (r_c/r) = 0 \cdot 6805$.

For circuit shown in Fig. 2:

r_b = resistance of portion of potential divider shunted by capacity $C = 72 \cdot 8$ ohms.
Z_b = combined impedance of potential divider and capacity.
Y_a = total admittance of primary resistor R_1 in parallel with impedance Z_b.
$\phi = \omega C r_b$.
$\beta = (r_b/r) = 0 \cdot 364$.

(1) INTRODUCTION.

In 1913–14, two papers were published in the German technical Press describing a bridge method of testing current transformers.* This method was simple to use, and had the further advantage that it could be made direct-reading. The accuracy attainable was of the order of 0·1 per cent for ratio. That attainable in the phase-angle measurement would depend to a large extent on the design of the component parts of the apparatus, and on the care taken in the set-up to avoid trouble from magnetic and electric fields. It would probably be of the order of a few minutes. For most work this accuracy is ample. The advent of high-precision current transformers with mumetal cores has, however, created a demand for testing to a higher degree of accuracy. An investigation was therefore carried out at the National Physical Laboratory in order to determine whether this method was capable of giving greater accuracy. It was found that, provided certain precautions were taken, it was possible to determine the ratio of transformers to 0·01 per cent, and their phase angles to 0·1 minute (0·00003 radian). It is, however, impossible to attain this accuracy and, in addition, to make the apparatus direct-reading. The direct-reading principle has not been entirely sacrificed, for it is possible by the use of a few small correction terms to correct the direct readings of ratio and phase angle in order to obtain the true values.

At the same time, a modification of this method was developed which has greater sensitivity and is capable of rather greater accuracy. The two methods are useful as a check on one another. The greater sensitivity of the modified method makes it very useful for studying small changes in the characteristics of transformers or for determining their stability. It is not direct-reading and is not quite as flexible as the original method. Both methods will be considered in this paper. The method, developed in Germany, which has been adopted by the National Physical Laboratory for routine test work will be referred to as the "potential-divider bridge" method. The modified method, developed at the National Physical Laboratory, which is used only for special work and as a check on the potential-divider bridge method, will be referred to as the "direct bridge" method.

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* E. ALBERTI and V. VIEWEG: *Archiv für Elektrotechnik* 1913, vol. 2, p. 208; also H. SCHERING and E. ALBERTI, *ibid.*, p. 263.

The development of this apparatus to give the above-mentioned accuracy has shown that the characteristics of well-designed transformers are quite stable to this limit. In another paper [*] results are given which show that the characteristics of well-designed mumetal transformers are stable, at least to the limit of sensitivity of the testing apparatus. From this point of view, therefore, the increased accuracy is justifiable.

(2) The Potential-Divider Bridge.

(*a*) *Description.*—The circuit employed is shown in Figs. 1 and 2. The primary winding of the current transformer T, which is being tested, is connected, in series with the non-inductive resistor R_1 and any convenient current-measuring device, to the supply. The supply, for high-precision work, should be obtained from a separate generator, and should always be fed through an isolating transformer. The ratio of this transformer will depend on the primary current of the transformer to be tested. The primary current of the transformer under test is usually measured by means of an accurate current-transformer, M, and an ammeter, A. The secondary winding of the transformer under test is connected to a non-inductive resistor R_2. If the rated secondary current of the transformer is 5 amperes, R_2 is 0·1 ohm. In order to keep the primary current of the transformer well away from the galvanometer and from R_2, it is necessary to employ rather long leads from the secondary terminals of the transformer to the terminals of R_2. These are conveniently made exactly 0·1 ohm, and should be twisted together in order to make them non-inductive. The minimum external resistance in the secondary of the current transformer is therefore 0·2 ohm, corresponding to a burden of 5 volt-amperes at rated current. If it is desired to test the transformer on higher burdens than this, additional loading resistance may be inserted in the secondary circuit.

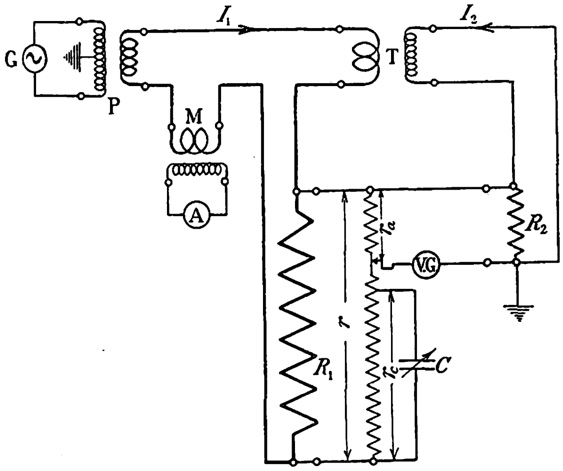

Fig. 1.—Diagram of connections of potential-divider bridge for testing a current transformer, the secondary current of which leads the primary current.

G = Generator.
P = Power and isolating transformer.
M and A = Current transformer and ammeter for measuring primary current of transformer under test.
T = Transformer under test.
V.G. = Vibration galvanometer.

A resistance of 200 ohms is connected in parallel with the resistor R_1. This resistance constitutes the potential divider of the apparatus. A suitable voltage is tapped off from this potential divider and opposed to the voltage-drop across R_2 through a vibration galvanometer.[*]

When the transformer under test is carrying its rated current, its secondary current will be 5 amperes and the voltage-drop across R_2 will be 0·5 volt. R_1 is of such a value that the voltage-drop across it, when carrying the rated current of the transformer under test, is 2 volts. If, therefore, the ratio of the transformer is correct, one-quarter of the voltage across the potential divider will have to be tapped off in order to balance the voltage-drop in R_2. The potential divider consists of two wound sections of 48 ohms and 148 ohms respectively, with a slide-wire of 4 ohms connected between them. A moving contact connected to the galvanometer moves over this slide-wire. Thus any ratio error up to ± 4 per cent may be measured on this bridge.[†] The slide-wire is calibrated to read ratio error directly. To balance the quadrature component of e.m.f., a variable condenser is connected across part of the potential divider. The capacity required to balance the quadrature e.m.f. is proportional to the phase angle of the transformer. In most transformers the reversed secondary current leads the primary

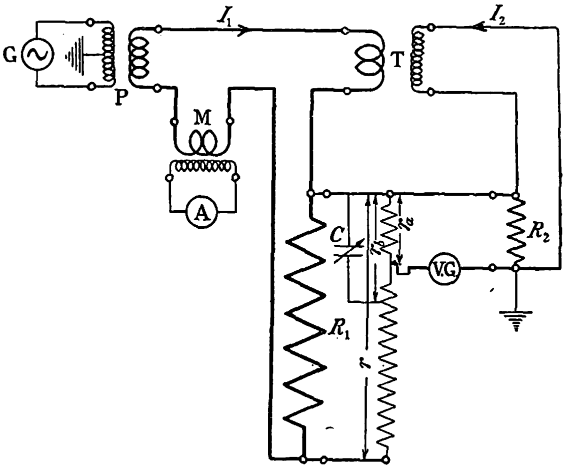

Fig. 2.—Diagram of connections of potential-divider bridge for testing a current transformer, the primary current of which leads the secondary current.

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[*] R. S. J. Spilsbury and A. H. M. Arnold: "Some Accessory Apparatus for Precise Measurements of Alternating Current," *Journal I.E.E.* 1930, vol. 68, p. 889.

[*] In the actual apparatus used, a second potential divider is connected across R_2, so that only a fraction of the voltage-drop across R_2 may be used if required. This is simply for the sake of flexibility, as rather fewer values of R_1 are then required for testing transformers of different ratios. The theory is not affected by this second divider, and it has therefore been omitted from Figs. 1 and 2.

[†] If the ratio error exceeds ± 4 per cent, balance can only be obtained by altering the resistance of R_1 or R_2.

current, and for this case the condenser is connected as shown in Fig. 1. The resistance, r_c, across which it is connected is 136·1 ohms, so that, at a frequency of 50 cycles per sec., 0·01 μF corresponds to a phase angle of 1 minute, and the phase angle may be read directly from the value of the condenser shunt. If the reversed secondary current lags on the primary current, the condenser must be connected as shown in Fig. 2, and this is effected by means of a change-over switch. In this case it is connected across 72·8 ohms (r_b), and 0·02 μF corresponds to a phase angle of 1 minute at 50 cycles per sec., so that the phase angle may be deduced from the condenser reading almost as easily as in the normal case.

The double balance is very quickly attained in practice, but, in setting up the apparatus, care should be taken that the voltage-drop across R_2 is opposed to the voltage-drop across the tapped portion (r_a) of the divider, and is not in series with it.

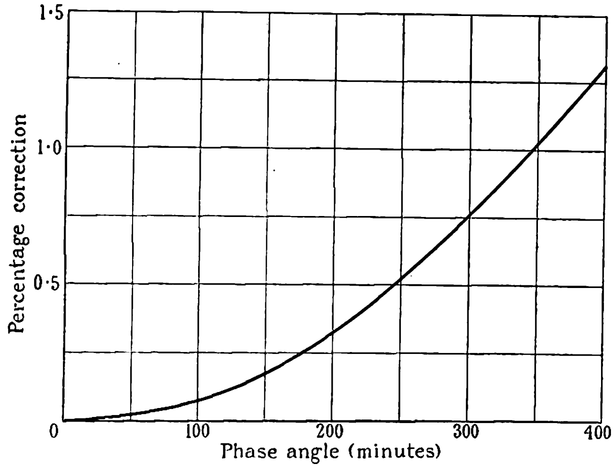

FIG. 3.—Percentage correction to be subtracted from apparent value of $\frac{\text{True Ratio}}{\text{Nominal Ratio}}$ to allow for the shunting effect of the capacity across r_c.

Percentage correction $= -44\cdot 9\theta^2$.

The accuracy of the ratio reading will depend on the accuracy of the adjustment of R_1 and R_2, and on the calibration of the potential-divider scale. The ratio reading will also be affected by the capacity shunt. For phase angles not exceeding 100 minutes, the shunting effect of the capacity will alter the ratio reading by less than 0·1 per cent. The shunting effect is proportional to the square of the phase angle, and for large phase angles the shunting effect becomes serious. Transformers with phase angles exceeding 100 minutes do not usually need to be tested to a very high degree of accuracy. At the same time, the shunting effect of the condenser increases so rapidly, as the phase angle increases above 100 minutes, that it is undesirable to neglect this effect. A curve showing the effect of the capacity shunt is given in Fig. 3.

The accuracy of the phase-angle reading depends first on the accuracy of r_c and of the condenser. Neither of these require to be known to a very high degree of accuracy, since the errors that they introduce are proportional to the phase angle measured. Thus, an error of 0·1 per cent in the value of the condenser would introduce an error of 0·1 per cent in the phase-angle measurement, i.e. 0·1 minute for a phase angle of 100 minutes. For phase angles of less than 100 minutes, the error would be proportionally less than 0·1 minute.

More serious errors may be introduced by the residual phase angles of R_1 and R_2, and by capacity and magnetic effects from other parts of the circuit.

The development of this apparatus for high-precision testing consists, therefore, of three parts:—(i) a theoretical consideration of the effect of the residuals and of the capacity shunt; (ii) the measurement of the residuals, and also the measurement of the resistances used in the circuit; and (iii) the elimination of stray magnetic and capacity effects from the circuit.

Two types of transformers are affected by the theoretical consideration. Firstly, it is desirable to test very good transformers, having small phase angles, to the highest possible degree of accuracy: the effect of the residuals must be considered, but the effect of the capacity shunt will be negligible. Secondly, it will not be necessary to test transformers with large phase angles to a high degree of accuracy: so that the residuals may be neglected, but the effect of the capacity shunt cannot be neglected. A single theoretical consideration is given in which both the effects of residuals and of the capacity shunt are considered, and a series of correction factors are deduced. In utilizing these correction factors, only those terms which are of importance in the case of the particular transformer tested need be considered.

(*b*) *The Effect of the Residuals and the Effect of the Capacity Shunt.*—In order to deduce simple correction-factors, it is necessary to neglect certain small terms. To determine phase angles to 0·1 minute, no term should be neglected which may introduce an error exceeding 3 parts in 100 000. Limiting values must, therefore, be assigned to the residuals and to the capacity shunt. The following terms will be neglected in comparison with unity:—

(i) All powers of X_1/R_1, X_2/R_2 and R_1/r, above the first power, and any products of two or more of these terms.
(ii) All powers of X_1/R_1, X_2/R_2, and R_1/r, multiplied by any power of θ or ϕ above the first power.
(iii) All powers of θ or ϕ above the third power.

The residual inductance of the potential divider will be completely neglected, as it can easily be made very small (under 0·1 minute).

The magnitude of R_1/r depends on the rated primary current of the transformer tested. It has a maximum value of 0·002 for a 5/5 transformer ($R_1 = 0\cdot 4$ ohm). It is convenient to fix the same upper limit for X_1/R_1 and X_2/R_2. This maximum value corresponds to a phase angle of about 7 minutes. This value should not be exceeded in well-designed resistors, even for very large currents. The value of θ (or ϕ) is proportional to the phase angle of the transformer under test, and has no definite limit. The highest precision will not be required in testing transformers with large phase angles, and it is possible, therefore, to fix a series of limits for θ with reduced accuracy as θ increases. The value of ϕ, which corresponds to a lagging secondary current, is never likely to be very large. For an accuracy of 3 parts in 100 000 (0·1 minute), θ should not exceed 0·07, corresponding to a transformer phase angle of 164 minutes. For an accuracy of 1 in 10 000 (0·3 minute), θ should not exceed 0·1, corresponding to a phase angle of 4 degrees. For an accuracy of 1 in 2 000 (2 minutes), θ should not exceed 0·15, corresponding to a phase angle of 6 degrees.

It is obvious that correction factors deduced on this basis will be amply accurate for all transformer tests. These correction factors will now be deduced.

Case (1)—I_2 *leading* I_1. *Circuit as shown in Fig.* 1.—

$$Z_c = r - r_c + \frac{r_c}{1+\theta^2} - j\frac{\theta r_c}{1+\theta^2}$$

$$= r\left\{1 - \alpha\theta^2 - j\alpha\theta(1-\theta^2)\right\}$$

$$Y = \frac{1}{R_1 + jX_1} + \frac{1}{r\left\{1 - \alpha\theta^2 - j\alpha\theta(1-\theta^2)\right\}}$$

$$= \frac{1}{R_1}\left\{1 + \frac{R_1}{r}\right\}\left\{1 + j\left(\alpha\theta\frac{R_1}{r} - \frac{X_1}{R_1}\right)\right\}$$

When the bridge is balanced (i.e. zero current in galvanometer)

$$I_1/I_2 = \left\{(R_2 + jX_2)Z_cY\right\}/r_a$$

$$= \frac{R_2 r}{R_1 r_a}\left\{1 + \frac{R_1}{r}\right\}\left\{1 - \alpha\theta^2 + \alpha\theta\left(\frac{X_2}{R_2} - \frac{X_1}{R_1}\right) + j\left(\frac{X_2}{R_2} - \frac{X_1}{R_1} + \alpha\theta\frac{R_1}{r} - \alpha\theta + \alpha\theta^3\right)\right\}$$

True ratio = Numerical value of (I_1/I_2)

$$= \frac{R_2 r}{R_1 r_a}\left\{1 + \frac{R_1}{r}\right\}\left[\left\{1 - \alpha\theta^2 + \alpha\theta\left(\frac{X_2}{R_2} - \frac{X_1}{R_1}\right)\right\}^2 + \left\{\frac{X_2}{R_2} - \frac{X_1}{R_1} - \alpha\theta\left(1 - \frac{R_1}{r} - \theta^2\right)\right\}^2\right]^{\frac{1}{2}}$$

$$= \frac{R_2 r}{R_1 r_a}\left\{1 + \frac{R_1}{r}\right\}\left\{1 - \tfrac{1}{2}\alpha\theta^2(2 - a)\right\}$$

$$= \frac{R_2 r}{R_1 r_a}\left\{1 + \frac{R_1}{r}\right\}\left\{1 - 0{\cdot}449\theta^2\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Tangent of phase angle

$$= \frac{\alpha\theta\left\{1 - (R_1/r) - \theta^2\right\} + (X_1/R_1) - (X_2/R_2)}{1 - \alpha\theta^2 + \alpha\theta\left\{(X_2/R_2) - (X_1/R_1)\right\}}$$

$$= \alpha\theta + \frac{X_1}{R_1} - \frac{X_2}{R_2} - \alpha\theta\frac{R_1}{r} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The simple formulæ, on which the direct-reading scales are based, are:—

True ratio $= (R_2 r)/(R_1 r_a)$
Phase angle $= \alpha\theta$

There are two correction factors for the ratio measurement. The first, $\left\{1 + (R_1/r)\right\}$, is to allow for the shunting effect of the potential divider on the resistance R_1. This shunting effect is conveniently combined with any correction due to the fact that the true value of R_1 is not equal to its nominal value. The maximum value of this shunting effect is 0·2 per cent when $R_1 = 0{\cdot}4$ ohm, the value used when testing a 5/5 transformer. The second correction factor, $(1 - 0{\cdot}449\theta^2)$, is to allow for the shunting effect of the capacity. Fig. 3 shows the percentage correction to (True ratio/Nominal ratio) plotted against transformer phase-angle. The residuals do not appreciably affect the ratio reading.

The phase angle is equal to the tangent of the phase angle within the limits of accuracy required for this work, so that there are three simple corrections to be made to the phase-angle reading. The first two are of opposite sign and allow for the residuals of R_1 and R_2. The third term, which is negligible in practically all cases, allows for the fact that the capacity C alters the phase angle of the whole primary impedance $(1/Y)$ by a small amount.

Case (2)—I_1 *leading* I_2. *Circuit as shown in Fig.* 2.—

$$Z_b = r\left\{1 - \beta\phi^2 - j\beta\phi(1 - \phi^2)\right\}$$

$$Y_a = \frac{1}{R_1}\left\{1 + \frac{R_1}{r}\right\}\left\{1 + j\left(\beta\phi\frac{R_1}{r} - \frac{X_1}{R_1}\right)\right\}$$

For balance,

$$\frac{I_1}{I_2} = \frac{(R_2 + jX_2)Z_bY_a}{r_a}\left\{1 + j\phi\right\}$$

$$= \frac{R_2 r}{R_1 r_a}\left\{1 + \frac{R_1}{r}\right\}\left\{1 + \phi(1-\beta)\left(\frac{X_1}{R_1} - \frac{X_2}{R_2}\right) + j\left(\frac{X_2}{R_2} - \frac{X_1}{R_1} + \phi - \beta\phi + \beta\phi\frac{R_1}{r}\right)\right\}$$

True ratio—

$$= \frac{R_2 r}{R_1 r_a}\left\{1 + \frac{R_1}{r}\right\}\left\{1 + \tfrac{1}{2}\phi^2(1-\beta)^2\right\}$$

$$= \frac{R_2 r}{R_1 r_a}\left\{1 + \frac{R_1}{r}\right\}\left\{1 + 0{\cdot}202\phi^2\right\} \quad . \quad . \quad . \quad (3)$$

Tangent of phase angle

$$= -\phi(1-\beta) + \frac{X_1}{R_1} - \frac{X_2}{R_2} - \beta\phi\frac{R_1}{r} \quad . \quad . \quad (4)$$

Equations (1) to (4) thus show that very simple correction terms will enable the ratio and phase-angle readings to be corrected to their true values with a very high degree of accuracy, provided that there are no observational errors and that the constants of the circuit are known to an equal degree of accuracy. This aspect of the problem will be considered in the next section.

(*c*) *The Determination of the Constants of the Circuit.*—The accuracy of each observation will depend, in the first place, on the accuracy to which the primary current and the burden are known. The transformer characteristics will vary more rapidly with current and burden in a bad transformer than in a good one, and these variables will therefore have to be determined with more care in the former case. There is little difficulty in determining the burden sufficiently accurately for this work, but in the measurement of the primary current it is necessary, in order to get reasonable deflections on an a.c. ammeter over considerable current ranges, to employ transformers of different ratios. Transformers are usually tested at $\frac{1}{10}$, $\frac{1}{5}$, $\frac{1}{2}$, $\frac{3}{4}$ and full rated current. The last three values are set by means of a 5-ampere substandard ammeter (12-in. scale), in conjunction with a current transformer of ratio equal to that of the transformer under test. The first two currents are set by the same ammeter in conjunction with a current transformer of ratio equal to one-quarter of the ratio of the transformer under test. The frequency of the generator is adjusted to within 0·1 per cent of the required frequency.

Each observation involves five resistances and one capacity. For reasons already given the values of r_c and C need not be known to the highest degree of accuracy, so that there remain four resistances, R_1, R_2, r and r_a, which must be known to a sufficient degree of accuracy to give the required accuracy to the reading, and their residuals must also be determined. r_a is a variable resistance with a variation between 48 ohms and 52 ohms. A scale attached to the slide-wire indicates the value of r_a, and also the ratio error, for any position of the sliding contact.

For $r_a = 50$ ohms, the ratio error = 0, and as far as the divider is concerned this is correct, provided that, at this point, $r_a = \frac{1}{4}r$.

The scale calibration can be made sufficiently correct to show changes in r_a of 1 part in 10 000, but in general, when the sliding contact is at $r_a = 50$, r_a will not be exactly $\frac{1}{4}r$, so that there is a zero error in the scale calibration. The resistance of r includes the resistance of the leads from the terminals of coils constituting the main part of r to the voltage terminals of the resistor R_1. The zero error of the scale has therefore to be determined by measuring r, including appropriate leads, and by measuring r_a, with the contact set at $r_a = 50$. Owing to the contact resistance of the sliding contact, three measurements are necessary: r, (r_a + contact resistance), and ($r - r_a$ + contact resistance). From these three measurements the ratio of (r_a/r), and therefore the zero error of the scale, can be determined. R_2 is a 4-terminal resistance and can be measured by a Kelvin double-bridge with an accuracy of approximately 1 in 100 000. The difference between the nominal and actual value of R_2 may be combined with the zero error of the divider scale to form the "overall" error of the bridge. The difference between the nominal and actual values of R_1 is not included in this overall error, because R_1 is different for different transformers and its error must therefore be considered separately. For primary currents up to 200 amperes, R_1 is a 4-terminal resistor designed to give a 2-volt drop with rated current. Its resistance may be determined by the Kelvin double-bridge, and its change of resistance with any current up to its rated current is less than 1 part in 10 000. Above 200 amperes, R_1 consists of a current transformer, with a 4-terminal resistance of 0·4 ohm connected to its secondary terminals. The nominal ratio of this current transformer is equal to the nominal ratio of the transformer under test, so that, at rated current, a current of 5 amperes passes through the 0·4-ohm resistance and gives a 2-volt drop between the voltage terminals. The potential divider is connected across the voltage terminals (Fig. 4). To determine the difference between the nominal and actual values of this "primary resistor," it is necessary to measure the resistance of the 0·4-ohm resistor on the Kelvin double-bridge, and to determine the ratio of the current transformer accurately. The characteristics of the transformer should be determined on a burden of 12·5 volt-amperes, consisting of a 0·4-ohm resistor and secondary leads of resistance 0·1 ohm. Current transformers are now available the ratios of which are constant to within 1 part in 10 000 for any current between rated current and 1/20th of rated current.*

The difference between the nominal and actual values of R_1 is combined with the shunt effect of the potential divider to give the overall error of the primary resistor.

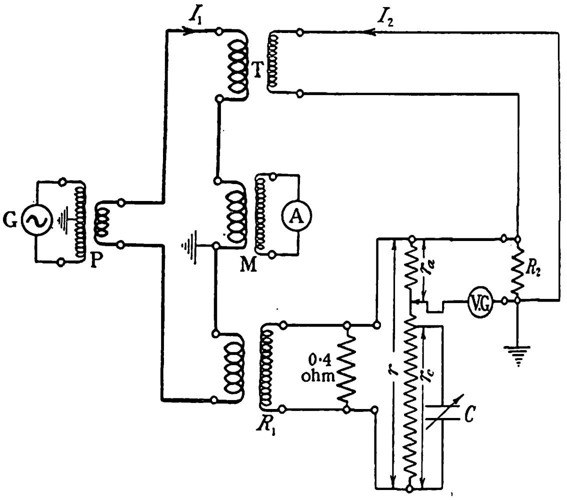

FIG. 4.—Diagram of connections of potential-divider bridge.

Standard current-transformer, with 0·4 ohm non-inductive resistance connected in secondary circuit, used as primary resistor (R_1) to provide the voltage for the potential divider.

It may be observed that, when the primary resistor consists of a current transformer in conjunction with a 0·4-ohm resistance, the shunting effect of the potential divider is 0·2 per cent for a current transformer of any ratio. The residual phase angles of R_2 and R_1 may be determined to within 1/20th of a minute by Hartshorn's double-bridge method.† If R_1 is a 0·4-ohm resistance combined with a current transformer, the phase angle of the current transformer must be added to (or subtracted from) the residual phase angle of the 0·4-ohm resistance. It is not at present possible to build current transformers the phase angles of which are constant to within 0·1 minute for all currents down to, say, 1/20th of rated current. For work of the highest precision it is therefore necessary to use a different correction term for different currents.

The primary resistor is, essentially, the standard against which the transformer is tested, and, except in the case of a 5/5 transformer, the characteristics of the transformer under test cannot be determined to a greater accuracy than the accuracy to which the constants of the primary resistor are known. On the other hand, the divider and the resistor R_2 are the bridge arms, and it is possible, by a method to be described, to determine the overall error of the bridge without knowing the errors of its component parts. This method is a most valuable check on the direct method of calibrating each component part.

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* R. S. J. SPILSBURY and A. H. M. ARNOLD, *loc. cit.*

† L. HARTSHORN: "Measurement of the Inductances of Four-Terminal Resistance Standards," *Proceedings of the Physical Society of London*, 1927, vol. 39, p. 377.

The test is carried out by means of two similar current transformers of any convenient ratio.* The transformers will be referred to as A and B. The characteristics of transformer A are determined, assuming the overall error of the bridge to be zero. The primary resistor used in this case is a simple resistance. The characteristics of transformer B are then determined similarly, first against the same primary resistor, and then against a primary resistor consisting of transformer A in conjunction with a 0·4-ohm resistance. If the overall error of the bridge is not zero the two calibrations of transformer B will not agree, and the difference between these two calibrations will be exactly equal to the overall error of the bridge. An example of this test is given in the Appendix, and it may be seen that the agreement between this method of determining the overall error of the bridge and the direct calibration method is within 1 part in 10 000 for ratio and within 1/20th of a minute for phase angle.

(*d*) *Stray-field Effects and Earthing.*—The reliability of measurements made may be considerably reduced unless care is taken to avoid trouble from stray fields. Electromagnetic fields are produced mainly by the primary-current circuit and will affect the phase-angle reading only. Capacity effects, which may be caused by capacity currents from the high-tension side of the power transformer, may affect the ratio or the phase-angle reading or both. Earth-current effects also may affect either or both readings.

If a moving-iron vibration galvanometer is used, it is very difficult to shield it effectively from magnetic fields, and it is recommended, therefore, that a moving-coil galvanometer should always be used for this work. With properly twinned galvanometer leads, no trouble need be experienced as a result of e.m.f.'s induced in the galvanometer circuit.

Magnetic fields may, however, induce e.m.f.'s in any of the resistances R_1, R_2 or r, and these e.m.f.'s will result in a change of the effective phase angle of the resistance involved. The elimination of trouble from this source is achieved by designing the resistor R_1 to be as nearly astatic as possible, by placing the bridge and galvanometer at least 1 yard, and preferably 2 yards, away from the primary circuit, and by avoiding large loops in the primary circuit. A suitable lay-out for a test is shown in Fig. 5.

Unfortunately, a large number of current transformers are of the " inserted " primary type, and it is customary in testing these to keep the return lead a considerable distance, say 1 yard, away from the transformer. This creates a large inductive loop which may introduce error into the measurements if the primary current is large. In this case it is necessary to make two observations at each point. The leads to the resistors R_1 and R_2 are reversed between the two observations. The mean of the two observations will be free from error due to electromagnetic or capacity effects. It is important to note that if the primary resistor consists of a current transformer in conjunction with a resistance, the mean of these two observations will not eliminate any change of phase angle in the current transformer. The phase angles of transformers are altered by magnetic fields, but the change of phase angle is not reversed when the magnetic field is reversed. A well-designed mumetal transformer will be very little affected by magnetic fields, but in cases where the primary current is very large, say over 1 000 amperes, the standard current-transformer should be placed at least 2 yards away from the transformer under test.

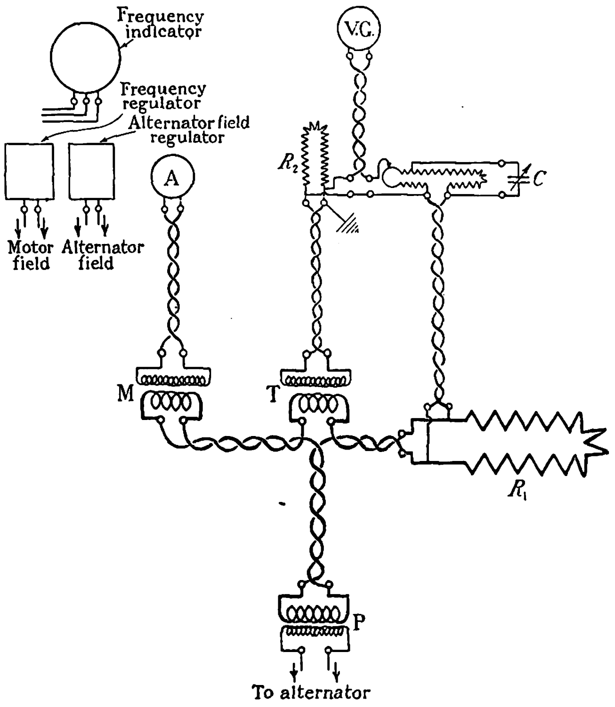

FIG. 5.—Diagram showing convenient lay-out for the potential-divider bridge circuit to minimize stray capacity and electromagnetic effects.

Capacity effects are best avoided by placing the power transformer as far as possible from the bridge. If possible, the mid-point of its primary winding should be earthed. It is essential to earth the bridge circuit and it is, therefore, very important that the insulation resistance between the primary and secondary windings of the power transformer should be high.

It has been found experimentally that one terminal of R_1 or R_2 should be earthed. Provided that the galvanometer is connected to the sliding contact of the divider, and not to the end of the divider, it is immaterial which of the four possible terminals is earthed. The terminal of R_2 to which the galvanometer is connected has been selected, so that the galvanometer is always at earth potential. If the primary resistor includes a current transformer, the primary circuit should be separately earthed (see Fig. 4).

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* Transformers with 5/5 ratio are most convenient, but the test can be carried out satisfactorily with other ratios.

(3) The "Direct Bridge."

The circuit is shown in Fig. 6. In this method the potential divider is eliminated, and the whole of the voltage-drop across R_1 is opposed to the voltage-drop across R_2. The adjustment for ratio error is obtained by shunting a high resistance, r, across R_1 or R_2, and the phase-angle adjustment is obtained by shunting a condenser across R_1 or R_2. Owing to the high capacitance required, it is impracticable to test transformers with large phase angles by this method. The capacity C and the high resistance r need not be known to a high degree of precision, so that only two resistances, R_1 and R_2, have to be measured. R_1 and R_2 are chosen of such values that the voltage-drops in them are approximately equal. If the voltage-drop across R_1 and R_2 is 2 volts at rated current, it is possible to detect changes of phase angle of 0·01 minute at one-fifth of rated current, using a moving-coil galvanometer of 8 ohms resistance.

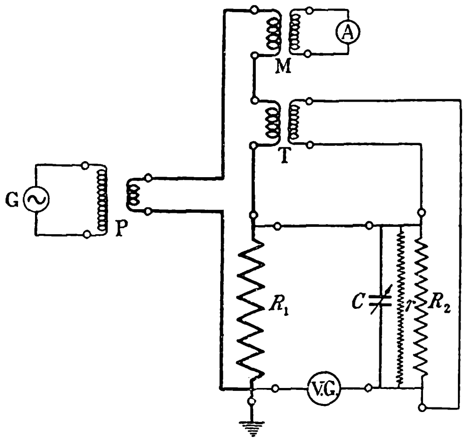

Fig. 6.—Diagram of connections of direct bridge for testing a current transformer, the secondary current of which leads the primary current.

The equations for balance are given below, for a case where both the resistance and capacity shunts are connected across R_2.

$$I_1(R_1 + jX_1) = I_2R_2\left\{1 - \frac{R_2}{r} - j\left(\omega CR_2 - \frac{X_2}{R_2}\right)\right\}$$

$$\therefore \quad \frac{I_1}{I_2} = \frac{R_2}{R_1}\left\{1 - \frac{R_2}{r} - j\left(\omega CR_2 + \frac{X_1}{R_1} - \frac{X_2}{R_2}\right)\right\}$$

$$\text{True ratio} \qquad = \frac{R_2}{R_1}\left\{1 - \frac{R_2}{r}\right\}$$

$$\text{Phase angle} \qquad = \omega CR_2 + \frac{X_1}{R_1} - \frac{X_2}{R_2} \text{ radians.}$$

APPENDIX.

Determination of the Overall Error of the Bridge in the Potential-Divider Bridge Method.

The test was carried out with a primary current of 100 amperes, using two transformers, A and B, with ratios of 200/5. Transformer A was tested on a burden of 12·5 volt-amperes, as this was the burden required when using it as the primary resistor. Transformer B was tested on a burden of 5 volt-amperes.

Test of transformer A.—Primary resistor R_1 = resistor of 0·01-ohm nominal resistance.

Corrections to ratio reading:—

Resistor, 8 in 100 000 (high).
Shunting effect of potential divider = 5 in 100 000.
Total ratio-correction = − 3 in 100 000.

The phase angle of the resistor R_1 was approximately nil, hence there was no phase-angle correction.

Ratio-error reading = $+ 0{\cdot}03_7$ per cent.
Condenser shunt = $+ 0{\cdot}013_8$ μF.

∴ Apparent ratio-error = $+ 0{\cdot}03_4$ per cent.*
Apparent phase angle = $+ 1{\cdot}3_8$ minutes.†

First test of transformer B.—Primary resistor the same as for test on transformer A.

Ratio-error reading = $+ 0{\cdot}04_1$ per cent.
Condenser shunt = $+ 0{\cdot}001_7$ μF.

∴ Apparent ratio-error = $+ 0{\cdot}03_8$ per cent.
Apparent phase angle = $+ 0{\cdot}1_7$ minute.

Second test of transformer B.—Primary resistor = resistor of 0·4-ohm nominal resistance connected in secondary circuit of transformer A. Primary of transformer A in series with primary of transformer B.

Corrections to ratio reading:—

0·4-ohm resistance = 26 in 100 000 (high).
Shunting effect of potential divider = 200 in 100 000.
Ratio error of transformer A = + 34 in 100 000.
Total ratio-correction = + 208 in 100 000.

Corrections to phase-angle reading:—

Phase angle of 0·4-ohm resistance = $+ 0{\cdot}1_2$ minute.
Phase angle of transformer A = $+ 1{\cdot}3_8$ minutes.
Total phase-angle correction = $+ 1{\cdot}5_0$ minutes.
Ratio-error reading = $- 0{\cdot}15_5$ per cent.
Condenser shunt = $- 0{\cdot}024_2$ μF.

∴ Apparent ratio-error = $+ 0{\cdot}05_3$ per cent.
Apparent phase angle $= (-1{\cdot}2_1 + 1{\cdot}5_0) = +0{\cdot}2_9$ minute.

Comparing the results of the two tests on transformer B, the overall errors of the bridge are:—

Overall ratio-error $= (+ 0{\cdot}05_3 - 0{\cdot}03_8) = + 0{\cdot}01_5$ per cent.
Overall phase-angle error $= (+ 0{\cdot}2_9 - 0{\cdot}1_7) = +0{\cdot}1_2$ minute.

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* Plus sign indicates that the primary current is high.
† Plus sign indicates that the reversed secondary current leads the primary current.

The corrections to be applied to readings are of opposite sign to the errors; thus the corrections to be made are as follows:—

Ratio correction for bridge error = $- 0{\cdot}01_5$ per cent.
Phase-angle correction for bridge error = $- 0{\cdot}01_2$ minute.

If these corrections are now applied to readings taken in these tests, the following results are obtained:—

Ratio error of transformer A = $+ 0{\cdot}01_9$ per cent.
Phase angle of transformer A = $+ 1{\cdot}2_6$ minutes.
Ratio error of transformer B = $+ 0{\cdot}02_3$ per cent.
Phase angle of transformer B = $+ 0{\cdot}0_5$ minute.
} by both tests.

Direct calibration.—

Total resistance of r, including leads, = $200{\cdot}16_4$ ohms.
Resistance of r_a, with contact set at "r_a = 50 ohms," = $50{\cdot}01_7$ ohms.
Zero error of scale = $200{\cdot}16_4 - (4 \times 50{\cdot}01_7)$ parts in 200 = + 48 parts in 100 000.
Secondary resistor, R_2, nominal resistance 0·1 ohm, = 67 parts in 100 000 (low).
∴ Ratio correction for bridge error = (+ 48 − 67) parts in 100 000 = $- 0{\cdot}01_9$ per cent.
Phase angle of secondary resistor R_2 = $+ 0{\cdot}1_5$ minute.
∴ Phase-angle correction for bridge error = $- 0{\cdot}1_5$ minute.

It may be seen that the corrections deduced by the two methods are in very close agreement. A final check was obtained by calibrating transformer A by the direct bridge method.

Primary resistor = 0·01-ohm resistance, 8 parts in 100 000 (high). Phase angle, nil.
Secondary resistor = 0·4-ohm resistance, 26 parts in 100 000 (high). Phase angle, $0{\cdot}1_2$ minute.

For bridge balance,

Shunt resistance across primary resistor = 221 ohms.
Shunting effect = $0{\cdot}00_5$ per cent.
Shunt condenser across secondary resistor = 3·22 μF.
Phase-angle effect of capacity = $(3{\cdot}22 \times 0{\cdot}4 \times 1{\cdot}08) = 1{\cdot}3_9$ minutes.
∴ Ratio error of transformer A = $(+ 0{\cdot}00_5 - 0{\cdot}00_8 + 0{\cdot}02_6) = + 0{\cdot}02_3$ per cent.
Phase angle of transformer A = $(+ 1{\cdot}3_9 - 0{\cdot}1_2) = + 1{\cdot}2_7$ minutes.

These results, also, are in very close agreement with the calibration of transformer A by the potential-divider bridge. For comparison, the results are tabulated below.

Calibration of transformer A *at half rated-current on a burden of* 12·5 *volt-amperes at a frequency of* 50 *cycles per second.*

Ratio error			Phase angle		
Direct bridge method	Potential-divider bridge method		Direct bridge method	Potential-divider bridge method	
	(1)	(2)		(1)	(2)
per cent $+ 0{\cdot}02_3$	per cent $+0{\cdot}01_9$	per cent $+0{\cdot}01_5$	minutes $+ 1{\cdot}2_7$	minutes $+1{\cdot}2_6$	minutes $+1{\cdot}2_3$

The results for the potential-divider bridge are given, using the correction for the bridge error deduced by both methods. The columns marked (1) show the calibration of transformer A, using the corrections deduced from the results of the tests on the two transformers. The columns marked (2) show the calibration, using the corrections deduced from the direct calibration of R_2, r and r_a.

The agreement between all three methods is within 1 part in 10 000 for ratio, and within 1/20th of a minute for phase angle.

[The discussion on this paper will be found on page 906.]

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION ON THE PAPERS BY MR. SHOTTER (SEE PAGE 873), MESSRS. SPILSBURY AND ARNOLD (SEE PAGE 889), AND DR. ARNOLD (SEE PAGE 898), 7TH FEBRUARY, 1930.

Dr. C. V. Drysdale: The great value of instrument transformers was obvious from the moment of their introduction, but the errors in their ratio and especially in their phase were at first too great to commend them to lovers of accuracy. With the advent of better design, methods of compensation and, above all, the use of nickel-iron alloy, the situation is now entirely changed, and precision instrument transformers can be employed without appreciable error for all commercial tests, and even for the majority of standardizing measurements. It is no exaggeration to state that such transformers are now effecting a revolution in a.c. measurement. These improvements have, however, accentuated the need for accurate tests of the transformers themselves, and the papers now before us are valuable contributions to this subject. Mr. Shotter's paper interests me greatly, as I believe that I was the first to make accurate measurements on the ratio and phase displacement of potential and current transformers, using a wattmeter method.* My methods were practically equivalent to Figs. 2 and 3 of the paper, but instead of using a null method by varying the resistance in one of the wattmeter shunts, I observed the wattmeter deflection and found the quadrature or phase-displacement component by replacing the series resistance in the moving-coil circuit by a condenser. This method worked well, and gave measurements which were consistent to about ± 0·05 per cent in ratio and ± 1 minute in phase angle. Mr. Shotter's null method is ingenious, convenient and probably rather more accurate, if the symmetry of the double wattmeter is sufficiently perfect, and care is taken to secure the correct phase relations. His theory of the method does not, however, seem to me to be very lucid, and a simple vector diagram (Fig. A) makes it more easily understandable. A wattmeter may be regarded either as an ammeter which measures the component of the current in phase with the potential or as a voltmeter which measures the component of the potential in phase with the current. Let OA be the primary vector current or potential, and OB the secondary current or potential, the latter generally being slightly smaller than OA and lagging behind it by a small angle. Assuming that the differential wattmeter is "excited" in phase with OA, it is evident that if OA could be reduced to OC (where BC is perpendicular to OA) there would be no deflection, and this effect can be produced by increasing the resistance in the corresponding wattmeter shunt, in which case it is evident that the percentage difference or loss of ratio:—(OA − OB)/OA × 100 = 100 CA/OA = the percentage increase of resistance required to produce balance. If we could measure the quadrature component BC, the phase displacement could be evaluated, as $\theta = BC/OA$ radians = 3 438 BC/OA minutes, approximately (assuming CA very small); in my own test this component was directly measured by changing the phase of the wattmeter shunt current or "excitation," to quadrature by the condenser. In order to measure it by a null method, Mr. Shotter causes the "excitation" to lag by 60° behind OA, in which case if the vector OA were increased to OD there would again be balance; and this can be effected by reducing the resistance in the wattmeter shunt. But CD = $\sqrt{3} \times$ BC, so that

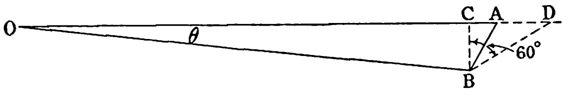

FIG. A.

$$\theta = (3\,438 \times CD)/\sqrt{3} \times OA = 1\,985\ CD/OA,$$

and if CD/OA is 1 per cent, $\theta = 19\cdot85$ or approximately 20 minutes. The phase-lag in minutes is therefore 20 times the percentage reduction of resistance from its previous value. Mr. Shotter's double resistance box enables these two changes of resistance to be made separately, and thus renders the method direct-reading. It should be observed, however, that the accuracy of the method depends materially upon the accuracy with which the wattmeter is "excited," firstly in phase with, and secondly lagging 60 degrees behind, the primary potential or current, as well as upon the accuracy of balance of the two sections of the wattmeter. If in setting up the apparatus great care is taken to secure accuracy in these respects, the method is convenient and accurate, but otherwise I should be inclined to adhere to my original deflectional method with a single wattmeter and condenser. Had I to make such measurements again, however, I should be inclined to use a bridge method such as that described by Dr. Arnold. Of the two methods which he describes I should employ his "Direct Bridge," but I should prefer to substitute a variable mutual inductance for the condenser shunt and to make the bridge direct-reading for a given frequency, as shown in Fig. B. In this diagram the primary and secondary coils of the transformer are connected in series with two non-inductive resistances R_1 and R_2, preferably of the Moore concentric form, the ratio R_1/R_2 being equal to the nominal ratio of the transformer. As the maximum secondary current is usually the standard 5 amperes, R_2 can be fixed, but it is made about 2 per cent higher than its nominal value, and has a second contact "b" at a point 2 per cent below the nominal value, a slide wire being connected between these two contacts "a" and "b" (the resistance should of course be adjusted with the slide wire connected). The main lead from "a" passes through the primary of an astatic shielded variable mutual inductance M to the load, and the vibration galvanometer is connected between R_1 and the slide-wire contact, through the secondary of M. If the transformer were perfect, balance would be obtained with the slide-wire contact at its centre or zero point and with zero inductance; the loss of ratio can be read directly from the slide-wire contact, and the phase displacement from the mutual inductance, since $\theta = 3\,438\ M\omega/R_2$. Allowing for a drop of $0 \cdot 5$ volt with 5 amperes (the secondary current), $R_2 = 0 \cdot 1$ ohm, and, for a frequency of 50 cycles per second, $\omega = 314$, so that $3\,438\omega = 1 \cdot 08 \times 10^6$. If the maximum phase displacement to be measured is $1 \cdot 5°$, or, say, 100 minutes, $M = R_2\theta/3\,438\omega = 0 \cdot 1 \times 100/1 \cdot 08 \times 10^6 = 10$ microhenrys approximately, and the scale of the mutual inductance can be marked off directly in minutes for that frequency. Dr. Arnold's shunting arrangement cannot be improved upon for accuracy, but the resistance shunt involves calculating reciprocals, and the mutual inductance should be cheaper than the variable condensers, and cover a greater range of phase angle. It should be pointed out that as the phase displacement produced by the condenser shunt is $\theta = 3\,438\ CR_2\omega \times 10^{-6}$ minutes if C is in microfarads, C must be approximately 10μF per minute of phase displacement for $R_2 = 0 \cdot 1$ ohm at 50 cycles per second, so that a very high capacity would be necessary for many commercial transformers. It would be more in conformity with other methods to connect the slide wire and mutual inductance in the primary rather than the secondary circuit, but the arrangement shown seems preferable on the ground that the maximum secondary current of transformers is generally fixed at 5 amperes, so that R_2 and M can be fixed, and different resistors can be used for R_1 according to the primary current. Mr. Spilsbury's form of resistor is probably as good a form as can be devised for the somewhat high drop of 2 volts for which it is designed, and his theory of correction by suitably tapping the p.d. points on the busbars is ingenious. Many years ago * I advocated the subdivision of low-resistance standards into a number of parallel circuits, in order to reduce their inductance, and he has now carried this method to perfection. Since the advent of Mr. Moore's concentric form of resistance, however, I have always felt this to be the best form to adopt wherever possible, and I do not think that it has received the appreciation which it deserves. On account of its tubular construction it is not suitable for resistances of a higher value than a few tenths of an ohm, but for this or any lower value I should use it in all precision measurements. For practical purposes, the oil-cooled double tubular form which Messrs. H. Tinsley have made to my designs for a.c. potentiometer work, seems to be more convenient, as it takes up less space and the low residual inductance can easily be calculated. I feel that the three papers which have been read have brought the important subject of instrument-transformer testing to a very satisfactory state, and that little further advance is now needed.

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* C. V. DRYSDALE: "Some Measurements on Phase Displacements in Resistances and Transformers," *Electrician*, 1906, vol. 58, pp. 160 and 199; also "The Use of Shunts and Transformers with Alternate Current Measuring Instruments," *Philosophical Magazine*, 1908, vol. 16, p. 136.

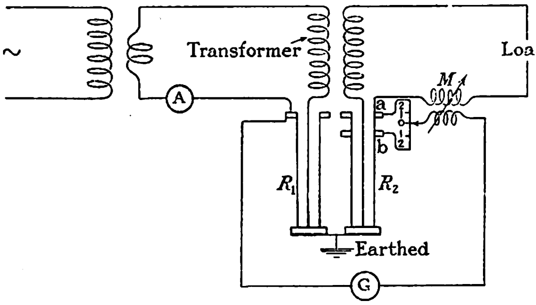

FIG. B.

Dr. E. H. Rayner: There are two things in this world which I had never expected to experience or see: one is transatlantic telephony, and the other is a perfect current transformer. I admit that the perfect current transformer has given me more trouble and worry than the telephony, because it has been one of the weak links in the chain of electrical measurements. It has been my experience to have to consider inquiries from almost all the large electrical manufacturing undertakings in this country as to how they can improve the accuracy of measurements of power in cases where power factors are very low; the light-load losses of large transformers which in these days are fixed by specification within closer limits than those between which it has been possible to measure them, are an example of this. The readings of the instruments are necessarily small when the power factor is of the order of 5 per cent, so that the errors, and especially the phase-angle error, make a very big percentage correction to the reading. The mumetal transformer has changed all this; and it has the advantage that whilst the phase angle, which has been largely the crux of the situation, has been reduced almost to zero, the ratio has also been kept constant. A new era of accurate electrical measurements has thus begun. It is rather peculiar that even now, as for many years past, the measurement of power and energy by alternating-currents has been simpler and more accurate than the measurement of direct current by wattmeters or watt-hour meters. A new stage in which the watt-hour meter is once more the focus of attention as regards the measurement of energy is just now beginning, and I hope that the development of the watt-hour meter will be stimulated by the perfection of the current transformer. These developments will make the measurement of the power and the energy produced by large plants and, indeed, of all kinds of electrical apparatus, more accurate. The designer will be able to obtain more accurate information as to the performance of his plant so that improvements will be facilitated. Eventually the effect will be felt throughout the whole field of alternating-current engineering, and it will stimulate the day-to-day improvements which are proceeding so rapidly all over the world. Mr. Spilsbury has mentioned the difficulty of measuring these large currents otherwise than by means of current transformers. These transformer methods have only recently become available, and he and Dr. Arnold have been working for months upon them. Many small details have cropped up and produced little anomalies which have been investigated at considerable pains; the work has, I believe, been carried to a greater accuracy than has ever before been achieved. Before the possibilities of mumetal had been explored, other methods of measuring power at currents upwards of 2 000 amperes had to be thought out, and I designed a non-inductive resistance for 5 000 amperes. The design has never been completed, partly on account of the introduction of mumetal. It is possible that, as the result of further investigation, this material may be applied to potential transformers. In my own experience we have already found it valuable in connection with potential transformers designed for certain specific purposes.

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* "New Low-Resistance Standards," *Electrician*, 1916, vol 77, p. 629.

Mr. E. V. Newbery: The conclusions of Mr. Spilsbury and Dr. Arnold with regard to the stability of mumetal cores are certainly very interesting, but they do not agree with my own experience at Rugby. The investigations which are going on there have shown certain variations with regard to mechanical treatment and over-magnetization. Although these are comparatively small and do not affect the value of mumetal for many industrial applications, they tend to show that the concluding paragraph of the paper is rather too sweeping in its assertions. Mumetal cores have, no doubt, a great future, but further investigations are necessary.

With regard to Mr. Shotter's paper, I notice that he has been using a standard transformer with a square core; the author rightly stressed the fact that with a square core the primary must always be wound in the same position in the hole, and with the same radius of turns. Some years ago the firm with which I am connected carried out experiments on this subject, when large variations were discovered, and this led to the abandonment of the use of square cores for precision work. It is true that if the radius of the primary turns is kept constant and the turns are placed in the centre of the hole, fairly good agreement can be obtained. In the case of a standard transformer with a varying number of turns, however, these cannot be placed in the same space in the centre of the core. With a ring-core transformer the position and radius of the turns do not materially affect the ratio or the phase angle, if the secondary is evenly distributed. I refer, of course, not so much to the high-precision work of the National Physical Laboratory as to commercial testing. With regard to the applications which Mr. Shotter suggests, I do not feel that they will be of great value. The measurement of losses on power transformers is certainly a very difficult problem in view of the low power factor, but modern research in the building of wattmeters has produced instruments which are capable of very accurate work, provided that allowance is made for the phase-angle errors of the instrument transformers. In the latter the mumetal core is of value, but the lengthy calculations involved in the computation of the losses when using the author's apparatus will probably discount any advantage which may be claimed for it. The Hopkinson method of testing machines is now no longer used for measuring efficiencies, as the British Engineering Standards Association definitely lays down the method of segregation of losses. With regard to the actual methods of testing current transformers, I am concerned in an investigation which employs the N.P.L. method. The apparatus, which is at present being prepared, embodies the modification of using a standard current transformer not only for the heavier currents but right down to the 5·5 ratio. A current transformer with 7 200 ampere-turns is being built for the purpose; it will have an ordinary 5-ampere secondary winding with two primary windings wound upon it. One of these will have the same number of turns as the secondary winding, but will be wound in 20 sections for series or parallel connection. A 5·5 ratio which will make the transformer self-checking is thus obtained. The second primary winding is designed for 60 turns wound in 20 sections, and these two primaries, together with turns which can be wound through the hole, will give every ratio in the standard line; there will also be tappings on the secondary winding for that purpose. The instrument will be calibrated by the N.P.L. to give the standard of precision necessary for accurate commercial testing. This type of transformer enables the whole of the testing to be carried out without the use of shunts—an important advantage over the more usual form of equipment. The idea of eliminating errors due to the human element, which the same author has devised, by introducing the use of dials on the instrument for the corrections of the standard transformer, is of value from the point of view of commercial testing. The equipment can be used either for current or potential transformers, and although this feature does not present very great advantages to large concerns in which separate apparatus for each is provided, it is nevertheless a point in its favour.

Mr. W. Holmes: It is not many years ago since current transformers and potential transformers were placed in two different categories. Phase-angle errors were not much understood. It was considered to be sufficiently accurate to test a wattmeter with and without its current transformer, and to ascribe the difference to the phase angle. This became such a habit that 20 minutes per 1 per cent error at a power factor of 0·5 was always assumed without reference to a cosine table. The method was technically accurate, but the observational and other errors were great. Mr. Shotter, after patient investigation, has produced a practical way of eliminating the errors. We have been working with the Shotter method for current-transformer and the Silsbee method for potential-transformer testing, but I now consider that testing institutions should adopt the Arnold method for current transformers. The method due to Mr. Shotter is suitable for an ordinary electricity supply laboratory and test room which has to deal with an output of transformers for meter work, because this method will test both current and potential transformers. When using the bridge method in our works we experience considerable disturbance of the galvanometers as the result of mechanical vibration from surrounding machinery, and this may give trouble in the test room of a generating station. I have been looking for wave-form errors in Mr. Spilsbury's paper, because if such errors exist it must be difficult to define phase-angle error. We have observed differences between the test results obtained when using a wave with a steep front compared with those obtained when a sine wave is used. From this point of view the Shotter method should give a more practical result, as transformers are generally used on dynamometers or induction wattmeters. Mr.

Shotter should perhaps describe it as a "balanced torque" rather than as a "null" method, as he applies full current and full potential to the instrument. I am glad that Mr. Spilsbury finds the 5 000-ampere-turn mumetal current transformer to be stable. Owing to the high cost, we are used to limiting mumetal to the bushing type of about 500 ampere-turns, and thus the errors are necessarily larger. In Fig. 14 of Mr. Shotter's paper a difference of 4 minutes is recorded between the results of his own and the N.P.L. tests, while the manufacturer's test result lies between the two. Differences of this magnitude frequently occur between tests made by different authorities. Recently we made a slightly compensated potential transformer and found it to have a phase-angle error of — 8 minutes on our test. It was sent first to a southern testing institution, which found the error to be — 2 minutes, and then to a northern testing institution, which reported an error of — 11 minutes, whilst our own test can only repeat — 8 minutes. I am therefore glad to see that testing methods are being thoroughly investigated.

Mr. W. Phillips: For routine testing of instruments it is necessary to have a quick and accurate method which at the same time involves the minimum of expense in the way of special plant and instruments. In this respect the Shotter apparatus is almost ideal; it requires only a sensitive differential wattmeter and a potential divider adjusted in percentages. Each of these pieces of apparatus has been designed as a separate unit, so that any instrument can be used with any resistance box. This, of course, tends to cheapness of production and ease of repair and replacement. Special transformers can evidently be dispensed with and any transformer of which the errors are known can be employed as a standard. This is, I think, a valuable feature. It is further stated that the errors can be estimated on the apparatus itself, provided that the transformer has a hole through the centre so that a primary winding giving a 1 : 1 ratio can be employed. The only other accessory, apart from the apparatus for phase-shifting to be found in every laboratory which deals with accurate testing of wattmeters and watt-hour meters, is a small transformer to supply the current coils of the indicator for testing potential transformers. This can be constructed in the test room or can be purchased for a few shillings. The method of test is quick and accurate; when the apparatus has been installed and permanent connections have been made, the complete testing of a current transformer for ratio and phase angle at one secondary burden takes about 5 minutes. The errors are usually not in excess of 0·02 per cent in ratio and 2 minutes in phase angle at full load. The only point that requires care is the application of the corrections, and this is largely a matter of experience. While the Shotter method is all that is required for use in industrial testing rooms, it is recognized that an absolute or precision method is necessary for ultimate standardizing work. The method in use at the N.P.L. and on the Continent incorporates a standard resistance, a potential divider, a balance indicator in the form of a vibration galvanometer and some means of balancing the quadrature component of the current. This latter consists of a subdivided condenser, in the equipment which has been described. Although rapid and accurate, the apparatus is expensive, as I found some time ago when I investigated the methods of precision measurement of current transformers and made an especial survey of this type. I found that the cost of the apparatus for testing current transformers up to a primary current of 100 amperes was between £250 and £300, and that if potential transformers were to be tested up to a voltage of 25 000 an additional £330 was necessary. These prices were quoted by a German company. It is evident, therefore, that this apparatus is beyond the reach of almost all testing rooms except those supported by a Government department. I cannot see why this scheme was chosen in preference to an older but equally accurate one of the type similar to that described by Dr. Drysdale, with the exception that the quadrature component is compensated by a phase-shifter or double generator. The method, which is due to P. de la Gorce,* employs standard resistances. It is very accurate and requires no special additional apparatus such as a standard condenser—most engineers regard these with doubtful enthusiasm, particularly when they are subdivided to such low values as 0·001 microfarad. One of the necessary accessories for current transformers is the standard resistance, and that described by Mr. Spilsbury seems to be an accurate and comparatively cheap instrument which overcomes all the difficulties involved in the design of standard resistances for large currents. I should like him to amplify his method of testing the resistance for phase angle. Referring to the use of mumetal current transformers as standards, my experience, extending over some 5 years, has convinced me that they offer a means of accurate current and power measurement hitherto unequalled. I have found no appreciable variations in phase angle or ratio and can endorse all the evidence that Mr. Spilsbury and Dr. Arnold have brought in their favour; in fact I consider a mumetal current transformer, used in conjunction with a 5-ampere wattmeter, to be the most accurate means of industrial power measurement in existence. In connection with the use of mumetal current transformers, it must be remembered that for the most accurate work the secondary burden should be kept low in order that the density in the core may remain at a value such that advantage can be taken of the high permeability of the metal.

Mr. R. S. J. Spilsbury: Mr. Shotter mentions the Silsbee method of testing current transformers, and suggests that his own is simpler. Actually there is not much to choose between the two from this point of view, the phase shifter and other auxiliary apparatus being common to both; the Silsbee method, however, uses only a single-element wattmeter instead of a double-element instrument, and it dispenses with the resistance box. The calculation of the phase angle is also rather simpler, because the auxiliary voltage is in quadrature with the current, so that no account has to be taken of the ratio error of either transformer. The secondary burden of 4 volt-amperes imposed by Mr. Shotter's method may be somewhat inconvenient when it is desired to make a test at a definite burden. It is suggested in the paper that this difficulty is easily overcome by making tests with two or more burdens and extrapolating the results to zero burden: it should be mentioned that the added burdens must have the same time-constant as the detector current coil, so that it would be of advantage to supply one or two accurately matched dummy coils with the equipment. The Silsbee method shows to advantage here, since the burden imposed is much less. Using the special instrument to which Mr. Shotter refers in the paper to test a current transformer having a ratio error of 1 per cent and a phase-angle error of 60 minutes (the limits for Class B accuracy), the added burden due to the detector is only 0·3 volt-ampere at full current, which is practically negligible. The points in the author's method which appeal most to me are the versatility of the equipment, and the ingenious method of compensating for the errors of the standard transformer on a separate set of dials; this latter feature will, I think, prove to be very valuable when the apparatus is used by relatively unskilled staff.

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* "Note sur L'Essai des Transformateurs de Mesure de Courant au Laboratoire Centrale d'Électricité," *Bulletin de la Société International des Électriciens*, 1916, vol. 6, p. 299.

Mr. G. W. Stubbings (*communicated*): Mr. Shotter's method for the determination of the phase error of a current transformer depends upon the fact that the fractional error of a wattmeter, due to this phase error, is approximately equal to $\alpha \tan \phi$, where α, the phase error, is expressed in radian measure. Tan $60° = \sqrt{3}$, and the radian measure of 20 minutes is very nearly $1/\sqrt{3}$ per cent. If, therefore, a wattmeter reads inaccurately, owing to the phase error of a current transformer with a circuit power factor of 0·5, the percentage error multiplied by 20 gives this phase error in minutes. Had the more rational method of specifying phase errors in percentages of a radian been adopted, the test could have been simplified by balancing the double wattmeter with a phase difference of 45 degrees between the current and voltage. Since $\tan 45° = 1$, the difference between the tests at power factors of unity and 0·707 gives the phase error directly in radians. The degree measure of small phase errors has to be converted to radian measure for correcting wattmeter readings, and it therefore seems best to record these errors in the form in which they will be used. A further advantage of carrying out the second balance test at a power factor of 0·707 is that the torque on the wattmeter is nearly half as much again as it is with a power factor of 0·5, and the sensitivity of the instrument is correspondingly increased.

Mr. G. F. Shotter (*in reply*): As Dr. Drysdale points out, it is essential that the phase relationship between the current and potential supplies to the detector must be accurately set. I, myself, experience no difficulty in this direction since I use a Tinsley-Drysdale phase-shifter.

Mr. Newbery confirms the precautions necessary when using a "hole" type current transformer. I am indebted to him for his remarks about the other applications of the method. They were only referred to from the point of view of interest, although I feel that the application of the method to the testing of power transformers would not be so complicated as he states.

I quite agree with Mr. Holmes's suggestion that "balanced torque" would be a more suitable title for the method than "null," as the theory of the method, as developed in the paper, is based on those lines.

I agree with Mr. Spilsbury regarding the inconvenience of the 4-VA burden of the detector in certain cases, although for commercial testing the errors introduced by this burden would be negligible. I think his suggestions as to accurately matched dummy burdens is a valuable one. However, it might be possible to decrease the burden imposed by the series coils if this was found to be necessary.

I agree with Mr. Stubbings that in the cases where the phase-angle errors of instrument transformers have to be applied to wattmeter or watt-hour meters at any power factor (e.g. when testing *in situ*) his method of correction is undoubtedly the right one, but when testing equipments in the laboratory at the British Engineering Standards test of unity and 0·5 power factors, I think the method of correction as outlined in the paper is much simpler, since the percentage errors (read directly on the testing box) obtained in the 60° test are the combined ratio and phase-angle errors of the instrument transformers at 0·5 power factor (lag), and can be directly applied to the wattmeter or watt-hour meter.

Mr. R. S. J. Spilsbury and **Dr. A. H. M. Arnold** (*in reply*): In reply to Dr. Drysdale we do not suggest the use of the "direct bridge" for general testing: it is used purely for work of the highest accuracy on transformers having very low errors, and for these the value of the capacitance required is not unduly large. We think that the method suggested by him has several disadvantages as compared with the "potential divider bridge." In the first place it is much less flexible and requires a different heavy-current resistance for each transformer ratio. A more serious objection is the use of a variable mutual inductor. Though such instruments are described as astatic, they are in reality appreciably affected by stray magnetic fields, and in testing bar-type current transformers such fields cannot be avoided. In our view the perfect astaticism of the condenser is a great advantage. The capacitance required at 50 cycles for a phase angle of 100 minutes is 1 μF, which is a convenient value. The method is direct-reading for ratio and phase angle. It is possible that Dr. Drysdale's method might be a little more rapid, but the saving in time could only be small. The Moore type of non-inductive resistor should be very satisfactory for low values of resistance and moderate currents, provided that a uniform distribution of current in the tube can be secured: for large power dissipations cooling would probably be difficult. We have, however, never seen a resistor of this type or any account of measurements of its characteristics. With Dr. Drysdale's own double tubular form we are more familiar: the residual inductance of this type is fairly low and is calculable. Owing to the method of cooling adopted it becomes rather bulky where large powers have to be dissipated, but the stability of the resistance should probably be better than that of the Paterson-Rayner type. For large voltage-drops at high currents this latter form appears still to hold the field, except in so far as the mumetal transformer replaces it.

We agree with Dr. Rayner that the mumetal-core transformer will make revolutionary changes in methods of precise electrical measurements. It is an interesting fact that one of the first effects of the introduction of mumetal, an alloy produced for quite different purposes, has been to extend indefinitely the range of powers which can be easily and accurately measured by the electrometer.

Mr. Newbery has doubts as to the stability of the mumetal-core transformer: we think, however, that if he will re-read the paragraph in our paper to which he refers he will see that it is a statement of fact. We entirely agree with him that very much more work will be necessary before the stability of commercial transformers using this material is established, but we feel that our results show that such stability is not impossible to attain. We think that the standard current transformer which Mr. Newbery describes should be a most valuable piece of apparatus.

Mr. Holmes mentions difficulties due to mechanical vibration. Such troubles are serious where precise testing has to be done near running machinery. Probably Mr. Holmes is already using a moving-coil vibration galvanometer: if not, the substitution of an instrument of this type for the moving-iron pattern will reduce the disturbance. With regard to wave-form errors it is, we believe, general experience that a normal current transformer reproduces the primary wave-form to a high degree of accuracy, even when this wave-form is badly distorted. The methods we have described, employing a vibration galvanometer, give the ratio and phase angle corresponding to the fundamental wave: this is, in general, what is required. Certain special types of transformer do give wave-form distortion, and for these no precise figures of ratio or phase angle can be obtained by any method. Mr. Holmes's figures with regard to voltage transformers are interesting, though hardly within the scope of our papers: we may, however, mention that discrepancies of this order can very easily occur unless great care is taken to eliminate or allow for the effects of earth capacitance in the voltage divider employed in the tests.

The cost of the complete apparatus for the "potential divider bridge" which Mr. Phillips mentions seems very high. The cost of the heavy-current resistances is a serious item for all "absolute" methods, but is actually lower than usual for the "potential divider bridge," since only a few values are required. Apart from the variable condenser, which would cost about £40, it should be possible to construct the apparatus quite cheaply. De la Gorce's method, which Mr. Phillips advocates, seems to us to have several disadvantages. Our main reason for abandoning the electrometer method which we had previously used was to enable current-transformer testing to be carried out on any single-phase supply, so that the de la Gorce method, which requires a phase-shifter or double-alternator set, was inadmissible. Apart from this, however, the method requires an additional setting (that of the phase of the auxiliary voltage) beyond the normal double adjustment of the bridge. The standard condenser used in the "potential divider bridge" is a very reliable piece of apparatus: if a change of value of one section were to occur it would make itself obvious, since the phase-angle values obtained for a transformer at various currents would no longer lie on a smooth curve. The method used for measuring the phase angles of the 200-ampere resistors was that described by L. Hartshorn in the *Proceedings of the Physical Society of London* (1926–7, vol. 39, p. 377). Another method, more suitable for use at power frequencies, is now being developed, and will probably be described shortly. We are very glad to learn Mr. Phillips's opinion, based on a much larger experience than our own, with regard to the stability of mumetal-core transformers: we agree with him that the days of the "straight-through" heavy current wattmeter are over.

AN ANALYSIS OF HEATING TESTS ON ELECTRICAL MACHINES.[*]

By EDWARD HUGHES, Ph.D., B.Sc., Member.

(*Paper first received* 20*th August, and in final form* 27*th November*, 1929.)

SUMMARY.

The factors governing the temperature-rise of electrical machines are so interwoven that the only satisfactory method of separating them is to test actual machines with different distributions of losses, different speeds, etc.; conclusions derived from tests on models must be accepted with caution. In this paper are given the results obtained on two electrical machines, one with a rotating armature and the other with a rotating field, which were tested with different load and field currents, different speeds, etc. The machines were also tested when totally enclosed and when cooled by an induced draught. Temperature-rises were measured by thermometer, by thermo-junction and by the increase of resistance. In the case of the machine with the rotating armature it was found possible to follow the temperature variation of the latter by placing a thermo-junction a short distance away from the armature, and it is suggested that this method might be used for shortening the duration of heat-runs.

INTRODUCTION.

An enormous amount of work has been done on various aspects of the rise and distribution of temperature in electrical machines. Many investigators—notably G. E. Luke in the United States—have endeavoured to analyse the various factors governing the temperature-rise of a machine by studying each factor separately on suitable models. This method simplifies the procedure and often results in important discoveries being made; but it must be borne in mind that the effect of two factors in combination may be different from their effects when acting separately. For instance, Luke[†] found that the heat dissipation from a rotor was increased (*a*) by increasing the peripheral speed with no forced axial ventilation, and (*b*) by increasing the forced axial ventilation when the rotor was stationary; but with a combination of peripheral speed and forced axial ventilation he found that, under certain conditions, less heat was dissipated with the rotor revolving than when it was stationary for the same rise of temperature and the same quantity of air through the air-gap per minute. Hence, if we are to separate the factors that determine the temperature-rise of various parts of an electrical machine and to find their interaction upon one another, the first step is to carry out an exhaustive series of tests on *one* machine, the losses in which have been measured accurately for the different test conditions. It is, of course, realized that the conclusions deduced from such an analysis cannot be applied indiscrimately to all types of dynamos and motors, but they do assist in elucidating the problem of heat dissipation.

In this paper the test-results on two machines have been investigated. Machine A was a standard d.c. machine except that the commutator was replaced by 3 slip-rings and, for this reason, was chosen for these tests. Its rated 3-phase output was 3·5 kVA, at 50 periods per sec. and 1 500 r.p.m. Machine B was also a 3-phase alternator with a revolving field and a stator winding of the concentric 2-plane type. Its rated output was 5 kVA at 60 periods per sec. and 1 200 r.p.m.

Test Procedure.—The machines were tested at different load currents, different exciting currents and different frequencies, each test being continued until the temperature became practically steady. Many of the tests were carried out with the field and output currents maintained constant throughout any one test. Other tests were performed by overloading either the field or the armature or both for the first half-hour or so, the currents being then adjusted to the correct values. The latter method is referred to in greater detail on page 922.

The temperature-rise of the field winding was determined by a bridge arrangement described in a previous paper,[*] whilst those of the armature and stator windings of machines A and B respectively were measured by noting the p.d. required for a known direct current, the machine being stopped occasionally for the few seconds required to take readings. In the case of machine A, the p.d. was determined by auxiliary copper-gauze brushes bearing on two of the rings.

Other temperature-rises were also measured; thus, on machine A, a copper-constantan thermo-junction was fixed midway between the uppermost pole-tips at a radial distance of 2·5 mm from the armature core. The object of this arrangement was to see whether it was possible to obtain externally an indication of the core temperature without having to stop the machine, and thus enable the heating test to be shortened, as discussed on page 921. Also, the temperature of the armature core was determined by thermometer at the completion of each test. With machine B, one thermo-junction was placed under the head of a screw inserted radially into the stator core on the external surface and midway along one batch of laminations. Another thermo-junction was rigidly fixed in the middle of the centre vent-duct at a point half-way between the internal and external surfaces of the stator core. The object of this junction was to investigate the temperature of the cooling air passing through the duct.

The iron losses corresponding to the various loads, speeds and excitations were determined by measuring the input power to the d.c. motor that was directly coupled to the alternator, and also the output power of the latter. Allowance was made for the copper loss in the armature winding, the contact-resistance loss at the slip-rings and the small increase of copper loss in the motor armature.

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] "Cooling of Electric Machines," *Transactions of the American I.E.E.*, 1923, vol. 42, p. 636.

[*] E. HUGHES: "Rise and Distribution of Temperature in Small Electrical Machines," *Journal I.E.E.*, 1924, vol. 62, p. 640.

(1) TESTS ON MACHINE WITH REVOLVING ARMATURE.

Temperature-Rise of the Field Winding.—Figs. 1 and 2 * show the variation of the temperature-rise per watt with the total armature loss for different exciting currents and different peripheral speeds. It will be seen that the temperature-rise per watt is a linear function of the armature loss, but that the effect is greatly influenced by the temperature-rise of the field relatively to that of the armature. In a previous paper † the author suggested that the temperature-rise per watt for the field could be represented in the form

$$\frac{\theta_f}{W_f} = \frac{k(1 + mW_a)}{1 + nv}$$

where W_a is the armature loss, v the peripheral speed, and k, m and n are constants for a given machine. The data then available were not sufficient to check the general applicability of this expression. From Figs. 1 and 2, however, it is evident that the coefficient m, namely the slope of the lines, varies with every variation of the exciting current and of the speed, and that no general expression for the temperature-rise of the field is complete if it does not take into account the speed and either the loss in, or the temperature-rise of, the armature.

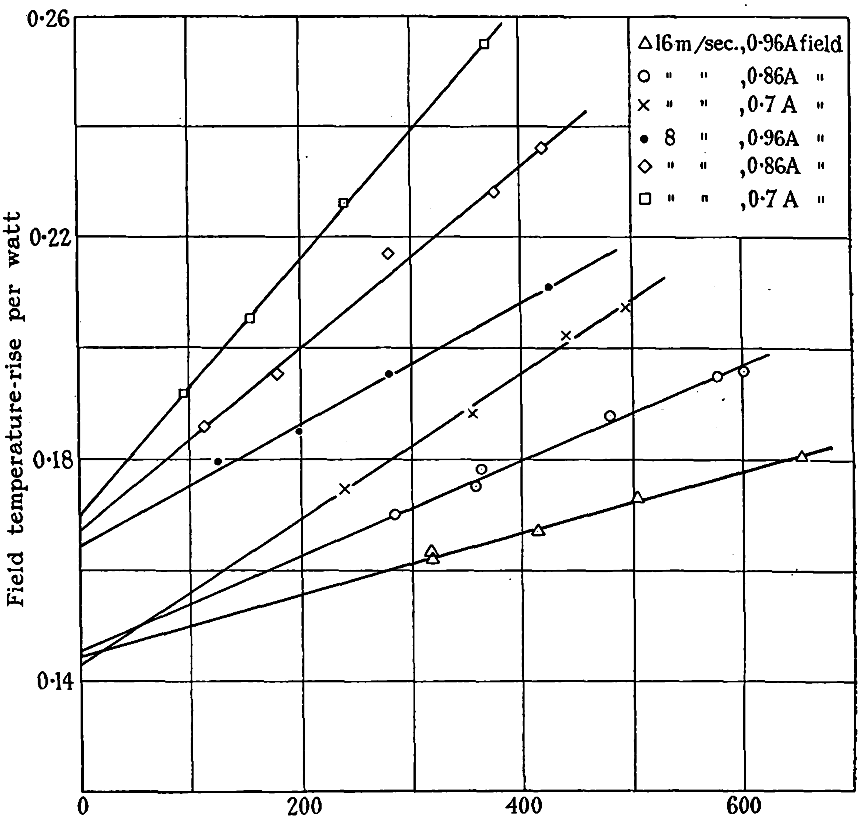

FIG. 1.

By producing the graphs of Figs. 1 and 2 back to the vertical axis, the temperature-rise per watt for zero armature loss can be determined for the various speeds and excitations. Graphs obtained by plotting the field temperature-rise per watt against the armature temperature-rise (by resistance) were of almost identically the same character as those of Figs. 1 and 2, and the values of θ_f/W_f for no temperature-rise of the armature winding agreed very closely with the corresponding values for no armature loss. The mean values of W_f/θ_f for no armature loss and for no armature temperature-rise, derived from these two sets of graphs, have been plotted in Fig. 3. If the curve through the mean of these points be represented by $A(1 + Bv^x)$, the value of x is found to decrease from 0·93 for a range of 0 to 5 metres per sec. down to 0·52 for a range of 11 to 16 metres per sec. These figures indicate that after the influence of armature heating has been eliminated, the effect of the speed upon the field is very similar to that found by Luke * for a cylinder rotating in air. From an analysis of Luke's curve the author finds that, up to a peripheral speed of 20 metres per sec., the watts dissipated per degree rise of temperature is represented by $A_1 + B_1v^{0\cdot 93}$, whilst for peripheral speeds of 25 to 50 metres per sec. it becomes $A_1 + B_2v^{0\cdot 6}$. It will be noticed that the *variation* of *x* is surprisingly similar to that found for the field coils above, and appears to be due to the air at the dissipating surface not being removed in proportion to the velocity.

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* The lines through the points corresponding to 1·86 metres per sec. have been drawn parallel to the respective lines for 3·73 metres per sec.

† *Loc. cit.*, p. 645.

* *Loc. cit.*, p. 646.

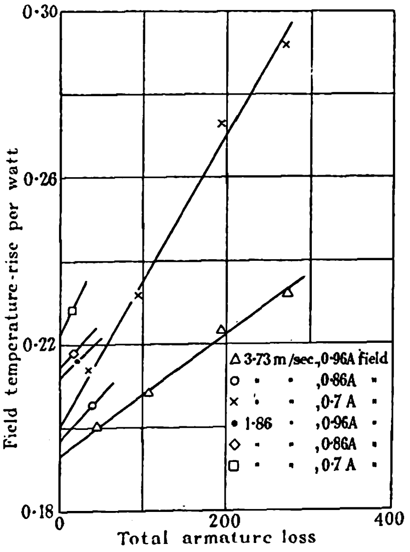

FIG. 2.

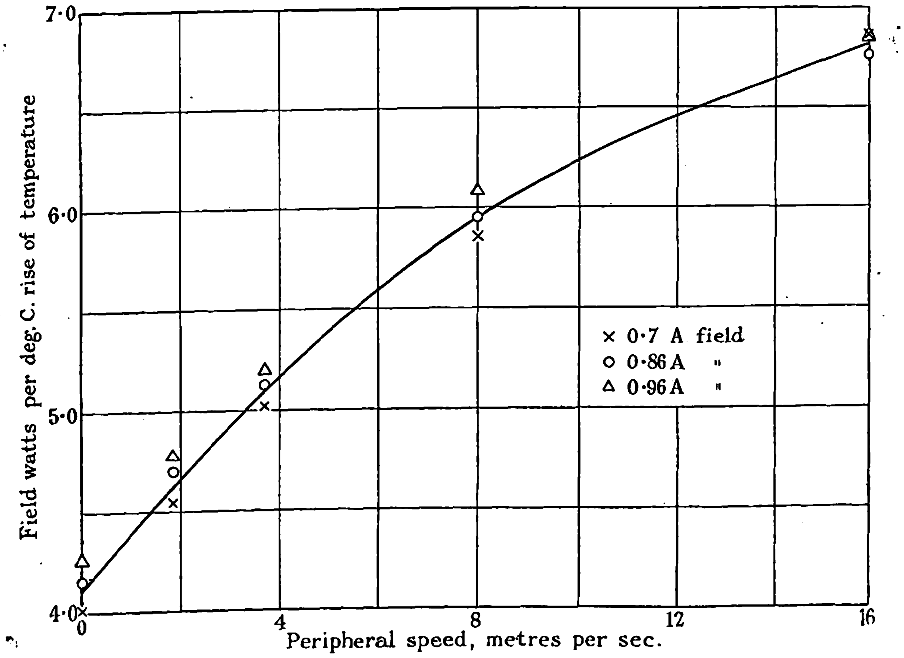

FIG. 3.

A simple mathematical expression giving a fair approximation to the graph of Fig. 3 is

$$W_f/\theta_f = 4\cdot 1(1 + 0\cdot 16\sqrt{v}) \quad . \quad . \quad . \quad (1)$$

A more cumbersome expression, but one which is in closer agreement with this graph, is

$$W_f/\theta_f = \frac{(v + 3\cdot 75)^{\frac{1}{3}}}{0\cdot 385} \quad . \quad . \quad . \quad . \quad (2)$$

Table 1 shows how the values calculated from expressions (1) and (2) compare with those obtained experimentally.

It will be evident from Table 1 that expression (1) underestimates the temperature-rise at low speeds.

TABLE 1.

Peripheral speed	W_f/θ_f from tests	W_f/θ_f from eqn. (1)	W_f/θ_f from eqn. (2)
m/sec.			
0	4·1	4·1	4·03
1·86	4·6	4·99	4·6
3·73	5·08	5·37	5·07
8·0	5·95	5·95	5·9
10·65	6·32	6·26	6·31
16·0	6·82	6·72	7·01

Effect of Armature Heating upon Field Temperature.—In any electrical machine working under normal conditions there is a rise of temperature of the armature—even on no load. It is therefore desirable to determine whether the effect of speed upon the field temperature is the same when the armature is hot as when it is at the room temperature, and, if possible, to derive an expression taking the temperature-rise of the armature into account.

In Fig. 4 the temperature-rise per watt of the field winding has been plotted against the difference between the temperature-rises of the field and armature windings (both measured by resistance) for different currents and different speeds. From these graphs it will be obvious that θ_f/W_f is almost independent of the field excitation and of the actual temperatures of the field and armature windings—as apart from the difference between their temperatures. The values of θ_f/W_f for the different speeds and for *equal* temperature-rises by resistance of the field and armature windings have been derived from these graphs and are indicated by crosses in Fig. 5. For purposes of comparison, curve A, showing the values of θ_f/W_f for no temperature-rise of the armature, has been included in this figure.

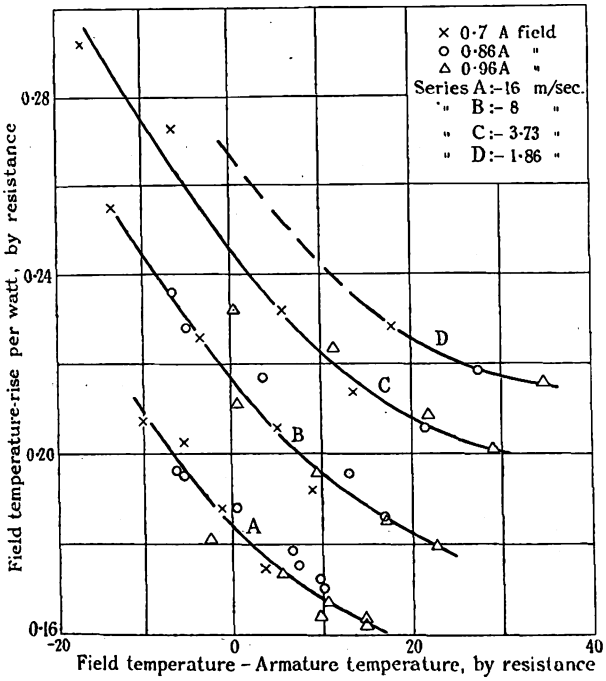

FIG. 4.

Since the more common practice is to measure the temperature-rise by thermometer, it is of interest to ascertain whether a similar result can be derived from such temperatures. Unfortunately, only a few thermometer readings had been taken for the field winding. From these readings, however, it was found that the temperature-rise by resistance was about 1·4 times that by thermometer, and the author had previously * found that this ratio was practically independent of speed and of excitation. By the aid of this ratio, the difference between the temperature-rises by thermometer of the field winding and armature core was estimated, and the results have been plotted against θ_f/W_f in Fig. 6. These curves again demonstrate that the effect of the armature heating upon the temperature-rise of the field is dependent upon the difference of temperature and is practically independent of the excitation.

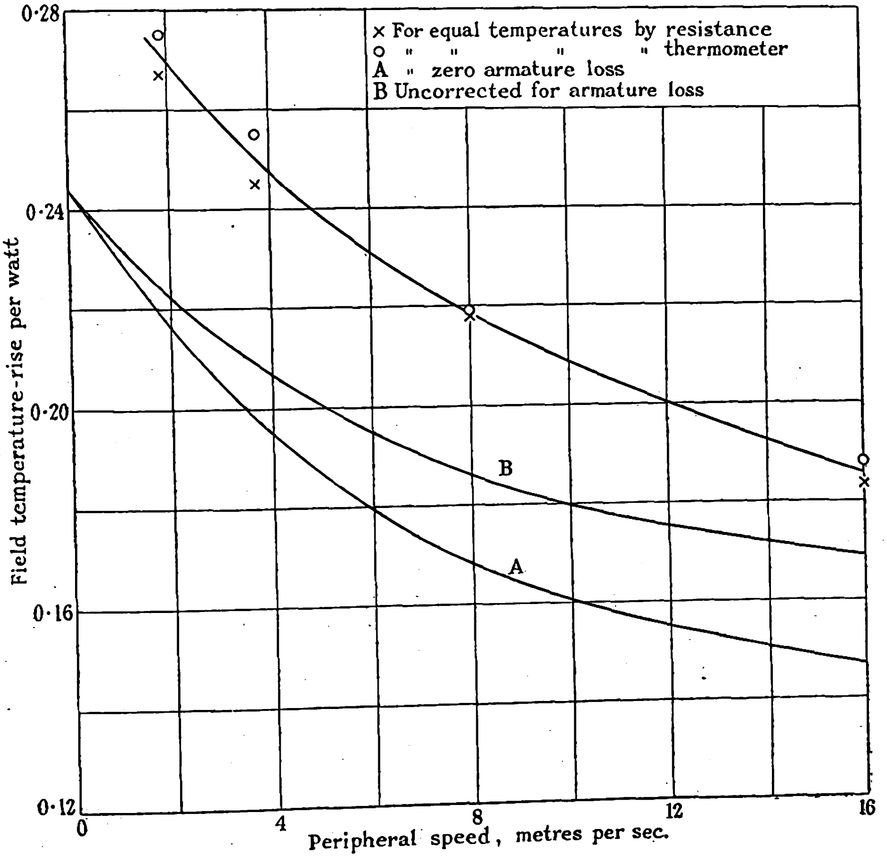

FIG. 5.

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* *Loc. cit.*, p. 646.

The values of θ_f/W_f for equal temperatures by thermometer are indicated by circles in Fig. 5 and are in close agreement with those derived from resistance measurements. The average of these two sets of points is represented very closely by

$$W_f/\theta_f = 2\cdot7(1 + 0\cdot25\sqrt{v}) \quad . \quad . \quad . \quad (3)$$

A comparison of expressions (1) and (3) shows that the speed is relatively much more important when the armature is hot than when it is cold; also, that the relationship between θ_f/W_f and speed, derived for no armature losses, does not apply when armature losses are present. That the relationship derived from the no-load tests, without any allowance for armature heating, is even more inaccurate—as far as speed is concerned—is evident from an inspection of curve B in Fig. 5, this curve being the mean for the three exciting currents with the armature on open circuit.

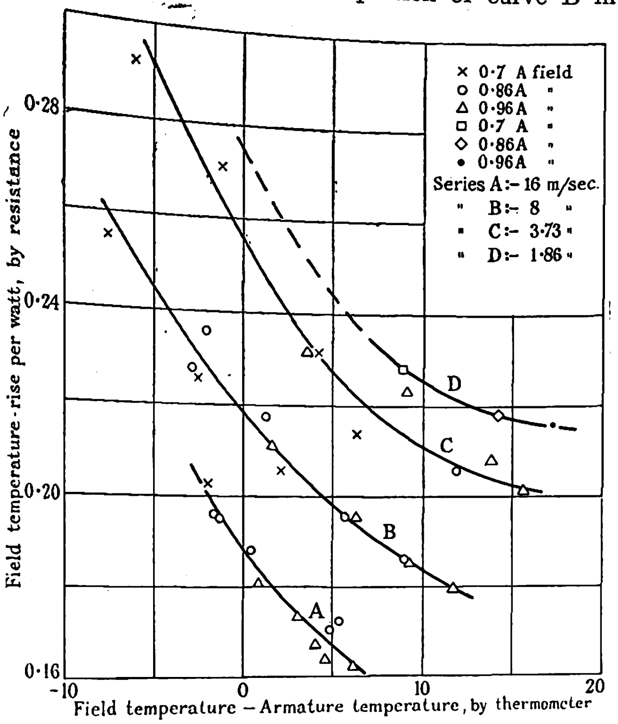

FIG. 6.

From Figs. 4 and 6 it will be obvious that the coefficient 2·7 in formula (3) requires to be modified whenever there is a difference of temperature between the field and the armature. Thus, in Fig. 4, a change from − 5 to + 5 deg. C. in the relative temperatures at a peripheral speed of 16 metres per sec. reduces θ_f/W_f from 0·1955 to 0·1745, a reduction of 10·7 per cent; whilst a change from − 10 to + 10 deg. C. results in a decrease of 20·3 per cent. The corresponding values for 8 metres per sec. are 10·6 and 20·2 per cent respectively, and those for 3·73 metres per sec. are 10·1 and 19 per cent. It therefore follows that a very close approximation may be made by allowing 1 per cent variation of θ_f/W_f for every 1 deg. C. variation between the temperatures of the field and armature windings when the temperatures are measured by resistance. For temperature-rises measured by thermometer (Fig. 6) it is found that the field temperature-rise varies about 1·4 per cent for every 1 deg. C. variation in the difference of the field and core temperatures.

These relationships may now be utilized for calculating the temperature-rise of the field under all conditions of load, speed and excitation, in the following manner:—

Let θ_f and θ_a = temperature-rises of the field and armature respectively;

c = percentage decrease of θ_f/W_f per degree increase of $(\theta_f - \theta_a)$;

d = value of θ_f/W_f when θ_f and θ_a are equal;

W_f = field loss at the final temperature.

Then

$$\theta_f/W_f = d\left\{1 - \frac{c}{100}(\theta_f - \theta_a)\right\} \quad . \quad . \quad . \quad (4)$$

If W = field loss at room temperature, which can be assumed to be about 15° to 20° C., and a = temperature coefficient of resistance at room temperature—for instance, about 0·004 for the above range—then $W_f = W(1 + a\theta_f)$.

Should θ_f be the temperature-rise by thermometer, it is necessary to make allowance in this expression for the ratio of temperature-rise by resistance to that by thermometer.

Substituting for W_f in (4) and solving for θ_f, we have

$$\frac{acdW\theta_f^2}{100} + \theta_f\left\{1 + dW\left(\frac{c}{100} - a - \frac{ac\theta_a}{100}\right)\right\} - dW\left(1 + \frac{c\theta_a}{100}\right) = 0 \quad . \quad (5)$$

For the machine under discussion, the value of c is about 1 per cent for temperature measured by resistance. Also, from (3), we have

$$d = \frac{0\cdot37}{1 + 0\cdot25\sqrt{v}}$$

At this stage it was felt desirable to check the temperature-rises calculated by the above formulæ against the test values over wide ranges of load and of speed. The results are given in Table 2.

Comparison of the last two columns shows that the agreement between the calculated and the observed temperature-rises of the field is very close—especially in view of the numerous factors that are involved. It is realized that the values of c derived above are only applicable to this particular machine, and that in most machines the field and armature windings are designed for the same temperature-rise. There are a few cases, however, such as variable-speed motors, where there may be considerable difference between the field and armature temperatures. In such machines, expression (5) can be of considerable assistance in determining the influence of the armature heating upon the temperature-rise of the field winding.

Temperature-Rise of the Armature.—The temperature-rise was determined both by resistance and by a thermometer placed on the core after the machine was shut down, as already detailed on page 912. In Fig. 7 the temperature-rise by resistance has been plotted against the total armature loss, and it will be seen that the two quantities are practically proportional to each other and that the relationship is independent of the field temperature but is greatly influenced by the speed.

TABLE 2.

Peripheral speed	Field current	Load current	Field loss at 15° C.	*d*	Observed temperature-rise by resistance		Calculated temperature-rise of field
					Armature	Field	
m/sec.	amps.	amps.	watts		deg. C.	deg. C.	deg. C.
0	0·7	0	89·1	0·37	4·0	24·6	26·4
0	0·96	0	168	0·37	8·3	47·7	46·1
1·86	0·7	0	89·1	0·276	4·7	22·4	23·0
1·86	0·96	0	168	0·276	8·7	43·5	38·2
3·73	0·7	0	89·1	0·25	7·4	20·9	20·4
3·73	0·7	8·85	89·1	0·25	46·3	29·4	29·1
3·73	0·96	0	168	0·25	10·7	39·8	36·7
3·73	0·96	8·6	168	0·25	47·0	47·1	48·8
8	0·7	0	89·1	0·217	9·4	18·4	17·9
8	0·7	9·33	89·1	0·217	39·0	25·4	25·5
8	0·96	0	168	0·217	12·6	35·0	33·7
8	0·96	9·05	168	0·217	41·4	42·1	42·0
16	0·7	0	89·1	0·185	13·1	16·6	16·1
16	0·7	7·6	89·1	0·185	24·9	19·6	19·0
16	0·96	0	168	0·185	17·0	30·9	30·2
16	0·96	9·76	168	0·185	37·5	34·9	35·5

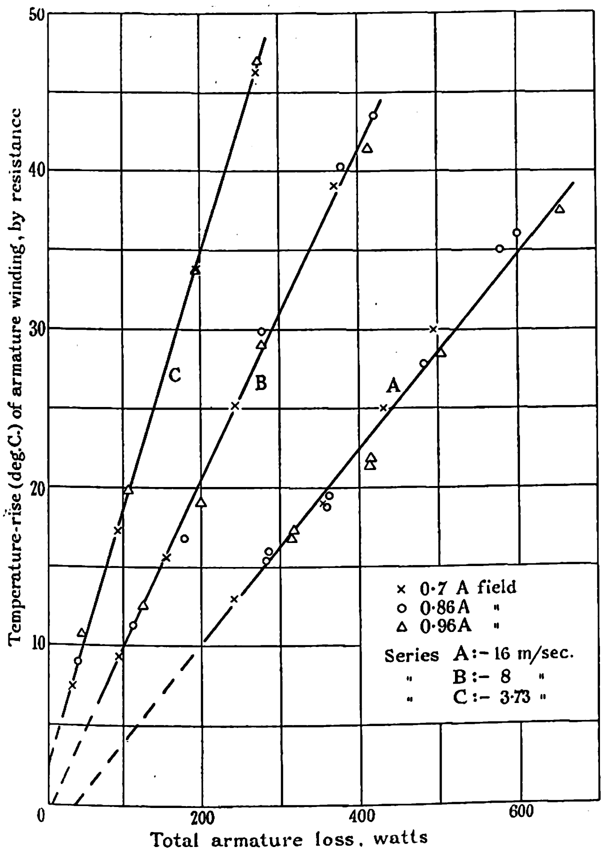

FIG. 7.

Attempts were made to find whether the temperature-rise by resistance could be related to any other quantity such as the armature copper loss, but none was found so satisfactory as the total armature loss.

In the same way, it was found that the temperature-rise of the core was most closely related to the sum of the iron and slot I^2R losses.

A thermo-junction was fixed midway between the uppermost pole-tips and 2·5 mm from the core, as mentioned on page 912, and the temperature-rises noted on this junction were also found to be more closely related to the iron and slot I^2R losses than to any other quantity. This relationship is seen in Fig. 8.

The simplest method of analysing these results so as to deduce a general expression involving losses and speed, was to calculate from Figs. 7 and 8 the watts

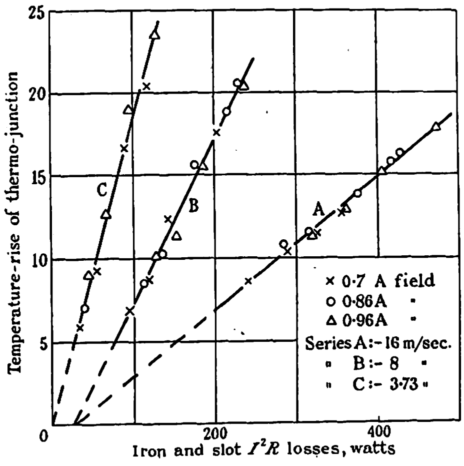

FIG. 8.

per deg. C. rise of temperature for various temperature-rises and then to plot these values against speed, as in Figs. 9 and 10.

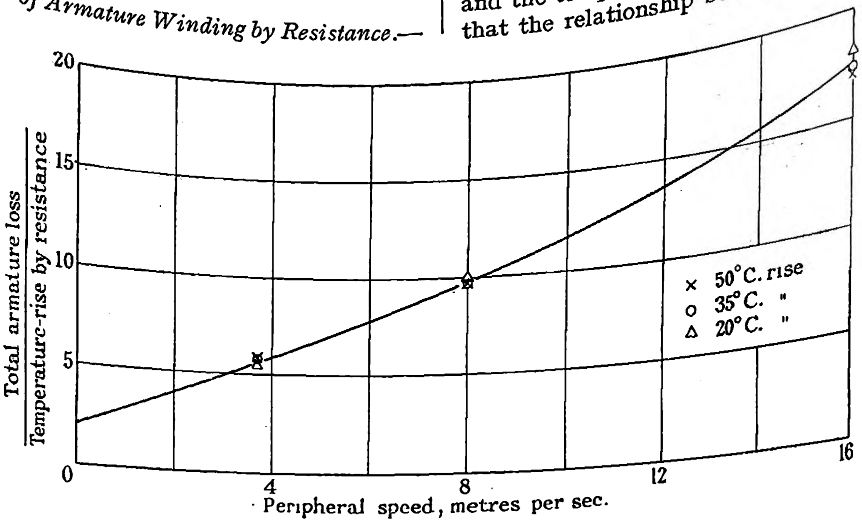

FIG. 9.

Temperature-Rise of Armature Winding by Resistance.—From Fig. 9 it will be seen that the armature loss per deg. C. is a linear function of the speed and is expressed by

$$W_t/\theta_r = 2(1 + 0\cdot485v)$$
$$\doteqdot 2(1 + 0\cdot5v)$$

where W_t and θ_r represent the total armature loss and the temperature-rise by resistance, respectively. The above approximation gives a round figure for the coefficient of v and is within the limits of experimental error. The external cylindrical area of the winding was 15·33 dm²; hence

$$\text{Watts/dm}^2\text{/deg. C.} = 0\cdot13(1 + 0\cdot5v) \quad . \quad (6)$$

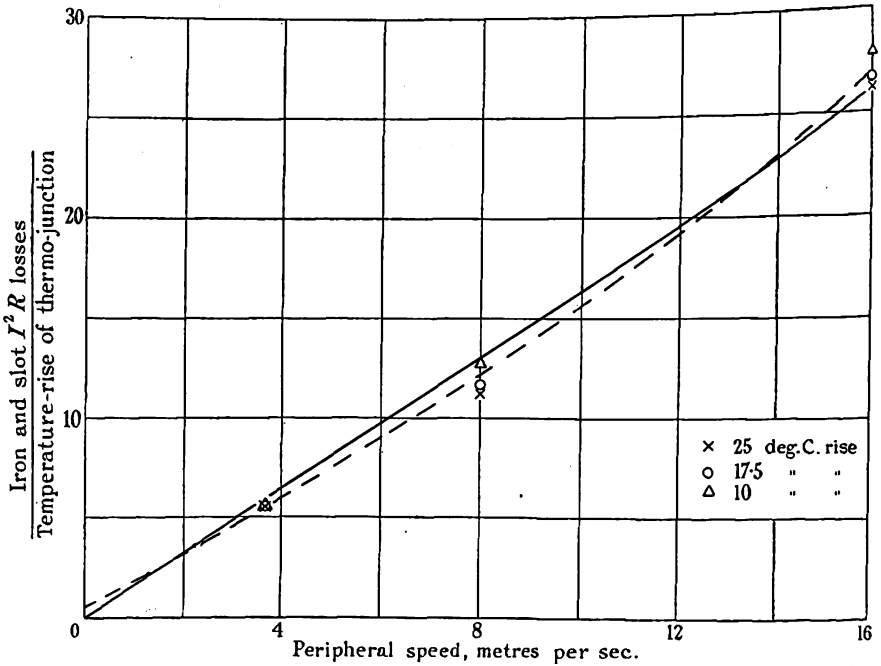

FIG. 10.

Temperature-Rise of Armature Core by Thermometer.—If the iron and slot I^2R losses be represented by W_c and the temperature-rise of the core by θ_t, it was found that the relationship between W_c/θ_t and the peripheral speed was very similar to that derived from the thermo-junction and represented in Fig. 10. The nearest mathematical representation of the curve through the mean of the points appeared to be given by

$$W_c/\theta_t = 1\cdot4 + 0\cdot65v + 0\cdot03v^2$$

but a close and simple relationship was given by

$$W_c/\theta_t = 1\cdot17v$$

Since the temperature-rise by thermometer is proportional to the iron and slot I^2R losses, the most reasonable surface to be taken into account is the external cylindrical area of the armature core, namely, 5·6 dm² for the present machine. Hence,

$$\text{Watts/dm}^2\text{/deg. C.} = 0\cdot 18v \quad . \quad . \quad . \quad (7)$$

Temperature-Rise by Thermo-junction Outside Armature Core.—The relationship between W_c/θ_j and the peripheral speed in Fig. 10 is expressed very closely by

$$W_c/\theta_j = 0\cdot 5 + 1\cdot 25v + 0\cdot 0246v^2$$

and fairly closely by

$$W_c/\theta_j = 1\cdot 64v$$

From the latter we have

$$\text{Watts/dm}^2\text{/deg. C.} = 0\cdot 252v \quad . \quad . \quad . \quad (8)$$

Comparison of the Above Results with those of Other Investigators.—It is of interest to compare expressions (6) and (7) with the two that are most commonly employed for estimating temperature-rise, namely

$$\text{Watts/dm}^2\text{/deg. C.} = A(1 + 0\cdot 1v)\ [*] \quad . \quad (9)$$

$$\text{Watts/dm}^2\text{/deg. C.} = B(1 + 0\cdot 097v^{1\cdot 3})\ [†] \quad (10)$$

where A and B are constants.

TABLE 3.

Peripheral speed	Relative values of temperature-rise/watt/dm².			
	From (6):— $\frac{8\cdot 5}{1 + 0\cdot 5v}$	From (7):— $\frac{15}{v}$	From (9):— $\frac{2\cdot 5}{1 + 0\cdot 1v}$	From (10):— $\frac{4\cdot 27}{1 + 0\cdot 097v^{1\cdot 3}}$
m/sec.				
0	8·5	—	2·5	4·27
5	2·43	3·0	1·67	2·39
10	1·42	1·5	1·25	1·45
15	1·0	1·0	1·0	1·0
20	0·773	0·75	0·833	0·743
25	0·63	0·6	0·71	0·583
30	0·532	0·5	0·625	0·473

Since our purpose just now is to examine the way in which the velocity enters into the various expressions for temperature-rise and to compare the results obtainable from them, the coefficients of expressions (6), (7), (9) and (10) will be so chosen as to give the same value, say 1·0, for the temperature-rise per watt per dm² at 15 metres per sec. On this basis Table 3 has been calculated.

From Table 3 it will be seen that at low peripheral speeds expression (9) considerably underestimates the temperature-rise, whilst at high speeds it tends to overestimate the rise; but if this formula be used only over a limited speed range it may be sufficiently satisfactory for most practical purposes. It is also evident from Table 3 that expressions (6) and (10) are in sufficiently close agreement between 5 and 30 metres per sec. as to be equally satisfactory. At very low speeds, however, even expression (10) may be in considerable error. A comparison of the values for (6) and (7) shows that, though they were derived from resistance and thermometer measurements respectively, they are in reasonably good agreement except at speeds below about 5 metres per sec.

Formulæ of the type represented by (9) and (10)—especially the former—have been so widely used by designers that the author would hesitate to suggest the modified forms (6) and (7) without other evidence. It is therefore of interest to note that both Luke [*] and Hinlein [†] found the temperature-rise per watt per dm² to fall very rapidly with increase of peripheral speed between 0 and 5 metres per sec. The values given in column (*a*) of Table 4 were obtained on a rotor, 25 in. diameter and 36 in. long, made of 0·875 in. bare monel-metal strip wound on the outside of a micarta drum, the strip acting as the heater. The drum was rotated in air with no housing surrounding it. The values in column (*b*) were obtained on an experimental model of end-windings, 25 in. diameter and 22 in. long. This was also rotated in air without any housing. The data by Hinlein were derived from a revolving cylinder coated with dynamo varnish. To facilitate the comparison of these results with one another and with the values given in Table 3, columns 5, 6 and 7 in Table 4 have been calculated on the basis of unity at 15 metres per sec.

TABLE 4.

Peripheral speed	Temperature-rise per watt per dm²			Relative values of temperature-rise per watt per dm²		
	Luke (*a*)	Luke (*b*)	Hinlein	Luke (*a*)	Luke (*b*)	Hinlein
m/sec.						
0	8·6	12·9	16·7	4·94	7·1	3·84
5	3·58	3·49	6·67	2·06	1·92	1·53
10	2·31	2·26	5·0	1·33	1·24	1·15
15	1·74	1·82	4·35	1·0	1·0	1·0
20	1·45	1·61	3·85	0·833	0·885	0·885
25	1·24	1·45	3·58	0·713	0·797	0·822
30	1·12	1·34	3·22	0·644	0·736	0·74

In view of the figures given in Table 4 and of the results embodied in expressions (6) and (7), the author has no hesitation in suggesting that the formula

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[*] After KAPP.

[†] C. C. HAWKINS: "The Dynamo," 6th ed., vol. 2, p. 210.

[*] *Loc. cit.*

[†] H. D. SYMONS and M. WALKER: "Heat Paths in Electrical Machinery," *Journal I.E.E.*, 1912, vol. 48, p. 689.

$A(1 + 0 \cdot 1v)$, so commonly employed for calculating temperature-rise, does not attach adequate importance to the velocity term. Formula (10) is more satisfactory than (9) but is much clumsier than either (6) or (7) above.

There is one other point of interest in Luke's results, namely the variation in the exponent of v. It has already been mentioned on page 914 that the watts/dm²/deg. C. for his rotating drum were represented by $(A_1 + B_1v^{0 \cdot 93})$ up to 20 metres per sec., and by $(A_1 + B_2v^{0 \cdot 6})$ above 25 metres per sec. For his rotating winding the expressions were of the form $(A_2 + B_3v^{0 \cdot 75})$ up to about 15 metres per sec. and $(A_2 + B_4v^{0 \cdot 54})$ between 15 and 50 metres per sec. On the machine tested by the author there was no indication of the exponent decreasing below unity; in fact, a curve drawn through the mean of the experimental points in Fig. 10 and the corresponding curve for the temperature-rise by thermometer have gradually increasing slopes corresponding to an exponent of about 1·1. The difference in behaviour between Luke's models and the actual machine may be due to air turbulence caused by the pole-tips of the machine; whereas with the models the air tends to be carried round with the rotor, there being nothing except centrifugal force tending to displace it. In other words, the results go to show that relationships derived from incomplete models must not be applied indiscriminately to actual machines.

Comparison of Temperature-Rises Measured by Resistance, Thermometer and Thermo-junction.—It has already been pointed out that both the thermometer and the thermo-junction gave readings that were proportional to the iron and slot I^2R losses, whilst the resistance measurements gave a temperature-rise that was proportional to the total armature loss. It has also been shown that, for the particular machine tested:—

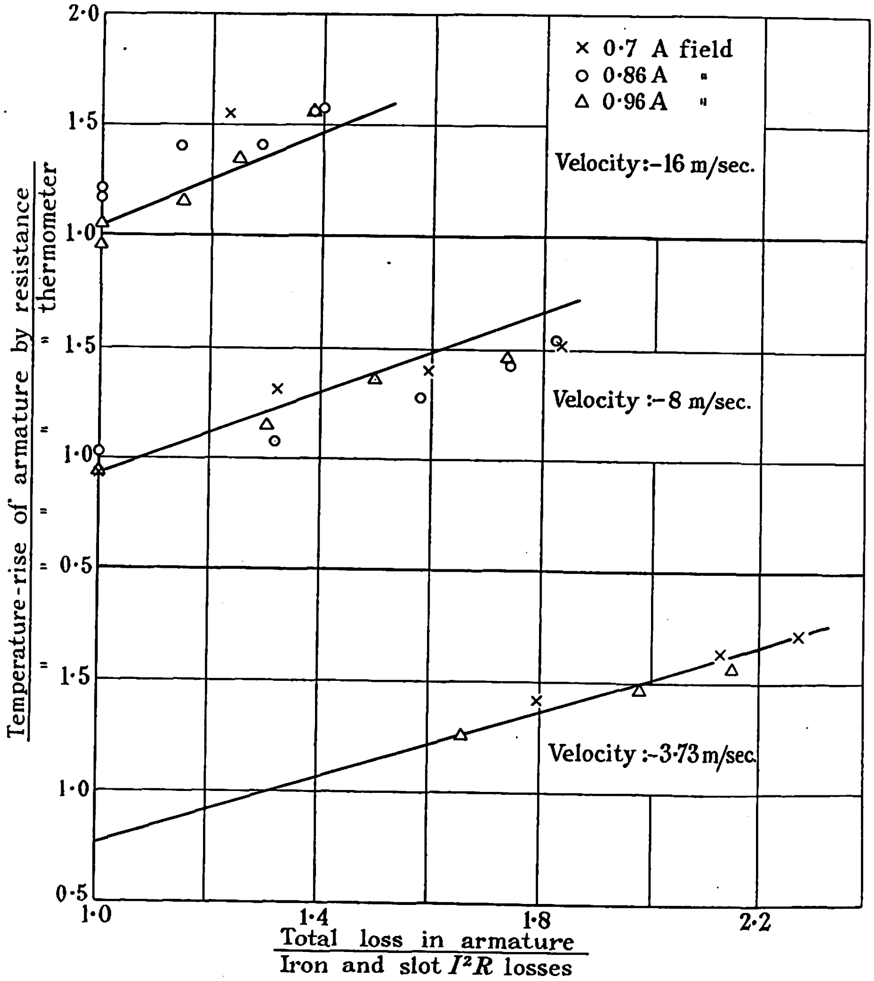

FIG. 11.

$$\frac{\text{Total armature losses}}{\text{Temp.-rise of winding by resistance}} = 2(1 + 0 \cdot 5v)$$

$$\frac{\text{Iron and slot } I^2R \text{ losses}}{\text{Temp.-rise of core by thermometer}} = 1 \cdot 17v$$

and

$$\frac{\text{Iron and slot } I^2R \text{ losses}}{\text{Temp.-rise by thermo-junction}} = 1 \cdot 64v$$

Hence

$$\frac{\text{Temp.-rise by resistance}}{\text{Temp.-rise by thermometer}} = \frac{\text{total armature losses}}{\text{iron and slot } I^2R \text{ losses}} \times \frac{0 \cdot 585}{(1/v) + 0 \cdot 5}$$

$$\frac{\text{Temp.-rise by resistance}}{\text{Temp.-rise by junction}} = \frac{\text{total armature losses}}{\text{iron and slot } I^2R \text{ losses}} \times \frac{0 \cdot 82}{(1/v) + 0 \cdot 5}$$

and

$$\frac{\text{Temp.-rise by thermometer}}{\text{Temp.-rise by junction}} = 1 \cdot 4$$

In Figs. 11, 12 and 13, the ratios of the temperature-rises obtained experimentally have been plotted against the ratio of the total armature losses to the iron and slot I^2R losses; and the straight lines in these diagrams represent the values calculated from the above expressions. The agreement between the calculated and the experimental values in Fig. 11 is sufficiently good to show that the ratio of the temperature-rise by resistance to that by thermometer is mainly dependent upon the ratio of the total losses to the iron and slot I^2R losses.

An attempt was made to apply Karapetoff's two-chunk theory * to the above results, but without any satisfaction.

Suggested Application of the Thermo-junction Method.—It will be seen from Fig. 13 that the temperature-rise indicated by the thermo-junction bears practically a constant ratio to that of the armature core as measured by thermometer, and that this ratio is almost independent of the distribution of losses, of speed and of excitation. It is therefore suggested that such a thermo-junction can with advantage be used for following the rise of temperature of the armature core during a heat test and for determining when the temperature attains a

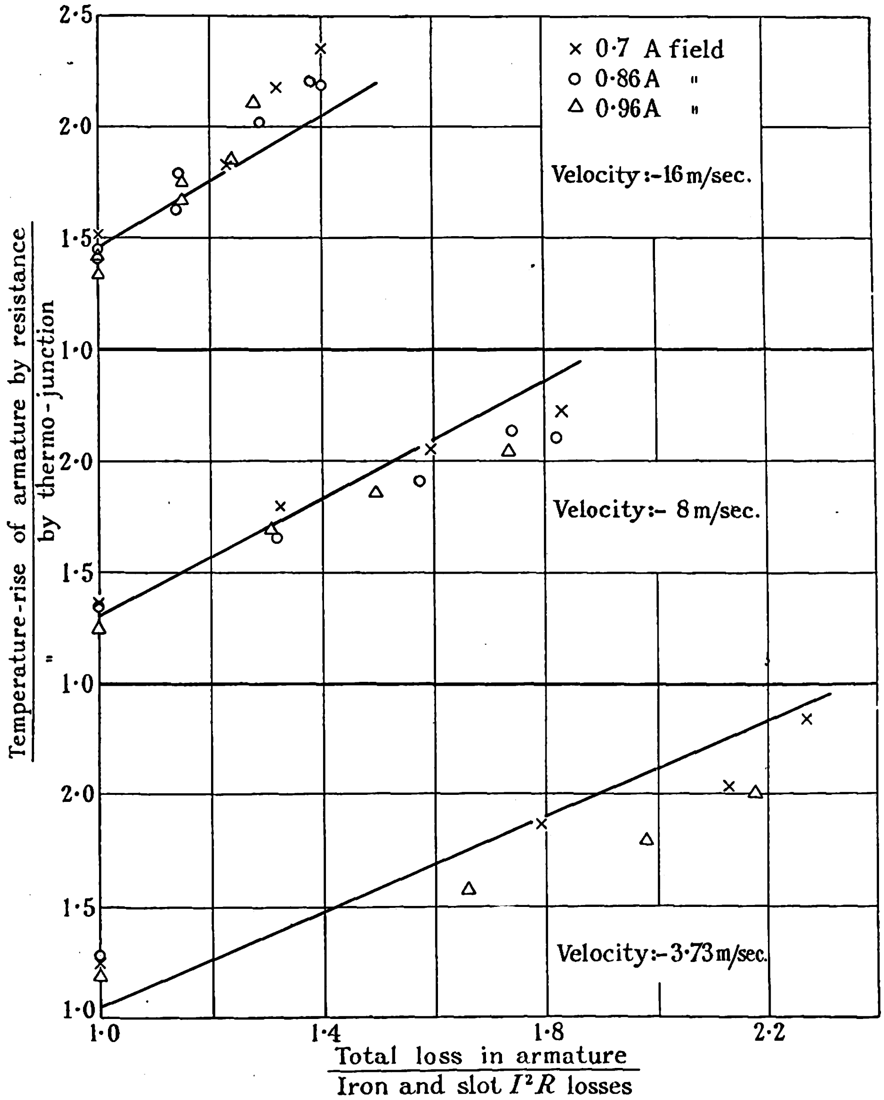

FIG. 12.

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* "Parameters of Heating Curves of Electrical Machinery," *Transactions of the American I.E.E.*, 1926, vol. 45, p. 349.

steady value. It will be granted that the heating time-constant of the armature is usually shorter than that of the field and that if the heating test be continued with a *constant* load until the field temperature is steady the temperature of the armature will also have attained its maximum value. By means of a thermo-junction, however, it is possible to shorten * the heat test considerably by overloading the armature and field until their temperatures have attained approximately their anticipated values. The load and exciting currents are then re-adjusted to the correct values and the changes in the temperatures of the field and thermo-junction noted.

The curves in Fig. 14 are typical of the results obtained under these conditions. In this particular test the armature and field currents were kept at 10·5 and 0·96 amperes respectively for 76 minutes and then reduced to 9·22 and 0·86 amperes. The curves obtained with this method of loading all exhibited the peculiarity that, after readjustment of the currents, the temperatures first of all fell and then increased again to their final values. This phenomenon appears to be due to the time-lag in the temperature-rises of the armature and pole-cores, and was much more marked for the armature winding than for the thermo-junction.

In view of this possible application it is desirable to investigate how the temperature of the junction varies with its radial distance from the armature core. The curves in Fig. 15 show the results obtained on two machines. The latter were run on load until the temperature became steady, and readings were taken with the junction at different radial distances from the core, the load being maintained constant. Curve A applies to the machine on which all the preceding tests were performed, and curve C was obtained on a 7·5-b.h.p. shunt motor. Further particulars of these tests are given in Table 5.

It will be seen that the temperature of the thermo-junction falls very rapidly near the surface and then becomes fairly constant. The greater radial distance over which the temperature fell in machine C was probably due to the longer air-gap allowing a greater thickness of air to be carried round with the armature; and the slight rise in curve C between 1 and 5 cm may be due to the comparatively small clearance between the field coils in this particular machine.

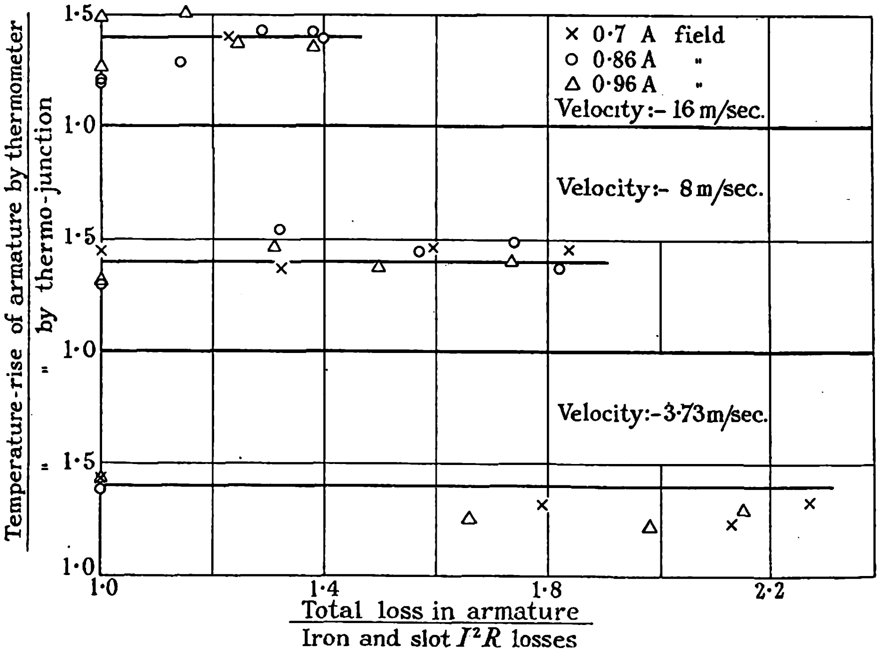

FIG. 13.

These tests appear to indicate (*a*) that so long as the thermo-junction is at a distance greater than the gap length from the core, its temperature is fairly constant for a relatively large variation of that distance; and

TABLE 5.

Machine	Curve A	Curve C
Temp.-rise of armature core by thermometer ..	28 deg. C.	20·8 deg. C.
Temp.-rise of armature winding by resistance ..	40·3 deg. C.	—
Temp.-rise of field winding by resistance	35·2 deg. C.	34·6 deg. C.
Peripheral speed, metres per sec.	8	12·6
Radial length of air-gap, mm.	1·8	2·6

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* It has often been suggested that the final temperature-rise can be computed from short heat-runs by assuming the heating curve to be exponential. This problem is fully discussed by the author in another paper (see page 932), where it is shown that the steady temperature-rise of windings calculated from the initial portion of the heating curves plotted from carefully observed readings is less than the actual value.

(*b*) that the temperature-rise of the core as measured by thermometer is about 1·4 to 1·5 times that indicated by the thermo-junction under these conditions.

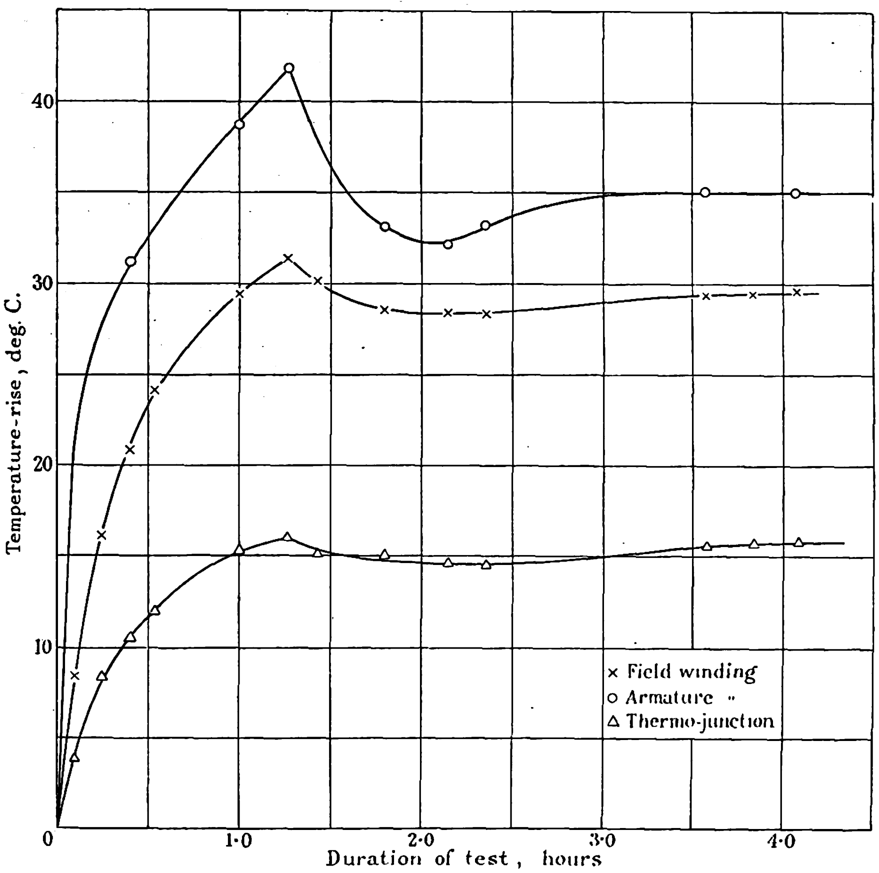

FIG. 14.

(2) TESTS ON MACHINE WITH REVOLVING FIELD.

Temperature-Rise of Field Winding.—The variation of the field temperature-rise per watt with speed, excitation and total stator losses was somewhat similar to that already found for the stationary field winding of machine A and represented in Figs. 1 and 2. From the graphs, the watts per deg. C. rise for *no* stator loss have been derived for different speeds and are represented by curves C and D in Fig. 16. These curves are represented very closely by

$$W_f/\theta_f = 2\cdot4 + 0\cdot71\sqrt{v} \text{ for C}$$

and

$$W_f/\theta_f = 2\cdot7 + 0\cdot71\sqrt{v} \text{ for D}$$

In view of the results obtained with machine A when the values of θ_f/W_f were plotted against the difference of field and armature temperatures, the same procedure was tried with machine B, the values being shown in Fig. 17. It will again be seen that the temperature-rise per watt of the field winding is a function of the difference between the temperature-rises of the field and stator windings and is practically independent of the exciting current. From Fig. 17 the values of W_f/θ_f at different speeds for equal temperature-rises of the field and stator windings have been determined and plotted in Fig. 16. These points lie very closely to a curve representing the formula

$$\begin{aligned} W_f/\theta_f &= 2 + 0\cdot57\sqrt{v} \\ &= 2(1 + 0\cdot285\sqrt{v}) \quad . \quad . \quad . \quad . \quad (11) \end{aligned}$$

It did not appear possible to develop a general expression in any way comparable with (5) for machine A. The main conclusions, however, are that the value of the temperature-rise per watt is considerably influenced by the stator temperature and a function of the square root of the speed.

It is interesting to compare the thermal behaviour of a rotating field with that of the rotating armature previously investigated. Thus, we find that:—

(*a*) The temperature of the rotating field is influenced by that of the stator, whereas the temperature of the rotating armature is independent of that of the field winding. This difference seems to be due to the insulating cheeks of the field winding, together with the pole-tips in the latter case preventing any radiation towards the armature; whilst, in the former case, heat is radiated inwards partly from the end windings towards the field winding and partly from the internal surface of the stator core.

(*b*) The effect of speed upon the temperature-rise of the rotating field is not nearly as great as in the case of the rotating armature, as will be evident from a comparison of (11) and (6). This difference would appear to be due to the relatively smaller loss by convection from the rotating field than from the rotating armature.

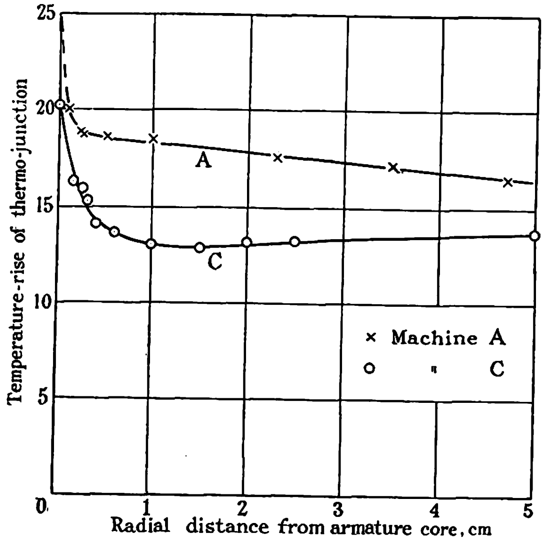

FIG. 15.

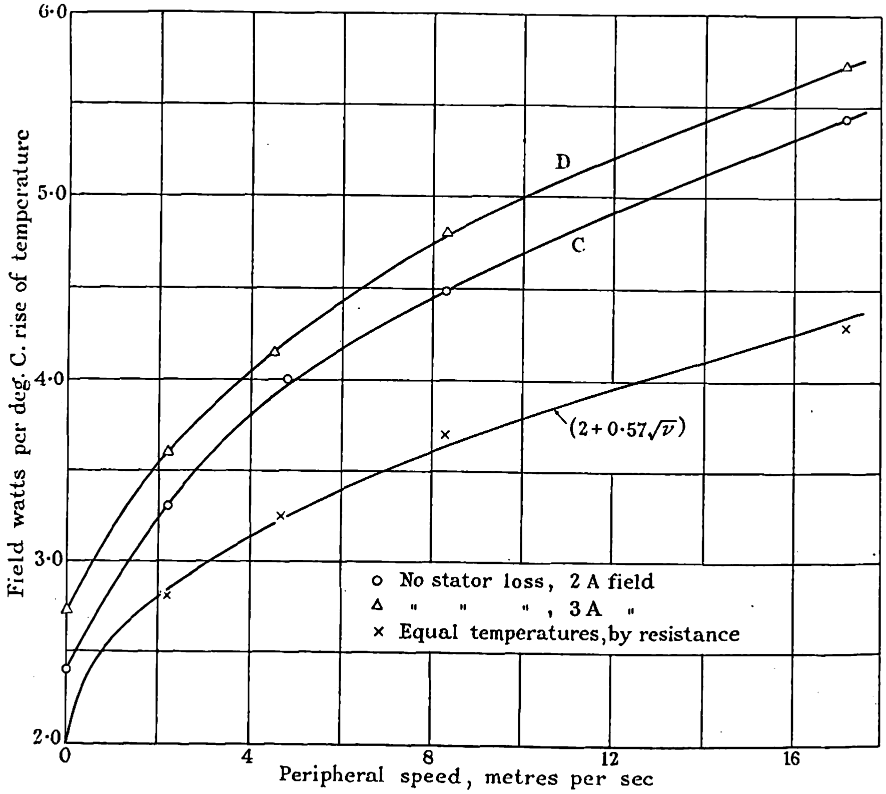

FIG. 16.

(*c*) A comparison of (3) and (11) shows that the variation of the temperature-rise per watt with speed for the rotating field is surprisingly similar to that for the stationary field.

Temperature-Rise of Stator.—Temperatures were measured by (*a*) increase of resistance of the winding, (*b*) thermo-junction attached to the outer surface of the core, and (*c*) thermo-junction inserted in the radial duct, as described on page 912. Difficulty was at first experienced in deciding whether the temperature-rise of the winding, for instance, was a function of the total stator loss or of the I^2R loss only, as both relationships gave good linear graphs. This difficulty was overcome by plotting the corresponding values for excitations of 2 and 3 amperes on the same axes. If the curves thus obtained were reasonably parallel, as in Figs. 18 and 19, the particular temperature concerned could be taken as a linear function of the quantity plotted as abscissa. On the other hand, if the curves intersected so that some of the temperature-rises for 2-ampere excitation were greater than those for 3 amperes, such relationships could not be accepted even if the points did give straight-line graphs. In this way it was found:—

(*a*) That the temperature-rise of the stator winding, measured by resistance, was a linear function of the stator I^2R loss (Fig. 18). This conclusion is conceivable from the fact that 63 per cent of the winding was accounted for by end-connections. Furthermore, most of the heat due to the iron loss probably flows outwards to be dissipated by the external surface of the core.

(*b*) That the temperature-rises of the core and duct were linear functions of the total stator losses (Fig. 19). It had been anticipated that these temperatures would have been more closely related to the iron and slot I^2R losses; but this was not supported by experimental evidence. On the other hand, the ventilating air on its way outwards would tend to convey some heat from the end connections to the core.

The next problem was to investigate the effect of speed upon the stator temperature. It will be seen from Fig. 18 that the temperature-rise of the winding at a given speed can be regarded as being due to (*a*) the interception the vertical axis—a quantity that appears to be mainly a function of the excitation—and (*b*) to a component that is proportional to the stator copper loss;

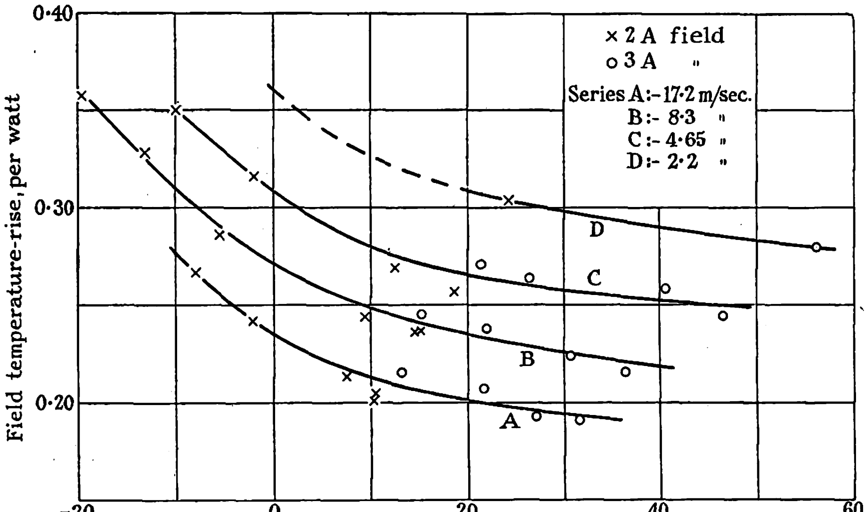

FIG. 17.

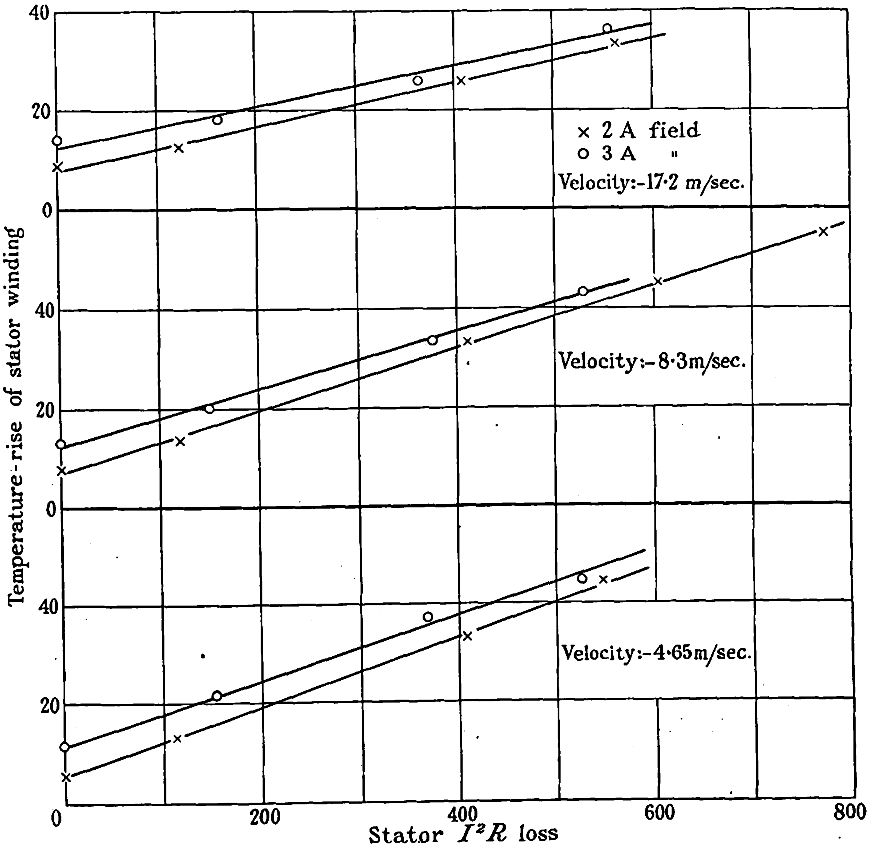

FIG. 18.

i.e. the temperature-rise by resistance can be represented approximately by

$$\theta_r = a_r\theta_f + b_r W_c$$

where W_c = total copper loss,
b_r = a coefficient that is a function of the speed,
and $a_r\theta_f$ = temperature-rise due to the excitation.

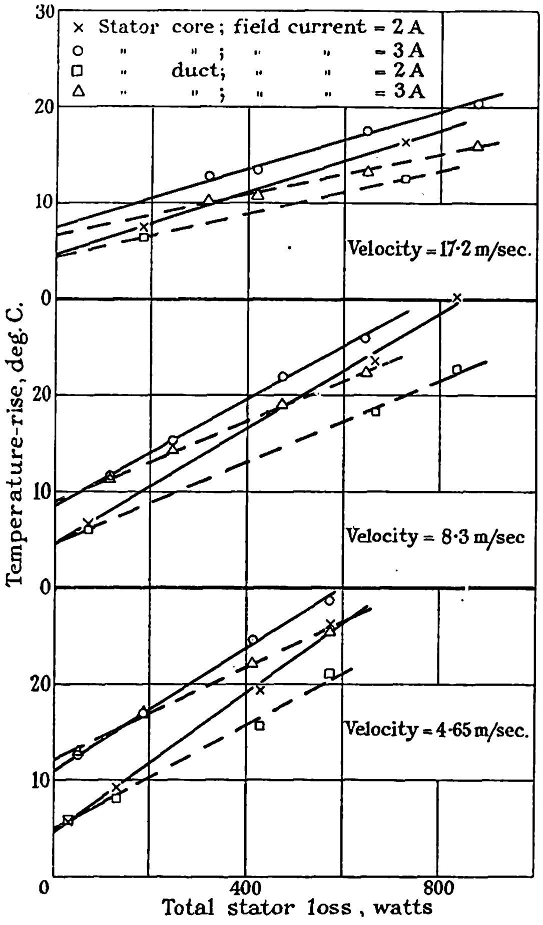

FIG. 19.

Similarly, for the core and the duct junctions, we have

$$\theta_c = a_c\theta_f + b_c W_t$$

and

$$\theta_d = a_d\theta_f + b_d W_t$$

where W_t = total stator loss.

The relationships between the speed and the various coefficients b were determined by plotting $1/b$, i.e. the inverse of the slopes of the different graphs in Figs. 18 and 19 against speed as in Fig. 20. From the latter, it is obvious that the relationship is of the form

$$1/b = c + dv^x$$

The value of c is slightly affected by the excitation, but the values of d and x are practically the same for exciting currents of 2 and 3 amperes. From logarithmic curves, x was found to be 1·79 for curves A, 2·08 for B and 2·10 for C; in other words, the exponent of v for the three curves is approximately 2. By taking the mean of each of the pairs of curves in Fig. 20, it was found that the following expressions represented fairly closely the relationships between the temperature-rises, the power and the speed:—

$$\theta_r = a_r\theta_f + \frac{W_c}{13\cdot5(1 + 0\cdot0027v^2)} \quad . \quad . \quad (12)$$

$$\theta_c = a_c\theta_f + \frac{W_t}{27(1 + 0\cdot0043v^2)}$$

and

$$\theta_d = a_d\theta_f + \frac{W_t}{37(1 + 0\cdot0045v^2)}$$

It is of particular interest to find that these expressions involve the second power of the velocity, whereas for the stationary field-winding of machine A the velocity appeared as a square-root term. Further, most investigators have found that with forced ventilation the exponent of the velocity lies between 0·5 and 1·0; thus J. A. Hughes [*] gives the loss of heat from different cylindrical tubes at 100° C. as proportional to v^n, where n varies from 0·55 for a 0·17-in. diameter tube to 0·98 for a tube 2 inches in diameter. The heat dissipation due to an air-flow between two parallel flat plates with various spacings was found by Luke [†] to be proportional to $v^{0\cdot8}$. With various other arrangements of surfaces he found the heat transfer to be proportional to v^n, where n ranged from 0·7 to 0·93. In Luke's experiments, however, the air-flow was parallel to the dissipating surface. Also, the theoretical investigations of Rice [‡] and Davis [§] suggest that the exponent of the velocity may vary between about 0·5 and 1.

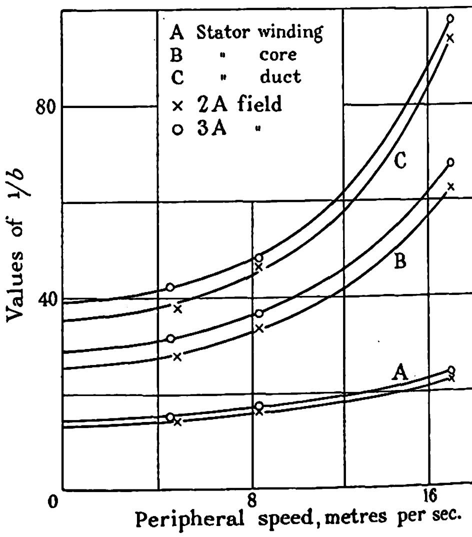

FIG. 20.

In contrast with the above are the results obtained by Symons and Walker [‖] for the temperature-rise of a coil and of a brass cylinder for different air velocities up to 3·5 metres per sec., the air being blown on to the coil from two diametrically opposite sides. For the brass cylinder and the coil of cotton-covered wire the temperature-rises per watt per dm² were $9\cdot 1/(1+0\cdot 78v^2)$ and $9\cdot 1/(1+0\cdot 54v^2)$ respectively. The radial depth of the cylinder and coil was small compared with the diameter. Also, the diameters employed were far greater than those of the wires and tubes used by the other investigators. In view of the results obtained with induced draught in Section 4 of this paper, this matter is discussed more fully at the end of that section.

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[*] *Philosophical Magazine*, 1916, vol. 31, p. 118; see also G. E. LUKE: *loc. cit.* p. 640.

[†] "Surface Heat Transfer in Electric Machines," *Transactions of the American I.E.E.*, 1926, vol. 45, p. 1036.

[‡] "Free and Forced Convection of Heat in Gases and Liquids," *Transactions of the American I.E.E.*, 1923, vol. 42, p. 652.

[§] "The Heat Loss by Convection from Wires in a Stream of Air, and its Relation to the Mechanical Resistance," *Philosophical Magazine*, 1921, vol. 41, p. 899.

[‖] "Heat Paths in Electrical Machinery," *Journal I.E.E.*, 1912, vol. 48, p. 674.

(3) MACHINE B (ROTATING FIELD) AS A TOTALLY-ENCLOSED TYPE.

The machine was made totally-enclosed by fitting sheet-iron covers over all the openings. The test procedure was precisely the same as before.

Temperature-Rise of Field Winding.—The field temperature-rise per watt was found to be dependent upon the speed, the excitation and the total stator losses in a somewhat similar manner to that found for the same machine arranged as a protected type. From graphs based upon test results, the values of W_f/θ_f for zero stator loss have been derived and plotted in Fig. 21. These curves are represented fairly closely by

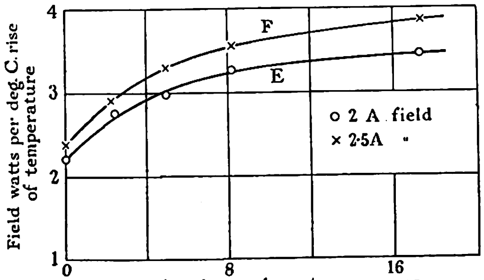

FIG. 21.

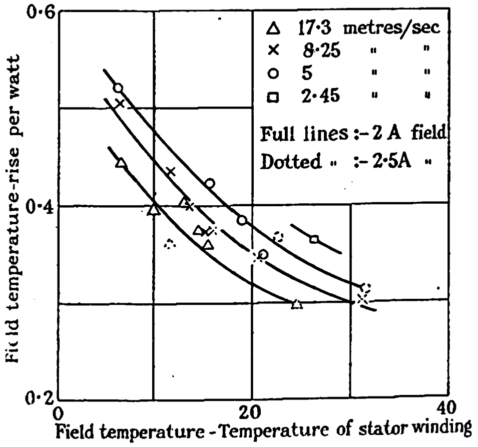

FIG. 22.

$$W_f/\theta_f = 2\cdot 2 + 0\cdot 33\sqrt{v} \text{ for E}$$

and
$$W_f/\theta_f = 2\cdot 4 + 0\cdot 38\sqrt{v} \text{ for F}$$

A comparison of these expressions with those obtained for the machine as a protected type (page 923) shows that the first term is almost identical, probably due to its representing the heat dissipated by radiation. The second term, however, is practically halved, thus showing that the effect of speed on the cooling of the rotating field is far smaller in a totally-enclosed than in a protected-type machine.

Fig. 22 shows the variation of θ_f/W_f with the difference between the temperature-rises of the field and stator windings. It will be seen that the results did not cover a sufficiently wide range to enable the values of θ_f/W_f to be deduced for equal temperature-rises, but they do show that the temperature-rise per watt of the field winding is dependent upon the difference of rotor and stator temperatures and upon the peripheral speed of the rotor but is practically independent of the exciting current. The influence of the relative temperatures of the rotor and stator is, in fact, much greater than for the machine as a protected type (Fig. 17).

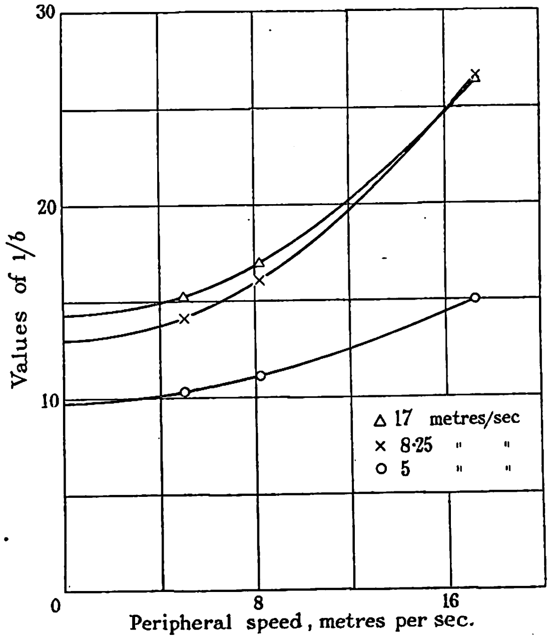

FIG. 23.

Temperature-Rise of the Stator.—The same procedure as that employed in Section (2) was again used for the analysis of these results. Thus, it was found that the temperature-rises of the winding, of the core and of the duct were all functions of the *total* stator loss. From the graphs it was found that the temperature-rise could again be represented by an expression of the form

$$\theta = a\theta_f + bW_t$$

where $a\theta_f$ = temperature-rise due to influence of excitation,

W_t = total stator loss,

and b = a coefficient that is a function of the speed.

The inverse of the slopes of the various graphs, namely $1/b$, has been plotted against the peripheral speed in Fig. 23, from which the relationship again appears to be

$$1/b = c + dv^x$$

The value of x is very nearly 2 in each case; and the temperature-rises are given very closely by

$$\theta_r = a_r\theta_f + \frac{W_t}{9\cdot8(1 + 0\cdot0019v^2)}$$

$$\theta_c = a_c\theta_f + \frac{W_t}{13\cdot1(1 + 0\cdot0034v^2)}$$

and $$\theta_d = a_d\theta_f + \frac{W_t}{14\cdot3(1 + 0\cdot0028v^2)}$$

where θ_r, θ_c and θ_d are the temperature-rises of the stator winding, core and duct respectively.

The question of the velocity entering as a square function has already been referred to in Section (2) and is again discussed on page 929. A comparison of the above expressions with those given for the protected type on page 926 shows that in the totally-enclosed machine the speed is relatively not so important, though the reduction for the stator is less than that already noted for the field winding.

(4) MACHINES A AND B, PIPE-VENTILATED WITH INDUCED DRAUGHT.

Induced ventilation was arranged in each case by fitting a short pipe, 7·5 cm internal diameter, to the sheet-iron cover of one of the bottom openings in the bearing bracket on the slip-ring side, and attaching a metal funnel to the sheet-iron cover on one of the upper openings in the bearing bracket on the coupling side, the outlet being diametrically opposite to the inlet. The air was drawn through the machine by a fan at the outer end of the funnel. The velocity of the air was measured at the inlet by means of a Negretti and Zambra anemometer.

The tests on machine B (revolving field) were performed with the idea of determining the influence of different air velocities with (*a*) different rotor speeds, and (*b*) different distributions of losses in stator and rotor. From the results with 2-ampere excitation, the following quantities have been plotted against air velocity in Fig. 24:—

(*a*) θ_f/W_f, where θ_f and W_f are respectively the temperature-rise and the field loss,

(*b*) θ_r/W_t, where θ_r is the temperature-rise by resistance of the stator winding and W_t is the total stator loss,

(*c*) θ_c/W_t, where θ_c is the temperature-rise of the core, and

(*d*) θ_d/W_t, where θ_d is the temperature-rise of the duct.

An inspection of the curves in Fig. 24 shows shat:—

(1) The shapes of the curves for θ_f, θ_r, θ_c and θ_d are very similar for a given rotor speed; and that all the curves, except those for 17·3 metres per sec., possess a double inflexion, and even these curves seem to indicate that if the draught speed had been increased far enough they also would have had a double inflexion.

(2) The lower the rotor speed, the lower is the air velocity at which the slope of the curves is a maximum.

(3) The effect of the speed of the induced draught upon the temperature-rise bears some resemblance to that of the rotor speed upon the temperature-rise of the stator when the machine is arranged as a protected type and also when it is totally enclosed.

It was at first thought that the difference in the shape of the curves in Fig. 24 might have been due to a variation in the distribution of the losses. This possibility was checked by taking a set of readings at a peripheral speed of 8·4 metres per sec. with a different exciting current, but keeping the total stator loss as nearly as possible the same as with the 2-ampere excitation. The results were similar in every respect to those obtained at the same peripheral speed with the latter excitation; hence the difference between the curves in Fig. 24 was not due to any redistribution of losses. This conclusion was also supported by similar results obtained on machine A.

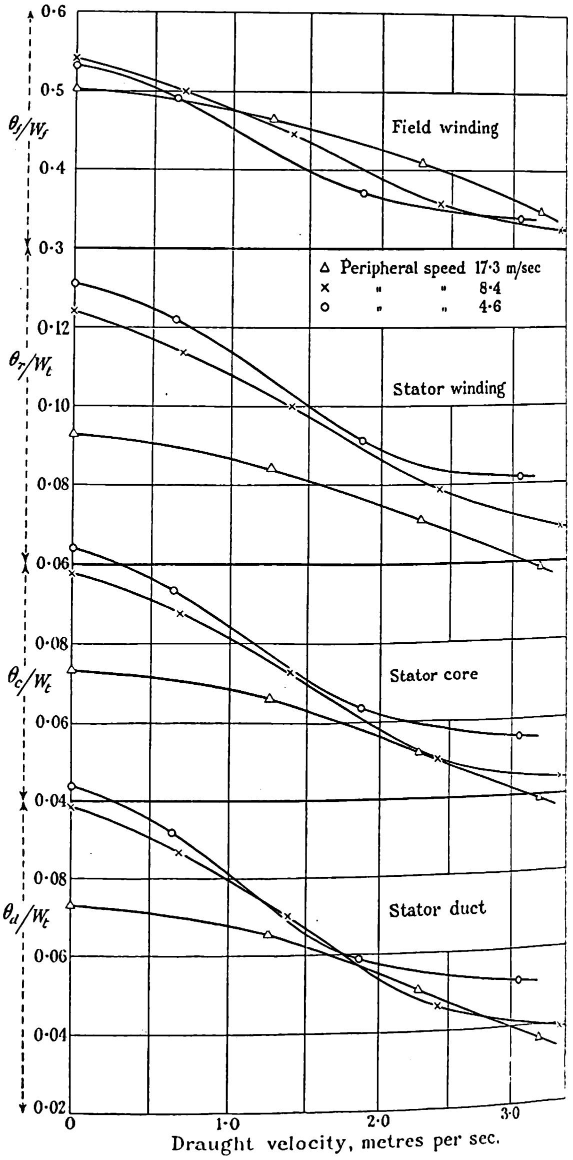

FIG. 24.

It was then thought that the difference was due to the influence of the induced draught upon the direction of the air currents inside the machine. Thus, it can be imagined that with a very low peripheral speed of the rotor the induced draught distributes itself more or less uniformly over the internal section of the machine; and since its direction is mainly axial as it passes the windings it is roughly in space quadrature with that of the air currents set up by the rotor. Consequently, the higher the peripheral speed the greater must be the draught velocity to produce a given change in the magnitude of the resultant air velocity, and thus the higher the draught velocity at which the inflexions noted in Fig. 24 may be expected to occur. Suppose v_r to be the radial air velocity at a certain point due to the speed of the rotor only. Then, if v_a be the axial speed of the air draught at that point due to the external fan, the resultant air velocity is given by $v = \sqrt{(v_r^2 + v_a^2)}$. Let us assume for simplicity that the heat dissipation depends upon the first power of the velocity, as has already been found for the armature of machine A; that is

$$\theta/W = \frac{k}{1 + av}$$
$$= \frac{k}{1 + a\sqrt{(v_r^2 + v_a^2)}} \quad . \quad . \quad . \quad . \quad (13)$$

where k and a are constants for a given machine.

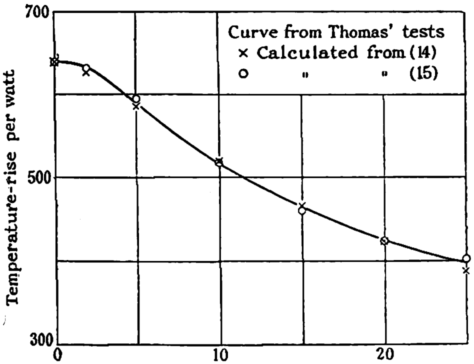

FIG. 25.

The curves in Fig. 24 and similar curves for machine A were investigated from the standpoint of this expression, and it was found that with a fixed value of v_r for a given peripheral speed of a machine the values calculated from (13) agreed very well with the experimental values.

This explanation also provides the reason for the features already noted for the curves of Fig. 24. Thus, the higher the peripheral speed of the rotor the greater is the value of v_r in expression (13), and consequently the greater must be the velocity of the induced draught to cause a given percentage change in the actual air velocity and thereby in the heating of the machine.

A further confirmation of the above explanation is to be found in the experimental work of J. S. G. Thomas.[*] From Fig. 2 of his paper, the temperature-rise per watt of the first of 11 filaments fixed in the same plane inside a tube has been calculated for different air velocities and is represented by the curve in Fig. 25, the only assumption being that the temperature of the incoming air was 15° C. As the temperature of the filament ranged from 560° to 220° C., an error of a few degrees in the air temperature makes very little difference to the calculated values. That this curve is closely represented by expression (13) is obvious from the crosses in Fig. 25, which represent points calculated from

$$\frac{\theta}{W} = \frac{680}{1 + 0 \cdot 03\sqrt{(2^2 + v^2)}} \quad . \quad . \quad . \quad (14)$$

where v = axial speed of air current in cm per sec.

In view of the square-law relationship already derived for the effect of peripheral speed on the cooling of the stator for both the protected and the totally-enclosed types, it is of interest to find that the curve in Fig. 25 is also represented very closely by

$$\frac{\theta}{W} = 350 + \frac{290}{1 + 0 \cdot 0073v^2} \quad . \quad . \quad . \quad (15)$$

Points calculated from this formula are indicated by circles.

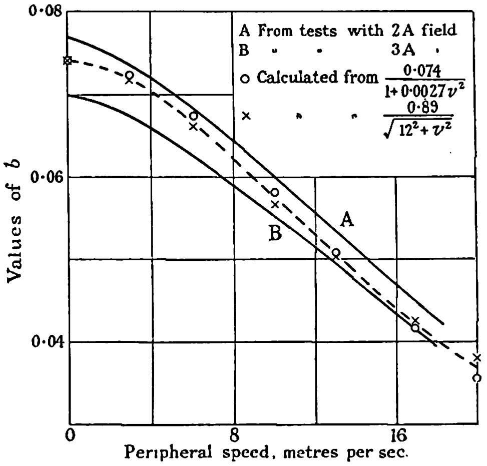

FIG. 26.

The agreement between the results calculated from (14) and (15) suggests that the relationships obtained on pages 926 and 928 should be replaced by expressions of the form represented by (14). In other words, it is suggested that the variation in the slopes of the graphs in Figs. 18 and 19 might be due to the combined effect of the natural draught produced by the hot windings and core and the forced draught caused by the rotation of the field winding. For instance, in Fig. 26 are given curves showing the variation of b (i.e. the slope of the graphs in Fig. 18) for the stator winding of the protected-type machine; and the values calculated from the second part of expression (12) have been indicated by circles. Further, the mean of the curves is represented fairly closely by

$$b = \frac{0 \cdot 89}{\sqrt{(12^2 + v^2)}} \quad . \quad . \quad . \quad . \quad (16)$$

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[*] "Thermal Effect of a Slow Current of Air Flowing Past Heated Platinum Wires," *Philosophical Magazine*, 1921, vol. 41, p. 240. Somewhat similar experimental results have recently been obtained by R. S. MAXWELL (*ibid.*, 1928, vol. 56, p. 945), by noting the cooling of a filament attached to the prong of a fork.

points calculated from (16) being indicated by crosses. Similar results were obtained with the core and the duct for both the protected and the totally-enclosed types.

It will be seen from (16) that this hypothesis requires the speed of the natural convection currents to be equivalent to those produced by a rotor peripheral speed of about 12 metres per sec. Such an assumption appears almost inconceivable, especially as the two components are only in space quadrature at diametrically opposite points on a horizontal plane through the centre of the machine. At the top of the machine the two components are in the same direction, whereas at the bottom they are in opposition. Also, the objection might be raised that the effect of these natural convection currents was not noticeable with the field winding of either of the machines tested, nor was it noticeable with the winding of the rotating armature. In the latter case, however, it should be pointed out that the results for the core and the thermo-junction (Fig. 10) can be taken as indicating the presence of appreciable natural convection. In the case of the field windings, the air tends to glide over the surface rather than impinge against it. With the stator winding and core, on the other hand, the air is impelled towards them, and this may account for the exponent of the air velocity being higher than for the field winding. This suggestion is supported by the results obtained by J. A. Hughes and quoted on page 926, namely that the exponent increases with increase in the size of the pipe. If Langmuir's film theory be accepted, it follows that the larger the diameter of the pipe the thinner relatively is the air film, and consequently the greater the tendency for the air to impinge normally on to the surface of the pipe.

It appears likely that a good deal of the discrepancies between the experimental results obtained by different investigators is due to the difference in the mode in which the air comes into contact with the dissipating surface and to the disposition of the latter. Thus, the cylinder and coil tested by Symons and Walker and referred to on page 927 appear to be about 8 in. long and 4 in. diameter and were tested with their axes vertical, the air being directed against diametrically opposite portions of their surfaces. Under these circumstances, natural convection would undoubtedly influence the lower portions of the curves in Figs. 11 and 12 of Symons and Walker's paper.

From the above discussion, however, it is obvious that for most practicable purposes it is not possible to take into account all the factors that are introduced even by one variable such as the air velocity; and that in such cases one is forced to use formulæ similar to (12) which may not be fundamentally sound but which are comparatively simple and at the same time give a reasonable degree of accuracy over the ranges for which they have been derived.

CONCLUSIONS.

(*I*) *Protected-Type Machine with Rotating Armature.*

(*a*) *Field Winding.*

(1) The temperature-rise per watt is dependent upon the difference between the temperature-rises of the field and armature windings, the variation of θ_f/W_f per deg. C. difference of temperature being about 1 per cent for temperatures measured by increase of resistance and about 1·4 per cent for those measured by thermometer.

(2) For equal temperature-rises of the field and armature, the temperature-rise per watt is represented by $2 \cdot 7(1 + 0 \cdot 25\sqrt{v})$.

(3) For field temperature-rises deduced on the assumption that the armature has no loss, the variation of W_f/θ_f with speed is very similar to that derived from models by G. E. Luke, but is different from that with the armature loaded.

(4) By means of expression (5), the effects of speed and of armature temperature can be allowed for in calculating the temperature-rise of the field.

(*b*) *Armature Winding.*

(1) The temperature-rise of the winding is practically proportional to the total armature loss and independent of the field temperature.

(2) The temperature-rises of the core and of the thermo-junction placed just outside the armature are practically proportional to the iron and slot I^2R losses and independent of the field temperature.

(3) The watts dissipated per dm^2 per degree rise of temperature is practically a linear function of the speed, being $0 \cdot 13(1 + 0 \cdot 5v)$ for the armature winding and $0 \cdot 18v$ for the armature core.

(4) The effect of velocity is much greater than is represented by the expression $(1 + 0 \cdot 1v)$ commonly used. The latter may considerably underestimate the temperature-rise at low speeds. Hawkins's formula is in fairly good agreement with that obtained for the armature winding but is much more awkward to manipulate. The importance of the velocity term is also confirmed by the experiments of Luke and Hinlein.

(5) The ratio of the temperature-rise by resistance to that by thermometer is a function of the ratio of the total armature loss to the iron and slot I^2R losses, and is also influenced by the peripheral speed.

(6) The ratio of the temperature-rise of the core to that of the thermo-junction remained practically constant at about 1·4. This ratio was only slightly affected by a variation in the distance between the armature and the junction, so long as this distance exceeded the length of the air-gap. It is suggested that by the use of such a thermo-junction the duration of the heating test can be shortened by an initial overloading of the armature and field windings. When the temperatures have attained their anticipated values the currents are adjusted to their normal values. It is shown in a separate paper * that it is impossible to calculate accurately the final temperature-rise from the initial portion of the heating curve.

(*II*) *Protected-Type Machine with Rotating Field.*

(*a*) *Field Winding.*

(1) For equal temperature-rises of the field and stator windings, the power in watts dissipated per degree rise of temperature is represented by $2(1 + 0 \cdot 285\sqrt{v})$.

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* E. HUGHES: "Determination of the Final Temperature-Rise of Electrical Machines from Heating Tests of Short Duration," *Journal I.E.E.*, 1930, vol. 68, p. 932.

This relationship is very similar to that for the stationary field-winding.

(2) The temperature-rise per watt is dependent upon the difference between the temperatures of the field and stator windings, but the variation is smaller than that for the stationary field-winding.

(*b*) *Stator.*

(1) The temperature-rise of the winding is a linear function of the stator I^2R loss.

(2) The temperature-rises of the core and duct are linear functions of the total stator losses.

(3) The temperature-rises of the winding, core and duct appear to be functions of the square of the speed [see IV (4) below].

(*III*) *Totally-Enclosed Machine with Rotating Field.*

(*a*) *Field Winding.*

(1) The temperature-rise per watt derived for no stator loss is very similar to that for the protected-type machine, except that the effect of the speed is much smaller.

(2) The temperature-rise is more affected by the stator temperature than in the case of the protected-type machine.

(*b*) *Stator.*

(1) The temperature-rises of the winding, core and duct are all linear functions of the total stator loss.

(2) They also appear to be functions of the square of the peripheral speed, though the effect of the speed is not so great as in the protected-type machine [see IV (4) below].

(*IV*) *Both Machines, with Induced Draught.*

(1) The curves of temperature-rise per watt plotted against draught velocity possess a double inflexion, and the lower the rotor speed the lower is the draught velocity at which the slope is a maximum.

(2) The difference between the shapes of the curves for different peripheral speeds is not due to any alteration in the distribution of the losses.

(3) The double inflexion appears to be due to the actual air velocity in the vicinity of the windings being the resultant of two air currents in space quadrature, namely, the induced draught and the radial air currents set up by the rotation of the machine. Consequently, the higher the peripheral speed of the rotor, the greater must be the draught velocity to produce a given percentage change in the resultant air velocity.

(4) The relationship between the temperature-rise and the draught velocity is very similar to that connecting the peripheral speed with the temperature-rises of the stator winding, core and duct of the protected and totally-enclosed machines and attributed to the cooling being a function of the square of the velocity. In consequence, it is suggested that much of the discrepancy concerning the effect of air velocity between the experimental results of different investigators is due to the presence of natural convection currents of air, the magnitude of which depends upon the disposition and the relative proportions of the cooling surfaces.

The author desires to express his gratitude to the Principal and the Governors of the Municipal Technical College, Brighton, for facilities to carry out the experimental work described in this paper.

DETERMINATION OF THE FINAL TEMPERATURE-RISE OF ELECTRICAL MACHINES FROM HEATING TESTS OF SHORT DURATION.[*]

By EDWARD HUGHES, Ph.D., B.Sc., Member.

(*Paper first received 20th August, and in final form 27th November, 1929.*)

SUMMARY.

If the heating curve of a coil or a machine were exponential the final temperature-rise could be calculated from the initial portion of the curve and the heating test thereby shortened. A large number of heating curves have been examined, and it is found that the final temperature, as calculated from the rate of increase of resistance, is always less than—often considerably less than—the actual value. The greater part of the paper is devoted to an analysis of the influence upon the shape of the curve, and thereby upon the ratio of the calculated to the actual rise, of such factors as the variation of (*a*) speed, (*b*) power generated in winding, (*c*) the temperature-rise per watt as affected by radiation and natural convection, (*d*) thermal conductivity, (*e*) specific heat, (*f*) point of maximum temperature and (*g*) heating time-constant.

It has often been suggested that by observing the temperature-rise for the first half-hour or hour of a heating test it is possible to calculate the final temperature-rise from the exponential expression.

$$\theta_t = \theta\left\{1 - \epsilon^{-t/T}\right\} \quad . \quad . \quad . \quad . \quad (1)$$

where θ = final temperature-rise,
θ_t = temperature-rise after time t, and
T = heating time-constant.

The simplest method of applying this relationship for the above purpose is undoubtedly that due to Rowlands,[†] who pointed out that if θ_1 and θ_2 are the temperature-rises after intervals $\frac{1}{2}t$ and t respectively from the commencement of the test, then the final temperature is given by

$$\theta = \frac{\theta_1}{2 - (\theta_2/\theta_1)} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

There are many difficulties in the application of this formula, such as

(1) Uncertainty of the initial temperature of the winding or core under consideration.

(2) Fluctuation of the supply voltage, rendering it very difficult to obtain reliable and consistent results with the voltmeter-ammeter method, though this difficulty can be overcome by a "bridge" method described by the author in a previous paper.[‡]

(3) The greater difficulty of making accurate measurements in the case of windings of low resistance; where there are a large number of joints the method is impracticable.

(4) The continuous application of a thermometer may appreciably modify the temperature-rise of the winding or core.

(5) The complications involved when the temperature-rise of a rotating element is to be measured.

By giving careful attention to every detail, however, it is possible to obtain reasonably good curves of temperature-rise. Having reached this stage we find another difficulty, namely, that the temperature-rise calculated from the initial portion of the heating curve seldom agrees with the actual final temperature-rise.[*]

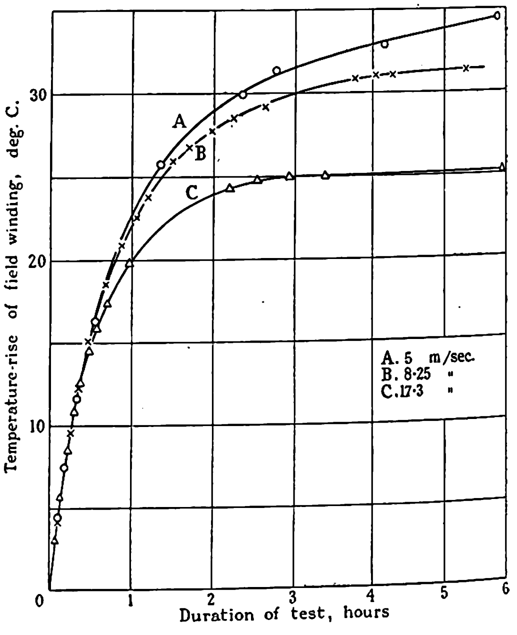

FIG. 1.

A large number of heating curves taken under various conditions have been analysed, and the following selection is typical of the results obtained:—

Case (1).—Machine B, referred to in another paper[†] by the author, when run as a protected type gave heating curves of which those plotted in Fig. 1 are typical. The temperature-rises of the field and stator windings were measured by the resistance method, and those of the stator core and duct by thermo-junctions placed as stated on page 912 of the paper mentioned above. The field current was maintained constant and the stator currents were 19, 19·3 and 18·4 amperes respectively in tests A, B and C; and the corresponding peripheral speeds were 5, 8·25 and 17·3 metres per second. It is obvious that the shape of the curves is different for the different speeds. Also, the heating time-constant (i.e. the time, according to the exponential expression, for the temperature-rise to attain 63·2 per cent of its final value) varied considerably both for speed and for the different parts of the machine.

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[†] T. R. ROWLANDS: "The Temperature Rise of Electrical Machinery," *Electrical Review*, 1924, vol. 95, p. 11.

[‡] E. HUGHES: "Rise and Distribution of Temperature in Small Electrical Machines," *Journal I.E.E.*, 1924, vol. 62, p. 628.

[*] In the *Transactions* of the American I.E.E. (1925, vol. 44, p. 147), V. KARAPETOFF states: "For a number of years we had at Cornell a student experimenting on temperature-rise in transformers, using and checking exponential curves. However, the discrepancy with the observed results was so considerable that we dropped the theory and left only the measurements."

[†] "An Analysis of Heating Tests on Electrical Machines," *Journal I.E.E.*, 1930, vol. 68, p. 912.

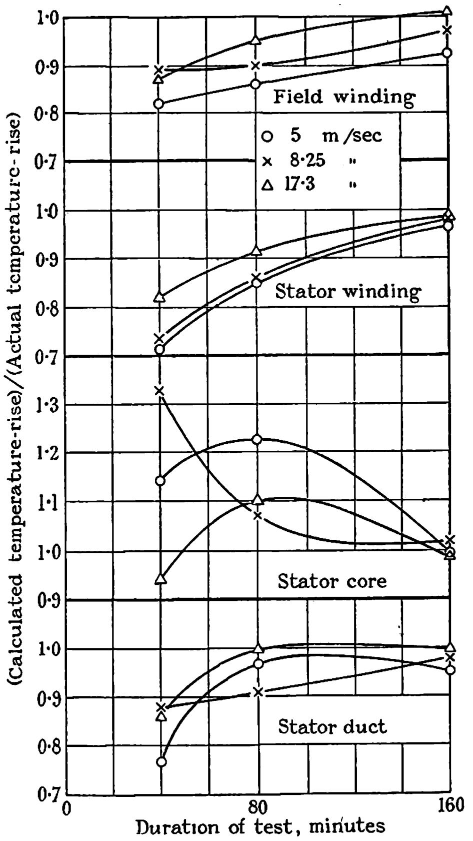

FIG. 2.

By means of formula (2), the final temperature-rises were calculated from each curve for $t = 40$, 80 and 160 minutes, respectively. These calculated values, θ_c, expressed as a fraction of the actual final temperature-rises, θ, have been plotted in Fig. 2. It will be observed that for the field and stator windings the ratio θ_c/θ deduced from a heating test of 40 minutes' duration may be considerably below unity, and that the discrepancy between θ_c and θ is greater (*a*) the smaller the value of t and (*b*) the lower the speed.

The question naturally arises: Should the values of θ_c/θ have been compared on the basis of equal duration of test or should the various "time intervals" * have been taken into account? From the standpoint of actual tests for calculating the final temperatures, the first alternative appears to be the correct one since all parts of the machine must be run for the same period for any particular test. However, in order to examine the discrepancy between the values of θ_c/θ for the different speeds, it is worth while noting the effect of this "time interval." The latter is obtained for each test by noting from the curve the time required for the temperature-rise to reach 63·2 per cent of the final value, and Table 1 shows how it varies for the different parts of the machine and also for the different speeds.

The variation of the heating "time interval" with speed might have been anticipated from a consideration of the usual exponential. Since the heating time-constant may be defined as the time required to attain the final temperature-rise if there were no losses and if the power generated remained constant,

$$T = \frac{\theta W}{P} = W \times \text{temperature-rise per watt}$$

where W = energy in joules to raise temperature 1 deg. C., and
P = power generated in watts.

The author has shown in his other paper † that the temperature-rise per watt for each part of the machine is smaller the higher the speed. Hence it might have been expected that, even for curves that are only approximately exponential, the heating time-constant would be shorter the higher the speed.

TABLE 1.

Test	Peripheral speed	Draught speed	Time interval, T_t			
			Field winding	Stator winding	Stator core	Stator duct
	metres/sec.	metres/sec.	minutes	minutes	minutes	minutes
A	17·3	—	35	13	48	34
B	8·25	—	46	25	61	53
C	5·0	—	58	29	70	64
D	8·25	3·44	51	32	78	69
E	8·25	1·4	80	73	109	100
F	8·25	0	129	134	158	158

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* The term "time interval" has been introduced to avoid applying the term "time constant" to non-exponential curves, and represents the time required for the temperature-rise to reach 63·2 per cent of the final value.

† See page 930.

From the values of T_i in Table 1 the ratio of θ_c/θ can now be plotted against t/T_i,* as in Fig. 3. It will be seen from the latter that the effect introduced by the speed in Fig. 2 has almost vanished.

Case (2). *Machine B, arranged for Pipe-Ventilation.*—The machine was run on a constant load of 15 amperes, with 2-ampere excitation and a peripheral speed of 8·25 metres per sec., and with induced-draught speeds of 3·44, 1·4 and 0 metres per sec. in tests D, E and F respectively. The difference between the shapes of the curves of temperature-rise for the different speeds was even more marked than that for case (1), a feature that is also evident from a comparison of Fig. 4 with Fig. 2. The values of θ_c/θ for the stator core are erratic and illustrate the impossibility of estimating the final temperature-rise of the core from a short heat-run.

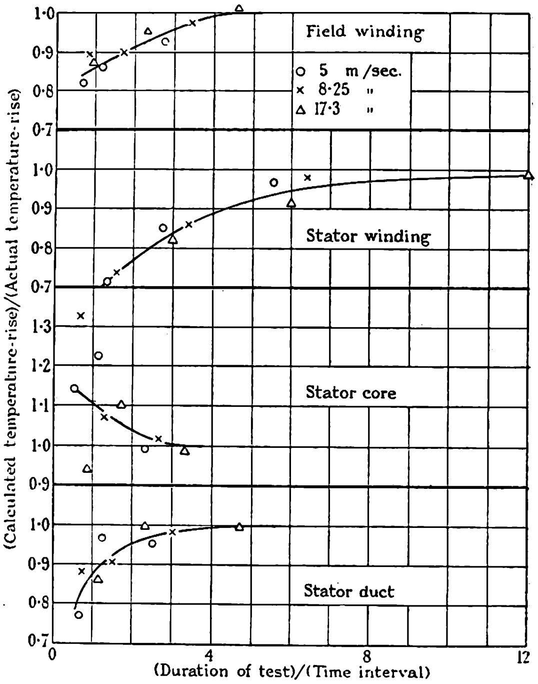

FIG. 3.

The "time intervals" derived from these heating curves have been incorporated in Table 1. The enormous influence of enclosure and of air velocity will be obvious.

TABLE 2.

Test	Field Current	Peripheral speed	Time interval, T_i		
			Field winding	Armature winding	Thermo-junction
	amps.	metres/sec.	minutes	minutes	minutes
A	0·86	16	28	22	32
B	0·86	8	29	42	67
C	0·96	0	40	—	—
D	0·7	0	37	—	—

In Fig. 5 the values of θ_c/θ have been plotted against t/T_i for the field and stator windings. The corresponding points for the stator core are so irregular as not to be worth re-plotting. It will be seen from this figure that for small values of t/T_i the values of θ_c/θ for various air velocities are in good agreement with one another; but with larger values of t/T_i the error in calculating the final temperature is greater the higher the air velocity.

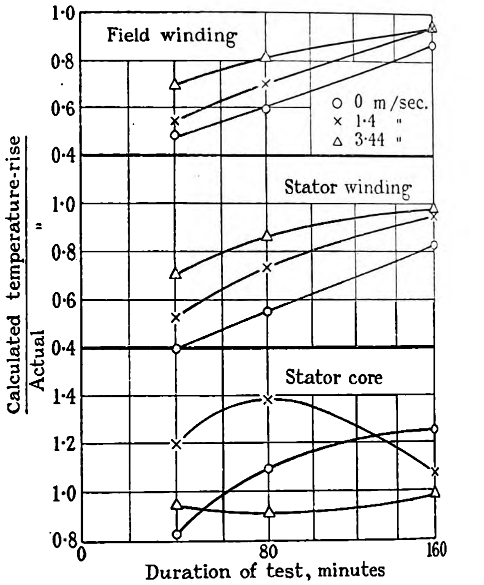

FIG. 4.

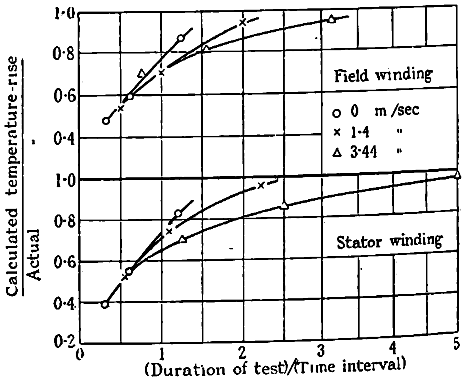

FIG. 5.

Case (3). *Machine A* (*rotating armature*) *as a protected*

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* Namely, the duration of the heating test up to the second reading used to calculate the final temperatures, divided by the "time interval."

type.—The only data available for plotting heating-curves on this machine had been taken on no load. The field and armature temperatures had been measured by the resistance method, and the temperature at a point midway between the pole-tips and 2·5 mm away from the armature had been noted by a thermo-junction. The values of T_i derived from these heating curves, together with particulars of the tests, are given in Table 2.

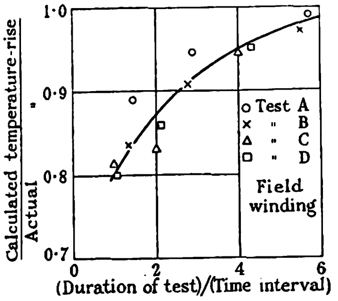

FIG. 6.

The large variation in T_i for the armature winding and thermo-junction seems to be due to these temperatures being greatly influenced by the speed.

The values of θ_c/θ for the field and armature windings and for the thermo-junction have been plotted against the corresponding values of t/T_i in Figs. 6 and 7. Here, again, it is seen that the final temperature-rise calculated from heat runs of short duration may be appreciably smaller than the actual value.

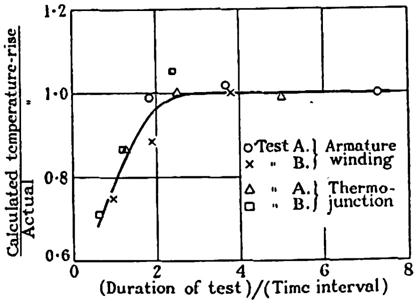

FIG. 7.

DISCUSSION OF THE ABOVE RESULTS.

There are a number of reasons that may be suggested to account for the most common feature noted above, namely that the temperature-rise of a winding calculated from the initial portion of the heating curve is always less than the actual value. Thus we have—

(1) *Variation of Power Generated in Coil.*

The usual exponential equation for the temperature-rise is based on the assumption that the power dissipated in the winding remains constant, whereas in all the above tests the current was kept constant, so that the power increased with increase of temperature-rise. This problem, however, has been fully discussed by the author in another paper,* where it is shown that the effect of the increase of resistance is to increase both the temperature-rise and the heating time-constant by $(1 + a\theta)$, but not to cause the heating curve to deviate from the exponential shape; and the temperature-rise calculated from the initial portion of the curve should agree with the actual value as far as this effect is concerned.

(2) *Variation of the Temperature-Rise per Watt with the Temperature-rise.*

The usual exponential expression assumes that the power dissipated is proportional to the temperature-rise. Actually, however, the power dissipated increases more rapidly than the temperature-rise; and from an analysis of tests on five coils suspended in air the author has found † that the temperature-rise per watt can be expressed very closely by

$$\frac{\theta}{P} = \frac{a}{1 + c\theta}$$

where θ = final temperature-rise, measured by resistance,
a = a constant for a given coil, and
c = a coefficient varying from 0·0036 to 0·005 for the five coils.

From tests on the field coils of six protected-type machines with their armatures stationary, it was found that the temperature-rise per watt was again represented by a similar expression, where a varied between 0·0023 and 0·0085 for the different machines. It is therefore desirable to consider to what extent such a relationship is in accordance with the recognized laws of radiation and of convection, and to see whether this variation in the watts dissipated per degree rise of temperature accounts for the results obtained in the first section of this paper.

(*a*) *Cooling due to Radiation only.*—Stefan-Boltzmann's law states that, for black bodies,

$$\text{Heat radiated per second} \propto \left(T_2^4 - T_1^4\right)$$

where T_2 = absolute temperature of the hot body, and
T_1 = absolute temperature of the surroundings receiving the radiation.

Then temperature-rise per watt

$$= \frac{\theta}{P} = \frac{T_2 - T_1}{P}$$
$$= \frac{k}{(T_2 + T_1)(T_2^2 + T_1^2)} \quad . \quad . \quad . \quad (3)$$

where k is a constant for a given surface.

By assuming the temperature of the surroundings to be 15° C. and k to be such that θ/P is unity when $T_2 = T_1$, the values of θ/P represented by crosses in Fig. 8 have been calculated.

It has previously ‡ been pointed out that for moderate temperature-rises these results are almost identical with those calculated from an expression of the form

$$\frac{\theta}{P} = \frac{1}{1 + 0{\cdot}006\theta} \quad . \quad . \quad . \quad . \quad (4)$$

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* *Loc. cit.*

† *Loc. cit.*

‡ *Loc. cit.*

where θ is the temperature-rise. The values obtained from (4) are shown by circles in Fig. 8, and it is evident from the latter that for temperature-rises within 100 deg. C. the difference between expressions (3) and (4) is so small that the second expression can be utilized for investigating the effect of Stefan-Boltzmann's law upon the shape of the heating curve.

Let W = energy in joules to raise the temperature of a coil 1 deg. C.,
P = initial power generated in coil,
β = final temperature-rise that would have been reached if the power remained at P, and
T = the corresponding time-constant.

Then $TP = \beta W$, so that $W = TP/\beta$.

If θ_t be the temperature-rise after a time t seconds, the power generated in the coil at that instant is $P(1 + \alpha\theta_t)$, where α is the temperature coefficient of resistance at initial temperature.

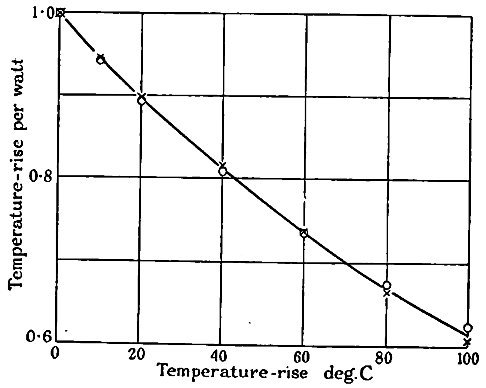

Fig. 8.

From expression (4) it follows that the power dissipated per degree rise of temperature of the coil can be represented by $k(1 + c\theta_t)$, where $c = 0{\cdot}006$ and k is a constant for a given coil. Then

$$P(1 + \alpha\theta_t)dt = Wd\theta + k(1 + c\theta_t)\theta_t dt$$

If θ be the steady temperature-rise of the coil when the *current* is maintained constant, then

$$P(1 + \alpha\theta) = k(1 + c\theta)\theta \quad . \quad . \quad . \quad (5)$$

$$\therefore\ k = \frac{P(1 + \alpha\theta)}{(1 + c\theta)\theta}$$

Substituting for k and W in the above equation, we have

$$P(1 + \alpha\theta_t)dt = \frac{TP}{\beta}d\theta + \frac{P(1 + \alpha\theta)(1 + c\theta_t)\theta_t dt}{(1 + c\theta)\theta}$$

$$\therefore \frac{d\theta}{dt} = \frac{\beta}{T}\left\{(1 + \alpha\theta_t) - \frac{(1 + \alpha\theta)(1 + c\theta_t)\theta_t}{(1 + c\theta)\theta}\right\} \quad . \quad (6)$$

Since

$$P = k(1 + c\beta)\beta \quad . \quad . \quad . \quad . \quad . \quad (7)$$

then, from equations (5) and (7), we have

$$1 + \alpha\theta = \frac{(1 + c\theta)\theta}{(1 + c\beta)\beta} \quad . \quad . \quad . \quad . \quad (8)$$

from which β can be found in terms of α, c and θ.

The simplest method of determining the shape of the heating curve corresponding to expression (6), and thus of comparing it with the exponential curve, is to assume $\theta = 50$ deg. C. (say) and $T = 30$ minutes (say) = 1 800 seconds. We can take α as $0{\cdot}004$ for an initial temperature of about 15° C., and c has already been given as $0{\cdot}006$. By substituting these values in (8) we find that $\beta = 43{\cdot}1$ deg. C.; and by substituting in (6) we have

$$\frac{d\theta}{dt} = 0{\cdot}02395(1 - 0{\cdot}014450_t - 0{\cdot}000111\,\theta_t^2)$$

By assuming various values of θ_t we can calculate the corresponding values of $d\theta/dt$; and since the change in slope of the heating curve is comparatively gradual it is possible by taking a sufficient number of values to derive the heating curve. Thus, for $\theta_t = 0$, $d\theta/dt = 0{\cdot}02395$; and for $\theta_t = 5$ deg. C., $d\theta/dt = 0{\cdot}02215$; so that the mean value of $d\theta/dt$ between 0 and 5° C. is $0{\cdot}02305$. Consequently, the time taken for the temperature to increase from 0° C. to 5° C. is $5/0{\cdot}02305$, namely, 217 seconds. Similarly, for $\theta_t = 10°$ C., $d\theta/dt = 0{\cdot}0202$; so that the mean slope of the heating curve between 5° C. and 10° C. is $0{\cdot}02117$, and the time taken for the temperature to rise this amount is 236 seconds. In this way the values represented by curve A in Fig. 9 were derived.

Let us now see how the final temperature-rises calculated from this curve by means of expression (2) agree with the actual values. The second column of Table 3 gives three values obtained in this way, and the ratio of the calculated to the actual rise has been added in the third column. A comparison of these results with the curves of Fig. 2 shows that the modification in the heating curve caused by Stefan-Boltzmann's law is in the opposite direction to that actually observed.

(*b*) *Cooling due to Natural Convection only.*—It has been demonstrated by numerous investigators * that the power dissipated by natural convection is proportional to (Temperature-rise)$^{1{\cdot}25}$,

$$\text{i.e. Power dissipated} = k\theta_t^{1{\cdot}25}$$

where k = a constant for a given coil, and
θ_t = temperature-rise after t seconds.

We can therefore proceed to determine the corresponding heating curve; thus, using the same symbols as in the preceding section, we have

$$P(1 + \alpha\theta_t)dt = Wd\theta + k\theta_t^{1{\cdot}25}dt$$

But

$$P(1 + \alpha\theta) = k\theta^{1{\cdot}25} \quad . \quad . \quad . \quad . \quad (9)$$

Substituting for W and k, we have

$$P(1 + \alpha\theta_t)dt = \frac{TP}{\beta}d\theta + \frac{P(1 + \alpha\theta)}{\theta^{1{\cdot}25}}\theta_t^{1{\cdot}25}dt$$

$$\therefore \frac{T\theta^{1{\cdot}25}}{\beta}d\theta = \left\{\theta^{1{\cdot}25} - \theta_t^{1{\cdot}25} + \alpha\theta\theta_t(\theta^{0{\cdot}25} - \theta_t^{0{\cdot}25})\right\}dt$$

Also

$$P = k\beta^{1{\cdot}25} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

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* "Dictionary of Applied Physics," vol. 1, pp. 473–7.

From (9) and (10), we have

$$\beta = \frac{\theta}{(1 + \alpha\theta)^{0\cdot 8}}$$

$$\therefore \frac{d\theta}{dt} = \frac{\left\{\theta^{1\cdot 25} - \theta_t^{1\cdot 25} + \alpha\theta\theta_t(\theta^{0\cdot 25} - \theta_t^{0\cdot 25})\right\}}{T\theta^{0\cdot 25}(1 + \alpha\theta)^{0\cdot 8}}$$

In deriving the heating curve corresponding to this equation, the same procedure was followed as in the last section; i.e. the values of θ and T were assumed to be 50 deg. C. and 1 800 seconds respectively, and the values of $d\theta/dt$ were calculated for various values of θ_t. The corresponding variation of temperature-rise with time is represented by curve B in Fig. 9, and the final temperature-rises calculated from the initial portion of this curve are given in column 4 of Table 3. The values of θ_c/θ have been added in column 5.

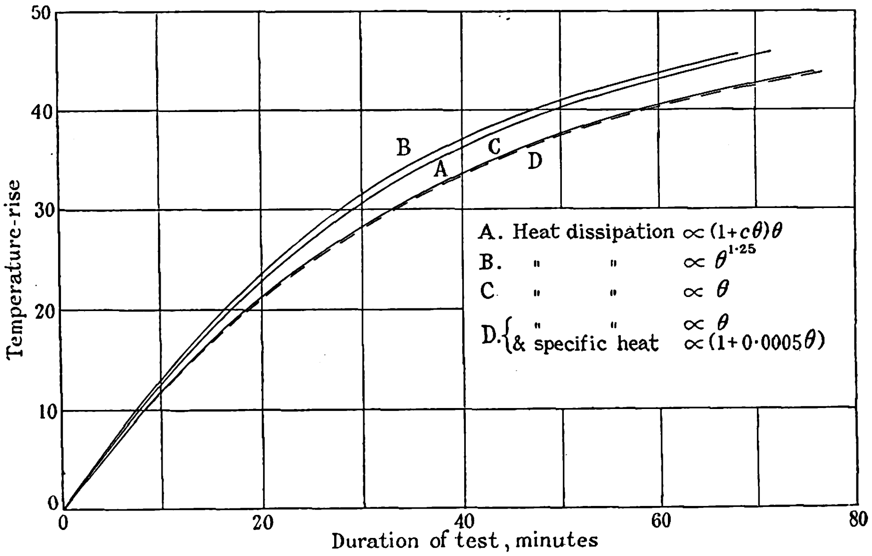

FIG. 9.

TABLE 3.

Time of second reading	Radiation		Natural convection		Variation of specific heat	
	Calculated rise	θ_c/θ	Calculated rise	θ_c/θ	Calculated rise	θ_c/θ
minutes	deg. C.		deg. C.		deg. C.	
13·3	68·1	1·36	72·6	1·45	48·9	0·98
26·6	57·0	1·14	57·2	1·144	49·5	0·99
53·2	52·4	1·048	52·5	1·05	49·6	0·992

Here, again, it is obvious that the effect of natural convection is to give exactly the opposite result to that experimentally observed on windings; i.e. natural convection tends to modify the heating curve so that the value of the final temperature calculated from the initial portion of the curve is greater than the actual value.

(*c*) *Cooling due to forced convection only.*—Both theory and experiment indicate that the loss of heat by forced convection is proportional to the difference of temperature between the hot surface and the ambient fluid.* Newton's law of cooling, upon which the exponential curve of temperature variation is based, was actually given for a body " not in still air but in a uniform current of air." Consequently, the effect of forced convection upon the heating curve is precisely that already assumed in deriving the exponential equation referred to in section (1), page 935, and it cannot therefore be responsible for the problem under investigation. For ease of comparison with the heating curves already derived, the exponential curve C in Fig 9 has been calculated for $\theta = 50$ deg. C. and $T = 1\ 800$ seconds.

(3) *Variation of the Thermal Conductivity of the Winding.* The thermal conductivity of copper † decreases about 1 per cent for an increase of temperature from 18° C. to 100° C. On the other hand, the thermal conductivities of cotton waste ‡ and of air § have been found to increase about 25 per cent and 27·5 per cent respectively between 0° C. and 100° C. Fig. 10 shows the variation in the effective thermal conductivity of the insulation (including the air space) deduced from tests ‖ made by the author on a coil fitted with five thermo-junctions embedded at

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* " Dictionary of Applied Physics," vol. 1, pp. 471–3.

† *Ibid.*, vol. 1, p. 443.

‡ *Ibid.*, vol. 1, p. 433.

§ *Ibid.*, vol. 1, p. 461.

‖ *Journal I.E.E.*, 1924, vol. 62, p. 632.

different depths. The coil consisted of 3 800 turns of No. 24 S.W.G. copper wire (d.c.c.). From this curve it will be seen that for a temperature-rise of 80 deg. C. the increase of thermal conductivity is only about 9 per cent.

The effect of an increase in the thermal conductivity is to reduce the ratio of the average temperature across the section of the coil to the surface temperature. If we assume, for simplicity, the heat generated in the coil and the emissivity of the latter to remain constant, the greater uniformity of the temperature throughout the coil due to an increase of the thermal conductivity means that the final temperature as measured by increase of resistance is smaller than that calculated from the initial portion of the heating curve. Hence, the phenomenon noted in the first part of this paper cannot be due to any increase of the thermal conductivity.

(4) *Variation of the Specific Heat of Copper.*

The specific heat of copper* increases about 5 per cent for an increase of temperature from 0° C. to 100° C., so that for a temperature-rise of θ_t it can be represented by $s(1 + 0\cdot0005\,\theta_t)$, where s is the specific heat at the initial temperature.

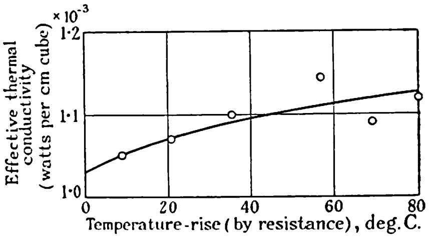

FIG. 10.

Let T be the time required to attain steady temperature-rise β if power and specific heat were to remain constant at their initial values and if no energy were being dissipated. Then

$$TP = bs\beta$$

where $b = 4\cdot2 \times$ mass (grammes) of copper

$$\therefore bs = TP/\beta$$

As we are at present only concerned with finding the influence of the variation of the specific heat upon the exponential curve, it will be assumed that the heat dissipation is proportional to the temperature-rise. Hence, we have

$$P(1 + \alpha\theta_t)dt = bs(1 + 0\cdot0005\theta_t)d\theta + k\theta_t dt \quad (11)$$

If θ be the steady temperature-rise when the *current* is kept constant, then

$$P(1 + \alpha\theta) = k\theta$$

$$\therefore k = \frac{P(1 + \alpha\theta)}{\theta}$$

Substituting for bs and k in (11), we have

$$(1 + \alpha\theta_t)dt = \frac{T}{\beta}(1 + 0\cdot0005\theta_t)d\theta + \frac{1 + \alpha\theta}{\theta}\theta_t dt$$

But $$\theta/\beta = 1 + \alpha\theta$$

Substituting for β and simplifying, we have

$$\frac{dt}{T(1 + \alpha\theta)} = \frac{1 + 0\cdot0005\theta_t}{\theta - \theta_t}d\theta$$

$$\therefore \frac{t}{T(1+ \alpha\theta)} = -\,0\cdot0005\theta_t$$
$$-\,(1 + 0\cdot0005\,\theta)\log_\epsilon(\theta - \theta_t) + A$$

When $t = 0,\quad \theta_t = 0$

$$\therefore A = (1 + 0\cdot0005\,\theta)\log_\epsilon\theta$$

Hence

$$\frac{t}{T(1 + \alpha\theta)} = (1 + 0\cdot0005\theta)\log_\epsilon\frac{\theta}{\theta - \theta_t} - 0\cdot0005\theta_t \quad (12)$$

If the specific heat were constant, we should have

$$\frac{t}{T(1 + \alpha\theta)} = \log_\epsilon\frac{\theta}{\theta - \theta_t}$$

$$\text{i.e. } \theta_t = \theta\left\{1 - \epsilon^{-t/T(1+\alpha\theta)}\right\}$$

which is the same as the expression referred to in section (1), page 935, and represented by curve C in Fig. 9.

A simple method of showing the effect of the variation of specific heat upon the heating curve is to assume $\theta = 50$ deg. C., $T = 30$ minutes and $\alpha = 0\cdot004$, as in the previous sections, and to calculate from equation (12) the values of t for temperature-rises of 5 deg. C., 10 deg. C., etc. The results are represented by curve D in Fig. 9, from which it will be seen that the deviation from the exponential shape is very small. From a carefully-drawn copy of curve D, values of the final temperature-rise were calculated and are given in column 6 of Table 3; and the corresponding values of θ_c/θ are given in column 7 of that table. It will be obvious that, while the increase of specific heat does tend to cause the phenomenon under investigation, the effect is so small as to be almost negligible.

In the above discussion the specific heats of the insulation and of the air enclosed in the interstices have been assumed constant. The specific heat of air has been found * to increase only 0·5 per cent between 20° C. and 100° C. and to be practically unaffected when the pressure is doubled. The author has not been able to find any data in regard to the variation of the specific heat of the insulation.

(5) *Variation of the Point of Maximum Temperature.*

When the temperature distribution across a section of a coil is determined experimentally, it is found that the point of maximum temperature shifts from the centre towards the inner side of the coil. Thus, Fig. 11 is typical of the results obtained by the use of five thermo-junctions on the coil referred to in section (3). In order that the relative shapes of the curves may be as clear as possible, the ratios of the actual temperature-rise to the corresponding temperature-rise at the centre of the coil and not the actual temperature-rises have been plotted. It is evident that the curve shifts inwards quite appreciably. The influence of this redistribution upon the heating curve was first investigated by plotting the heating curves obtained from the thermo-junctions situated in the centre and on the outside and inside respectively of the coil; and from these curves the corresponding final rises were determined by formula (2). The ratios of the calculated to the actual values, plotted in Fig. 12, are typical of those obtained with different currents, and indicate quite definitely that the ratio is less than unity except for the results derived from the earliest portion of the curve for the inner junction. They also show that the shape of the heating curve is not identical for the various depths of the coil.

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* "Dictionary of Applied Physics," vol 1, p. 41.

* "Dictionary of Applied Physics," vol. 1, p. 44.

Though the curves of temperature distribution are practically parabolic, it was not found possible to derive any mathematical formula whereby the effect of the shift of the point of maximum temperature upon the shape of the heating curve representing the average temperature-rise could be calculated. Consequently another method was tried, namely, to plot curves of temperature distribution—similar to those in Fig. 11—after 10, 20, 40, 80 and 160 minutes, and, finally, after 7 hours of the heating test. By measuring the areas enclosed by these curves, the corresponding average temperature-rises across the section were calculated, and the ratios of these temperatures to the average temperature after 7 hours have been plotted in Fig. 13. These curves indicate that the effect of redistribution of temperature is to modify the heating curve for the average temperature-rise, as determined from thermo-junction readings, in such a way that the ratio of the calculated final rise to the actual rise is less than unity and is therefore in agreement with the results obtained in the first part of this paper, though the magnitude of the effect is not nearly so great.

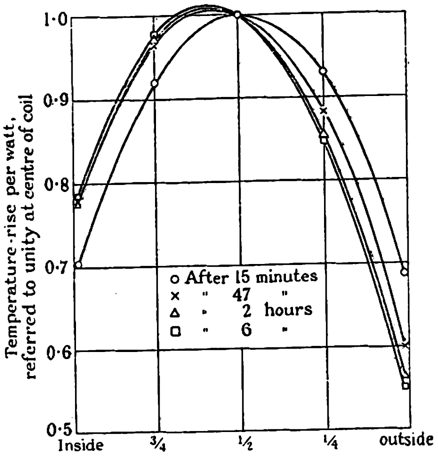

FIG. 11.

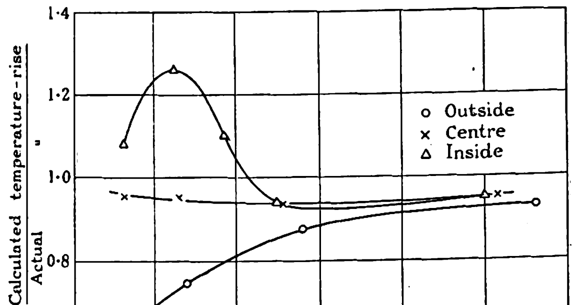

FIG. 12.

The shifting inwards of the point of maximum temperature is mainly due to the presspahn former on which the coil was wound, causing the dissipation of heat per unit area from the inner surface to be smaller than that from the outer surface. (The coil was suspended in air during the above tests.) The distribution of temperature may also have been modified by an alteration in the thermal conductivity of the cotton and of the air in the interstices of the coil, as discussed on page 937.

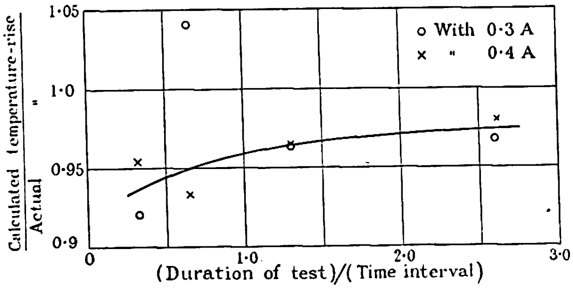

FIG. 13.

(6) *Variation of the Heating Time-Constant for Different Sections of the Winding.*

It has already been explained on page 933 that the better the facilities for heat dissipation, the shorter is the heating time-constant. It is obvious that for no winding is the heat dissipation per unit area uniform over the whole surface. Let us therefore consider an ideal case of a winding consisting of two sections—somewhat on the lines of an armature winding—but quite independent of each other, as far as the dissipation of the generated heat is concerned.

Let P_1 and P_2 be the *steady* powers generated in the two sections,

T_1 and T_2 be the corresponding time-constants,

θ' and θ'' be the corresponding final temperature-rises, and

θ'_t and θ''_t be the corresponding temperature-rises t seconds after commencement of heating test.

Assuming the usual exponential relationship, we have

$$\theta'_t = \theta'(1 - \epsilon^{-t/T_1})$$

and

$$\theta''_t = \theta''(1 - \epsilon^{-t/T_2})$$

Let R' and R'' be the initial resistances of the respective sections,

R'_t and R''_t be the respective resistances after t seconds, and

a be the temperature coefficient of resistance corresponding to the initial temperature.

Then $R'_t = R'(1 + a\theta'_t)$

and $R''_t = R''(1 + a\theta''_t)$

$$\therefore a(R'\theta'_t + R''\theta''_t) = R'_t + R''_t - (R' + R'')$$
$$= \text{increase in resistance of whole coil}$$
$$= r \text{ (say)}$$

If θ_t be the corresponding temperature-rise calculated from the increase of resistance of the *whole* coil,

then $r = a\theta_t(R' + R'')$

$$\therefore \theta_t = \frac{r}{a(R' + R'')} = \frac{R'\theta'_t + R''\,\theta''_t}{R' + R''}$$

If θ be the final temperature-rise calculated from the increase of resistance of the *whole* coil,

then $$\theta = \frac{R'\theta' + R''\theta''}{R' + R''}$$

By assuming different combinations of R' and R'', T_1 and T_2, etc., we can now calculate their influence upon the shape of the heating curve for the whole coil. For instance, assume $\theta' = \theta'' = 40$ deg. C.; $R' = 100$; $R'' = 200$; $T_1 = 20$ minutes; and $T_2 = 40$ minutes. Then for $t = 10$ minutes, $t/T_1 = 0\cdot5$ and $t/T_2 = 0\cdot25$.

$$\therefore \theta'_t = 40(1 - \epsilon^{-0\cdot5}) = 15\cdot74$$

and $$\theta''_t = 40(1 - \epsilon^{-0\cdot25}) = 8\cdot86.$$

Hence,

$$\theta_t = \frac{(100 \times 15\cdot74) + (200 \times 8\cdot86)}{100 + 200} = 11\cdot15$$

Similarly, for $t = 20$ minutes,

$$t/T_1 = 1\cdot0; \quad \theta'_t = 25\cdot3; \quad \text{and} \quad \theta''_t = 15\cdot74$$
$$\therefore \theta_t = 18\cdot91$$

By applying expression (2) we have

$$\left.\begin{array}{r}\text{Calculated final}\\ \text{temperature-rise}\end{array}\right\} = \theta_c = \frac{11\cdot15}{2 - (18\cdot91/11\cdot15)} = 36\cdot55$$

$$\therefore \frac{\text{Calculated final rise}}{\text{Actual final rise}} = 0\cdot914.$$

By repeating this calculation for different combinations of R', R'', etc., the results given in Table 4 have been obtained.

Comparison of the values obtained for θ_c/θ in Table 4 shows that:—

(*a*) Merely a difference of temperature-rise or of power or of both has no influence upon the ratio.

(*b*) Only a difference of time-constant causes θ_c/θ to be less than unity.

(*c*) If the difference in time-constant be accompanied by a difference in power dissipated, then the decrease of θ_c/θ is greater the larger the power dissipated in the section having the longer time-constant.

(*d*) The smaller the value of t/T for a given coil, the smaller is the corresponding value of θ_c/θ. The variation of θ_c/θ with the duration of the heating test for the conditions referred to in the first three rows of Table 4 and plotted in Fig. 14 is so similar to that experienced on actual coils that it would appear that the principal reason for the impossibility of calculating the final rise from the initial portion of the heating curve is the variation in the heat dissipation per unit area from the different portions of the winding.

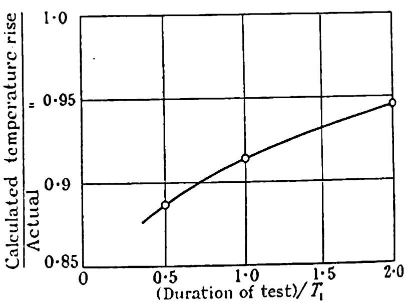

FIG. 14.

In the case of field windings, those portions of the surface that are most exposed dissipate considerably more power per unit area than the shielded portions such as those facing the pole cores; and it will therefore be evident from Table 4 that for such windings the final temperature-rise calculated from the initial portion of the heating curve should be less than the actual rise.

TABLE 4.

t/T_1	R'	R''	T_1	T_2	θ'	θ''	θ	θ_c	θ_c/θ
	ohms	ohms	mins.	mins.	deg. C.	deg. C.	deg. C.	deg. C.	
0·25 and 0·5	100	200	20	40	40	40	40	35·45	0·887
0·5 and 1	100	200	20	40	40	40	40	36·55	0·914
1 and 2	100	200	20	40	40	40	40	37·85	0·946
0·5 and 1	100	200	20	20	40	40	40	40·0	1·0
0·5 and 1	100	200	20	20	40	60	53·3	53·3	1·0
0·5 and 1	100	200	20	40	40	60	53·3	48·7	0·914
0·5 and 1	150	150	20	40	40	40	40	37·1	0·927
0·5 and 1	150	150	20	20	40	60	50	50·0	1·0
0·5 and 1	200	100	20	40	40	40	40	37·7	0·943
0·5 and 1	200	100	20	40	40	60	46·7	43·3	0·927

CONCLUSIONS.

(1) The final temperature-rise of windings as calculated by the exponential relationship from the increase of resistance during the initial part of the heating test is less than the actual value.

(2) The discrepancy between the calculated and the actual values is greater (*a*) the shorter the duration of the heating test, and (*b*) the lower the speed.

(3) The effect of speed was found to be due to the heating " time interval " (i.e. the time to attain 63·2 per cent of the steady rise), being shorter the higher the speed.

(4) The increase of power generated in a coil due to variation of resistance increases the temperature-rise and the heating time-constant, but does not cause the heating curve to deviate from the exponential shape.

(5) The decrease of the temperature-rise per watt with increase of temperature causes the heating curve to depart from the exponential form. This variation can be accounted for by the known laws of radiation and of natural convection; but the effect of both radiation and natural convection is to make the calculated final rise greater than the actual value. On the other hand, forced convection, being the basis of the usual exponential expression, cannot be responsible for any discrepancy between the calculated and the actual temperature-rises.

(6) The increase of thermal conductivity of the insulation tends to give a calculated final rise that is greater than the actual value.

(7) The increase of specific heat of copper modifies the heating curve in the required direction, but the magnitude is so small as to be almost negligible.

(8) The shifting of the point of maximum temperature towards the inner side of a coil also accounts for a small part of the discrepancy.

(9) The difference in the heating time-constants of the different portions of a coil seems to be mainly responsible for the difference between the calculated and the actual final rises. The better the heat dissipation, the shorter is the time-constant. The difference in the time-constants may or may not be accompanied by differences of power generated in, and of temperature-rise of, the different portions; but differences of power and of temperature-rise with no difference of time-constant do not account for the discrepancy.

(10) Owing to the impossibility of calculating the final temperature-rise from the initial portion of the heating curve, the only method of minimizing the energy consumed during a heat run and at the same time of ensuring reliable values for the final temperatures, is to maintain an overload on the machine until the temperatures approximate the anticipated values, and then to continue at full load until reasonably steady temperatures are attained. The temperature variation of the armature of a direct-current machine can be followed very closely by the aid of a thermo-junction fixed between the pole-tips, as described in another paper * by the author.

* "An Analysis of Heating Tests on Electrical Machines," *Journal I.E.E.*, 1930, vol. 68, p. 912.

INSTITUTION NOTES.

Library.

The Reference Library of the Institution will be closed from the 14th July until about the 30th September for structural alterations and re-decoration.

By courtesy of the Councils of The Institution of Civil Engineers and The Institution of Mechanical Engineers the Libraries of these Institutions will be available to members for reference purposes during that period.

Members desirous of availing themselves of these facilities should apply to the Secretary of the I.E.E. for a card of introduction.

Premiums.

In addition to the Premiums mentioned on page 795, the Council have awarded the following Premiums for the session 1929–30 for papers read before the Meter and Instrument Section and for Students' papers:—

METER AND INSTRUMENT SECTION PREMIUMS.

Silvanus Thompson Premium (*value* £10).

E. H. RAYNER, Sc.D., W. G. STANDRING, M.A., R. DAVIS, M.Sc., and G. W. BOWDLER, M.Sc.	" Studies in Low-Power-Factor Measurements at High Voltages."

A Premium (*value* £5).

A. E. MOORE, M.Sc.Tech., and W. T. SLATER, M.Sc.Tech.	" An Investigation of the Frequency Variations in Induction Watt-hour Meters."

STUDENTS' PREMIUMS.

Premiums of the Value of £10 *each:*

Author	*Title of Paper*	*Where read*
E. W. CONNON, B.Sc.(Eng.).	" Hydro-Electric Developments in Great Britain."	Liverpool
J. C. EMERSON, B.Sc., and J. W. MOFFATT.	" The Rotary Automatic Telephone System."	London
L. E. C. HUGHES, Ph.D.	" Engineering Acoustics."	London
C. S. T. PAUL.	" The Oil-Immersed Circuit Breaker."	Leeds
W. G. THOMPSON, B.Sc.	" The Electrical Propulsion of Ships."	Newcastle

Premiums of the Value of £5 each:

C. H. BRADBURY.	"Torsional Vibration in the Diesel-Electric Set."	Sheffield
S. M. LEJEUNE.	"Recent Developments in Alternating-Current Protective Gear."	London

The Students' Prize.

The Students' Prize of £10 offered by the Council for the best paper on the subject of "The Relations between Economics and Engineering" submitted by a Student, or a Graduate under the age of 28, during the session 1929–30, has been awarded jointly to Mr. V. A. H. Clements and Mr. A. K. Robinson for the papers submitted by them, the amount of the prize being divided equally between these two authors.

Nominations for Election to the Council.

In addition to those members nominated by the Council (see page 795) the following members have been nominated for ballot as Vice-President and Ordinary Members of Council respectively:—

Vice-President.

E. H. SHAUGHNESSY, O.B.E. (Nominated by W. T. Anderson, A. S. Angwin, D.S.O., M.C., B.Sc. (Eng.), E. S. Byng, A. O. Gibbon, H. H. Harrison, F. Hope-Jones, E. C. McKinnon, W. J. Medlyn, O.B.E., Sir William Noble, and H. C. Turner).

Ordinary Members of Council.

J. FRITH, M.Sc. (Nominated by D. Adamson, D.Sc., R. Brooks, B.Sc., A. G. Ellis, J. F. Fletcher, T. A. Kerr, A. L. Lunn, A. B. Mallinson, J. A. Robertson, L. Romero, and G. F. Sills).

R. B. MATTHEWS (Nominated by W. C. Bexon, J. H. C. Brooking, F. Christy, F. J. Down, B. G. Drummond, W. P. Gauvain, A. W. Isenthal, H. N. Prentice, A. L. Stanton, and F. H. Whysall).

V. WATLINGTON, M.B.E. (Nominated by H. H. Berry, H. W. Clothier, A. P. M. Fleming, C.B.E., M.Sc., S. Mavor, R. K. Morcom, C.B.E., M.A., E. S. New, M. J. Railing, A. E. Tanner, A. Vines, and E. B. Wedmore).

National Certificates and Diplomas in Electrical Engineering (England and Wales).

The undermentioned colleges have been approved under the scheme drawn up by the Board of Education and the Institution:—

Approved for Ordinary Grade Certificates (Senior Part-time Course).

Middlesbrough, Constantine Technical College.
Southall Technical Institute.
Treforest School of Mines.

Approved for Higher Grade Certificates (Advanced Part-time Course).

Derby Technical College.
Hull Municipal Technical College.
Leicester College of Technology.
Middlesbrough, Constantine Technical College.
Wolverton Technical College.

The Benevolent Fund.

On the last page of the cover of this issue of the *Journal* will be found particulars of certain publications, etc., which are on sale on behalf of the Benevolent Fund.

Proceedings of the Meter and Instrument Section.

8TH MEETING OF THE METER AND INSTRUMENT SECTION, 3RD JANUARY, 1930.

Mr. E. W. Hill, Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 6th December, 1929, were taken as read, and were confirmed and signed.

A paper by Messrs. J. G. Wellings, Associate Member, and C. G. Mayo, M.A., B.Sc., Graduate, entitled "Instrument Transformers" (see page 704), was read and discussed.

On the motion of the Chairman a vote of thanks to the authors was carried with acclamation, and the meeting terminated at 9.35 p.m.

9TH MEETING OF THE METER AND INSTRUMENT SECTION, 7TH FEBRUARY, 1930.

Mr. E. W. Hill, Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 3rd January, 1930, were taken as read, and were confirmed and signed.

A paper by Mr. G. F. Shotter, Associate Member, entitled "A New Null Method of Testing Instrument Transformers, and its Application" (see page 873), a paper by Messrs. R. S. J. Spilsbury, B.Sc., and A. H. M. Arnold, Ph.D., Associate Members, entitled "Some Accessory Apparatus for Precise Measurements of Alternating Current" (see page 889), and a paper by Mr. A. H. M. Arnold, Ph.D., Associate Member, entitled "Precision Testing of Current Transformers" (see page 898), were read and discussed.

On the motion of the Chairman a vote of thanks to the authors was carried with acclamation, and the meeting terminated at 9.35 p.m.

10TH MEETING OF THE METER AND INSTRUMENT SECTION, 7TH MARCH, 1930.

Mr. E. W. Hill, Chairman of the Section, took the chair at 7 p.m.

The Chairman having reported the death of Mr. C. H. W. Gerhardi, a member of the Committee, the members stood in silence as a mark of sympathy and esteem.

The minutes of the meeting held on the 7th February, 1930, were taken as read, and were confirmed and signed.

A paper by Messrs. A. E. Moore, M.Sc.Tech., Member, and W. T. Slater, M.Sc.Tech., Student, entitled "An Investigation of the Frequency Variations in Induction Watt-Hour Meters," was read and discussed.

The meeting terminated at 9.35 p.m. with a vote of thanks to the authors, which was moved by the Chairman and carried with acclamation.

Elections and Transfers of Members.

At the Ordinary Meeting held on the 10th April, 1930, the following elections and transfers were effected:—

ELECTIONS.

Member.

Home, Francis Wyville, Lieut.-Col. R. M.

Associate Members.

Aubrey, Lionel William, B.Sc.
Betts, Douglas.
Carne, William Alfred, B.Sc.(Eng.).
Clotworthy, Stanley Edward, B.Sc.(Eng.).
Edwards, Joseph James, B.Sc.(Eng.).
Hussain, Khateeb Mahmood, M.A.
MacCarthy, Arthur Felix.
MacKay, David Hymers, B.Sc.
Prado, Alberto.
Smith, John Arnold.
Tuck, William Douglas, B.Sc.(Eng.).
Withers, Arthur Sydney.

Associates.

Rolston, Frederick William.
Whelton, George Herbert.

Graduates.

Anderson, Frank Fitzgerald, B.Sc.(Eng.).
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THE JET-WAVE RECTIFIER: THE EXPERIMENTAL AND THEORETICAL BASIS OF ITS DESIGN.

By Professor JUL. HARTMANN, Dr.Tech., Member.

(*Paper first received* 26*th October,* 1928, *and in final form* 17*th April,* 1929; *read before* THE INSTITUTION 13*th February, and before the* NORTH MIDLAND CENTRE 11*th February,* 1930.)

SUMMARY.

The subject of this paper is the jet-wave rectifier, a purely mechanical device which, in the course of the last 15 years, has been developed into a means for high-power rectification. Prototypes of the constituent parts of the apparatus have been described elsewhere; in the present paper it is shown how the rectifier can be designed on the basis of these prototypes, and especially on the result of investigations with regard to the theoretical relations between their qualities. These relations are stated and are used in working out examples of typical designs. In addition, a review of the general properties of the jet-wave rectifier, and anticipations with regard to its future development, are given. It is concluded that a new high-capacity rectifier, of a character quite distinct from that of the mercury-arc rectifier, but likely to be used for similar duties, has been brought into existence.

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(1) PRINCIPLE OF THE JET-WAVE COMMUTATOR AND RECTIFIER.

The following is a review of the experimental and theoretical results upon which the design of the new mechanical rectifier for high powers, namely, the jet-wave rectifier, is based. The principle and the constructional development of this rectifier have already been described in previous papers,* and it is therefore thought to be unnecessary to discuss them in detail in the present paper. It may not, however, prove inappropriate to compare briefly the entirely new principle of the jet-wave commutator—the main constituent of the jet-wave rectifier—with the well-known principles of mechanical synchronous commutation. This is done in Fig. 1, in which (*a*) represents the well-known oscillatory principle and (*b*) the rotary principle. The principle of the new commutator may be termed the translatory principle, its moving member being a wave-shaped conductor J which travels with constant velocity, disappearing into the electrodes E_1 and E_2 and alternately connecting the two sides of the same with a special tapping electrode E. It is explained in the papers referred to how the wave-shaped conductor may be produced from a mercury jet through interaction between a constant field F, Fig. 2, and an auxiliary alternating current supplied by an auxiliary transformer V_A. It is highly essential for the proper understanding of the *modus operandi* of the commutator to note that the jet wave produced moves on as a whole

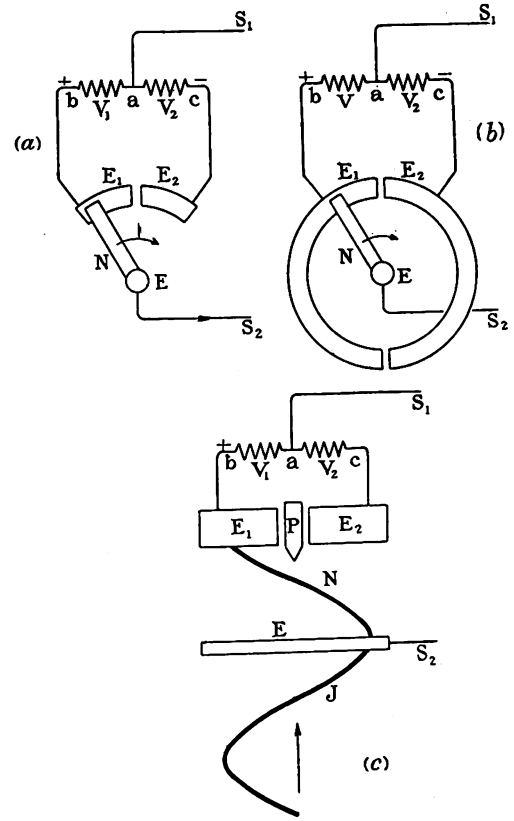

FIG. 1.

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* J. HARTMANN: "Development of the Jet-Wave Rectifier," Paper read before Section G of the British Association at Leeds, *Engineering*, 1927, vol. 124, pp. 338 and 377; J. HARTMANN: "Den konstruktive Udvikling af Straalebolgeensretteren, *Elektroteknikeren*, 1927, vol. 23, p. 541; O. A. GÜNTHERSCHULZE: "Die konstruktive Durchbildung des Quecksilber-Wellenstrahl-Gleichrichters," *Elektrotechnische Zeitschrift*, 1928, vol. 49, p. 1224; J. HARTMANN: "The Jet Wave," *Det kgl. danske Videnskabernes Selskabs Meddelelser*, 1929, vol. 9, p. 2.

with the velocity v of the original jet, each particle of the wave following a straight line through the centre of the field. If the wave is to be used for the rectification of an alternating voltage as indicated in Fig. 2,* it must advance half a wavelength ($\frac{1}{2}\lambda$) during half a period ($\frac{1}{2}$T) of the alternating voltage. This is achieved by utilizing a current synchronous with the voltage to be rectified for producing the wave. Furthermore, the cutting of the wave by the knife P should be effected at a definite point in the voltage wave, generally at the zero-point of the voltage. This may be brought about by adjusting the distance from the field to the electrode E_1E_2. The feature which makes the wave principle superior to the oscillatory and rotary principles [see Fig. 1 (*a*) and (*b*)] is the absolutely stiff coupling between the voltage to be rectified and the motion which effects the rectification, i.e. the motion of the "hitting-point" of the wave in E_1E_2.

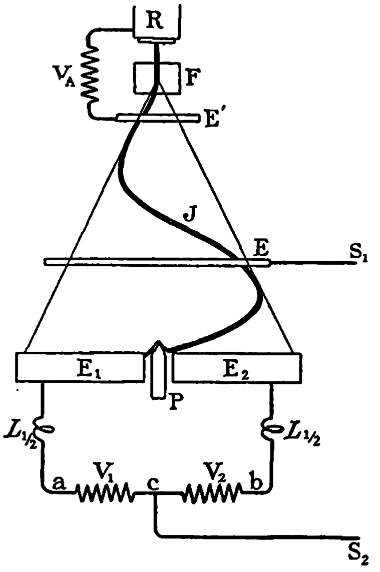

FIG. 2.

Rectification of multi-phase voltages may be effected in several ways by means of jet-wave commutators of the type shown in Fig. 2, or by other similar commutators. The rectifier which has so far been almost exclusively produced and studied is the 6-phase series type, which simply consists of three commutators similar to that in Fig. 2 connected to the 3 secondary phases of a 3-phase transformer, the three 2-phase rectifiers thus formed being connected in series. The resultant rectified voltage exhibits the ordinary 6 ripples per period, and the d.c. component is approximately 0·95 E_0, E_0 being the maximum value of the phase voltage of the transformer secondary.

(2) THE JET.

As the position of the main electrode, E_1E_2 in Fig. 2, depends on the velocity of the jet, this velocity must be kept constant within very fine limits, say within a few tenths of 1 per cent. The jet is therefore produced by means of a reservoir and a jet pipe, the level of the mercury in the former being kept constant by means of an overflow. For the constructional details of the jet-producing system, especially the means for electrically separating the jet from the pump and the commutation chamber (i.e. the so-called "drop separator"), reference should be made to the papers mentioned earlier. Here, only the essential properties of the jet will be considered.

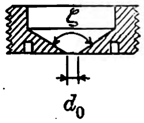

FIG. 3.

These properties are, first, the mass m per cm of the jet, and secondly, its velocity v. The former is determined by the equation

$$m = \rho(\tfrac{1}{4}\pi d^2) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

ρ being the density of the mercury and d the diameter of the jet. With the obtuse conical bore shown in Fig. 3, which is the standard form of the nozzle, the diameter of the jet, d, is determined by

$$d = c_c d_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where d_0 is the diameter of the bore and c_c the coefficient of contraction. The variation of the latter with the apex angle of the bore, ζ, may be derived from Fig. 4, which shows the percentage contraction. With the standard apex angle of 120° the contraction is 15 per cent. The velocity v of the jet may in all practical cases be calculated from the simple Torricelli expression

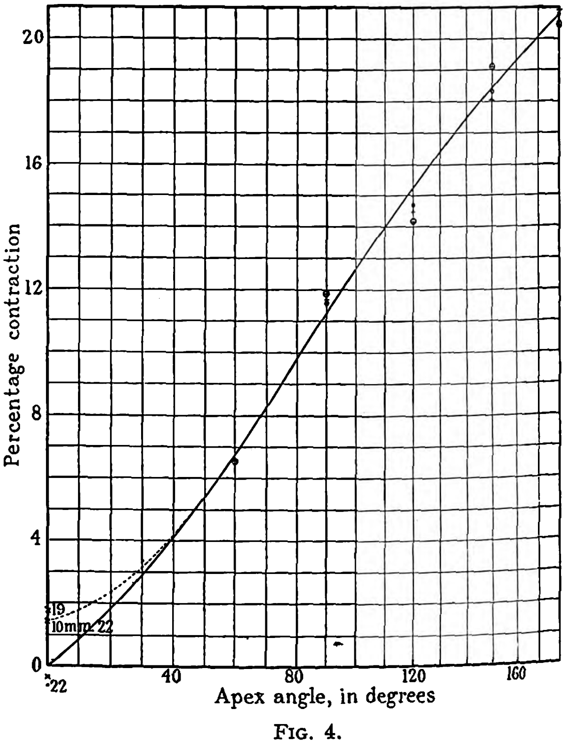

FIG. 4.

$$v = \sqrt{(2gh)} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

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* The function of the coils marked $L_{\frac{1}{2}}$ is explained in Section (9).

with an accuracy within, say, 1 to 2 per cent. The figures given in Table 1 for the percentage difference between the theoretical velocity v_t derived from expression (3) and the actual velocity v_a, which was about 6 metres per sec., were obtained with the same bores as the curve in Fig. 4.

TABLE 1.

ζ	60°	90°	120°	150°	180°
$\frac{v_t - v_a}{v_t} \times 100$	+ 0·9	− 0·05	− 0·6	− 0·3	+ 0·2

The constancy of the characteristics m and v of a jet produced by a standard nozzle is seen from Table 2, which contains repeated observations of the quantity emitted per sec. and the corresponding momentum.

TABLE 2.

Fluctuation of a Mercury Jet.

$d_0 = 3{\cdot}555$ mm, $\phi = 120°$, $v = 605$ cm per sec.

Quantity emitted mv	Deviation from mean quantity	Momentum of jet $\frac{mv^2}{g}$	Deviation from mean momentum
g/sec.	g/sec.		
594·96	+ 0·62	374·64	+ 1·41
596·35	+ 2·01	375·28	+ 2·05
597·74	+ 3·40	375·44	+ 2·21
591·83	− 2·51	375·29	+ 2·06
592·98	− 1·36	371·76	− 1·47
592·16	− 2·18	373·15	− 0·08
		375·57	+ 2·34
594·34		373·13	− 0·10
Maximum deviation from mean: 0·57 per cent.		373·13	− 0·10
		372·69	− 0·54
		371·61	− 1·62
		369·55	− 3·68
		370·70	− 2·53
		373·23	
		Maximum deviation from mean: 0·99 per cent.	

It follows from the figures in the table that the fluctuation in velocity cannot be greater than 0·6 per cent and is probably somewhat smaller. It may be noted that at the present time 6 metres per sec. represents the maximum velocity employed in jet-wave commutators, and that the percentage fluctuation generally diminishes somewhat with decreasing velocity. Nozzles with cylindrical bores or with conical bores of small apex angle cannot be used because the velocity exhibits sudden changes due to corresponding changes in the adhesion between the mercury and the walls of the bore.

(3) THE COMPLETE HYDRODYNAMIC CIRCUIT.

The maintenance of the jet requires a hydrodynamic circuit with a pump: a diagram of this circuit is given in Fig. 5. After being used in the jet wave, the mercury flows to the centrifugal pump P through the pit R_2 and the pipe T_4. The pump raises the mercury through the pressure pipe T_2 to the main reservoir R_1 with the drop separator D_1. The overflow T_3 opens into a container R_3, the bottom reservoir, which communicates with T_4 and serves to store the mercury from the upper part of the circuit when the rectifier is not working.

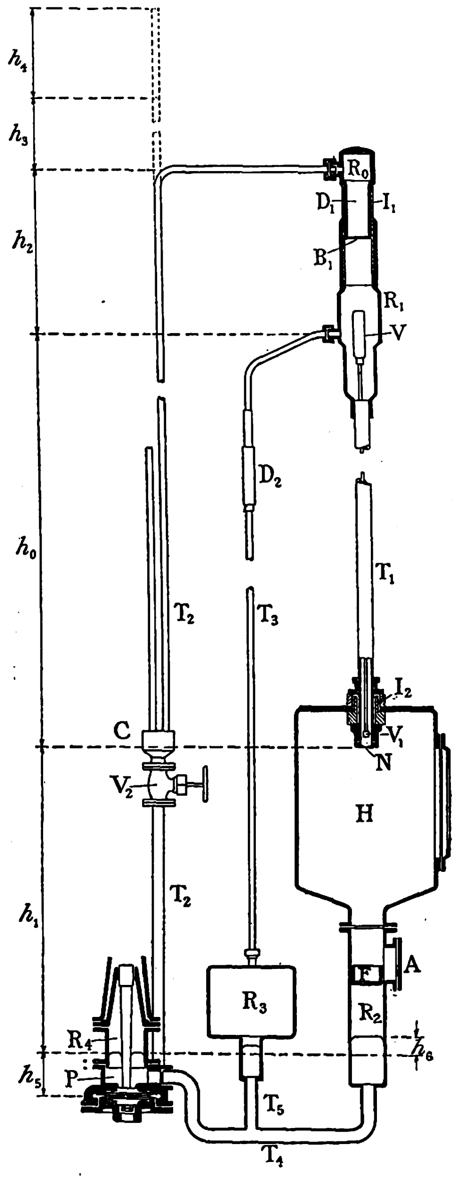

FIG. 5.

In the design of the hydrodynamic circuit two problems arise; first, the limiting velocities in the various parts of the circuit, and secondly, the permissible pressure-drop in the pipes.

With regard to the former, it should be noted that special care must be taken in the dimensioning of the members R_1, R_2, and R_4. If the velocity in the main reservoir be too great, air may be drawn down into the commutation chamber. This would be detrimental for two reasons. In the first instance an air bubble in the jet may cause the latter to break down, which again may cause the auxiliary electrodes E and E′ (Fig. 2) to be impaired. In the second instance the air will mix with the hydrogen (see Section 15) in the commutation chamber and, if the pump is running for any length of time with the rectifier disconnected from the transformer, may give rise to an explosion when commutation is again started. During commutation the oxygen of the air will combine with hydrogen to form water vapour, which will cause corrosion of the steel walls, etc., of the chamber. Again, if the velocity in the pit exceeds a certain limit hydrogen may be drawn out of the chamber and the consumption of this gas be thus increased. Finally, if the downward velocity in the space above the rotor of the centrifugal pump is too great air may be drawn into the rotor, causing irregular pumping. It has been found that the velocities in R_1, R_2, and R_4 should be kept below 10 cm per sec., and that the height of mercury above the bottom of the reservoirs should generally not be less than from 6 to 10 cm. In T_1 velocities up to 50 cm per sec. may be allowed. In T_4 a velocity of from 50 to 75 cm per sec. or even more is considered safe, and in T_2 the velocity is generally chosen at 150 cm per sec. It is essential to ensure a regular distribution of the flow to the surfaces in R_1 and R_2. With R_1 the drop separator solves the problem, while with R_2 a filter F serves as distributor.

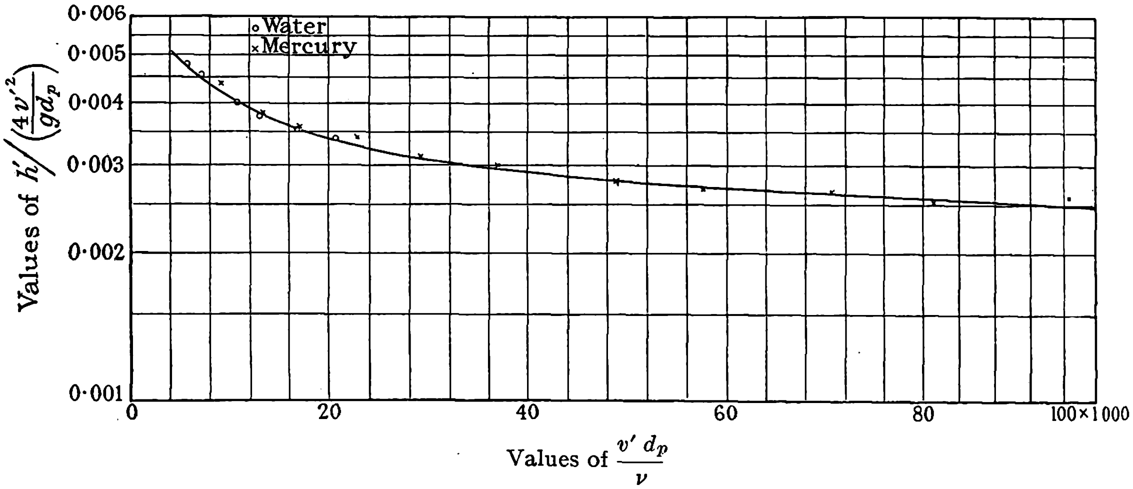

FIG. 6.

TABLE 3.

Temperature	Values of ν
C.	C.G.S. units
0°	0·00125
20°	0·00116
40°	0·00108
60°	0·00102
80°	0·00096
100°	0·00091
120°	0·00087

In order to elucidate the question of the pressure loss in the pipes, an investigation of the flow of mercury through steel pipes was undertaken,* and it was proved that the pressure-drop can be calculated by means of the expression

$$h' = \frac{4v'^2}{d_p g} f\left(\frac{v'd_p}{\nu}\right) \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where h' = pressure-drop per cm of the pipe, in cm of mercury,
v' = mean velocity over the cross-section of the pipe, in cm per sec.,
d_p = diameter of the pipe, in cm,
g = acceleration due to gravity, in cm per sec².,
ν = dynamic viscosity of mercury, in C.G.S. units,

and $f(v'd_p/\nu)$ = Osborne Reynolds's function.

The function $f(v'd_p/\nu)$ found from the investigation is shown graphically in Fig. 6. It is the same for water and for mercury, as might be expected from the law of similarity set forth by Osborne Reynolds. Values of ν corresponding to a series of temperatures are given in Table 3.

(4) The Pump and the Pump Loss.

The pump is a centrifugal pump and is ordinarily operated by an induction motor. The axis of the rotor passes freely down into the pump chamber R_4 (Fig. 5), and thus no stuffing box is provided. The efficiency of the pump aggregate is of great importance in the question of economy of the rectifier. From tests on various plants it has been proved that the highest efficiency is obtained with comparatively low-speed pumps. Hence in 6-phase rectifier plants of 50 periods a 1 400-r.p.m. induction motor is to be preferred to one of twice that speed. In Fig. 7, characteristic curves for a standard

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* "A Comparison between the Flow of Water and Mercury, etc.," *Mémoires de l'Académie Royal des Sciences et Lettres de Danemark, Copenhagen. Section des Sciences*, 1926, 8th series, vol. 10, No. 5.

1 400-r.p.m. pump are reproduced. The pump was designed for raising 1 200 cm^3 per sec. through a distance of 3·5 metres. The upper curve represents the available pressure h measured in cm of mercury. It is seen that at 1 200 cm^3 a head of 6 metres is available to cover the 3·5-metres pressure-drop in the pressure pipe and a necessary additional excess pressure. Furthermore, it is seen that the efficiency η_p of the pump proper amounts to about 36 per cent, while the efficiency η_a of the complete pump aggregate is nearly 30 per cent at full load. In larger pumps it is likely that efficiencies well above 30 per cent may be obtained, but the latter figure is now generally used in estimates of the efficiencies of rectifiers under design.

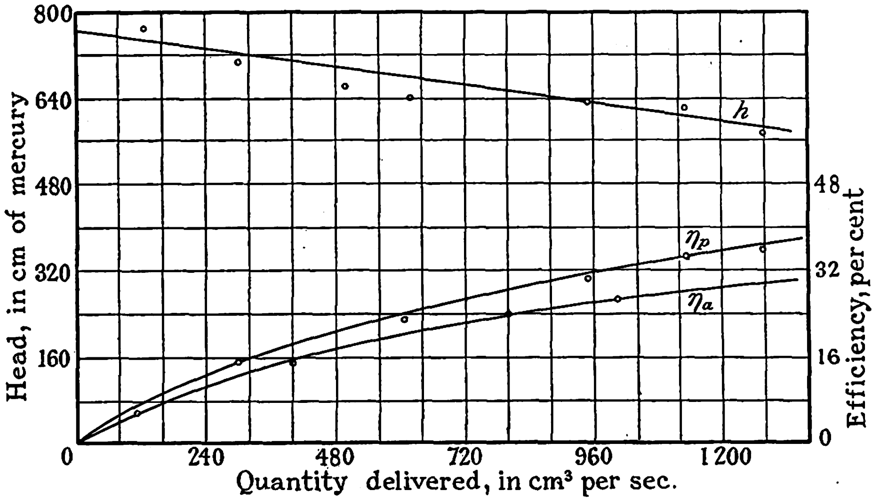

FIG. 7.

On the basis of the experimental facts now stated the power necessary for the maintenance of the jet can be calculated. The head for which the pump must be designed is indicated in Fig. 5, and comprises the heads, h_0, h_1, h_2, h_3 and h_4. Of these, h_3 denotes the excess pressure which is thought necessary to produce a well-defined flow through a nozzle inserted in T$_2$ at the entrance to the top reservoir R$_0$; while h_4 stands for the pressure-drop in the tube T$_2$ which is calculated on the basis of Fig. 6. In Table 4 two commutators with jets of 5 and 6 metres per sec. velocity respectively, and with a diameter $d = 4$ mm, are considered. V indicates the volume per sec. carried by a jet. To this volume 10 per cent is added in order to take into account the flow through the overflow T$_3$, Fig. 5. Q is the quantity in kg per sec. A density of 13·4 is assumed for the mercury, corresponding to a stationary temperature of about 80° C. The height h_0 is calculated from Torricelli's law,

$$v = \sqrt{(2gh_0)} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The sum $(h_1 + h_2)$ is taken from actual constructions. Under A_{net} the work per sec. found from

$$A_{net} = Qh_r . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

is stated, while A_a is the actual work per sec. based on the assumption of an efficiency of 30 per cent for the pump aggregate.

TABLE 4.

Pump Loss. $d = 4$ *mm,* $\eta_a = 30$ *per cent.*

Velocity v	Volume pumped $V + 0{\cdot}1V$	Quantity pumped Q	Pressure head					Work done		
			h_0	$h_1 + h_2$	h_4	h_3	$\Sigma h = h_r$	Actual $A_{net} = Qh_r$	Calculated $A_a = A_{net}/0{\cdot}3$	
m/sec.	cm³/sec.	kg/sec.	m	m	m	m	m	kg-m/sec.	kg-m/sec.	watts
5	69·3	0·927	1·27	1·23	0·5	0·75	3·75	3·48	11·6	114
6	83·2	1·115	1·84	1·56	0·5	0·75	4·65	5·18	17·3	170

The two jets referred to are at the present time considered suitable in the following commutators:

Commutator I: 20 kW, 75 volts, $d = 4{\cdot}0$ mm, $v = 5$ m per sec.

Commutator II: 33·3 kW, 180 volts, $d = 4{\cdot}0$ mm, $v = 6$ m per sec.

It is seen from Table 4 that the percentage pump loss with the 20-kW, 75-volt commutator is 0·57 per cent, and with the 33·3-kW, 180-volt commutator 0·51 per cent of the normal load. The two commutators specified will serve as examples throughout the paper.

In a 200-kW, 550-volt rectifier with 6 jets of 3·8 mm diameter and velocity 6 metres per sec. the total amount of mercury raised per sec. was 450 cm^3, or per jet per sec. 75 cm^3, representing 1 kg. The pump aggregate corresponding to Fig. 7 was employed. Its efficiency is only 17 per cent at 450 cm^3 per sec. Its pressure head is about 7·0 metres, of which the excess was absorbed in a valve. The power absorbed by the pump motor should accordingly be (1 × 7·0 × 100/17) kg-m = 41·0 kg-m, or 402 watts; or, again, (402/33 000) × 100 = 1·2 per cent with the jet used in a 33·3-kW, 180-volt commutator. Actually it was found that the pump consumed 2·86 kW, or 476 watts per jet, equivalent to a loss of 1·4 per cent. The slight difference between the actual value and that derived from the characteristics of the pump is probably due to the amount of mercury passing the overflow being somewhat larger than that assumed. Otherwise the example shows that the pump loss may be calculated with fair accuracy on the basis of the pump characteristics. The value of 0·51 per cent found above may therefore be relied on as the actual loss with a suitably chosen pump. The pump employed in the rectifier of the example was, as a matter of fact, originally designed for a rectifier with jets of velocity 7 metres per sec. and a total capacity of 1 200 cm^3 per sec. Hence the abnormally low efficiency of the pump.

(5) THE MAGNET AND THE MAGNET LOSS.

The jet wave is now almost always produced by means of a constant field in interaction with a synchronous alternating current passed through the jet as indicated in Fig. 2. For the production of this field an electromagnet is generally employed, the coils of which are kept outside the chamber in which commutation takes place, the limbs being carried through the top of the chamber and insulated from the top plate. The current for excitating the magnet is generally taken from a d.c. source, if available; otherwise the magnet is fed from a small d.c. generator which may be coupled to the axis of the a.c. motor operating the pump. With the coils taken outside the commutation chamber the latter need no longer contain any material which may be attacked by mercury (e.g. copper) or damaged by heat (e.g. cotton). Hence a considerable temperature can be tolerated in the chamber, say 100° C. or more, and artificial cooling of the chamber may in many cases be avoided. With a chamber of ordinary cast iron the intensity of the magnet field is reduced considerably by the magnetic flux straying to the top plate. The latter, or alternatively the whole chamber, should therefore be constructed of non-magnetic cast iron. It may be noted that magnets with coils enclosed in air-tight boxes of non-magnetic cast iron may be mounted wholly inside the chamber. The construction is, however, objectionable on account of the poor cooling of the coils. A good many types of magnets other than that indicated above have been tested. The pattern here described is, however, found to be the best suited to the purpose, especially as it leaves the space beneath the pole-pieces free for the mounting of the various electrodes of the commutator and for the easy inspection of the wave.

The characteristics of the magnetic field are its intensity *H*, its width *b* and its length *l*, i.e. its extension in the direction of the jet. The greater *H* the less is the auxiliary current necessary for the production of a given amplitude. For this reason it is desirable that the magnet should be built with as high an intensity as is consistent with a reasonable size of magnet. In Fig. 8, characteristic curves of a magnet of normal design are reproduced. With single-jet commutators field intensities of from 5 000 to 7 500 gauss are generally found convenient.

The width of the field-gap is, of course, determined by the diameter *d* of the jet, and with large commutators (d = 3 to 4 mm) is about 2 mm greater than *d*.

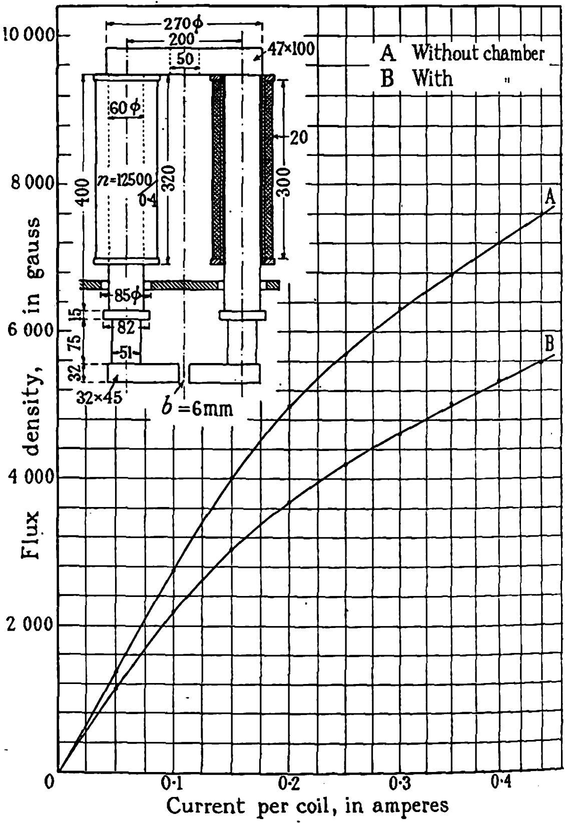

FIG. 8.

It is shown in the theory of the jet wave (see below) that the amplitude is proportional to sin $(\pi l/\lambda)$ provided the field is homogeneous. Thus a field of length $\frac{1}{2}\lambda$ would give maximum amplitude. Actually it does not pay to employ a field of this length; first, because of the very nature of the sine relationship, and secondly, on account of the field not being homogeneous. The actual shape of the field is generally as shown in Fig. 9, extending beyond the boundaries of the pole-piece. Such a field, as shown in the theory of the jet wave, is equivalent to a homogeneous field with the maximum intensity of the actual field and of a length somewhat greater than the height of the pole-piece. The "effective length of the field" may therefore be written

$$l_e = l + l'$$

where l' is roughly equal to the width b of the field. Under these circumstances l is generally $0 \cdot 3\lambda$ or somewhat less. Magnets of the type shown in Fig. 8 have been carefully studied in order to produce a safe basis for their design. From characteristics of the type shown in Fig. 8 it is known how many ampere-turns are necessary for the production of a field of given dimensions and intensity. From investigations on the variation of the flux round the magnetic circuit of the magnet the dimensions of the various members of the circuit are derived. In the design of the coils the number of ampere-turns and the interior diameter of the coils can therefore be considered as given. The voltage to be applied to each coil is, as a rule, predetermined. The problem is to design the coil in such a way that its stationary temperature does not exceed a certain limit.

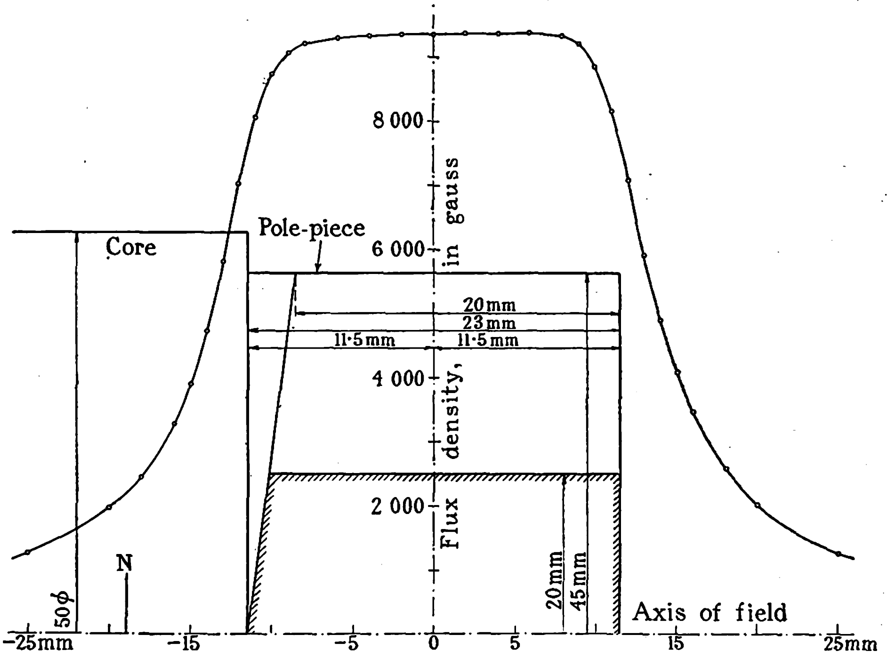

FIG. 9.

It would take too long to give the complete theory for the design of the magnet coils, and hence only a brief account of the investigations on which the determination of the heating of a coil is based will be given. In the stationary state it is assumed that the heat q resulting from the flow of a current i_s is carried away solely through the external cylindrical surface a_c of the coil. Now

$$q = \frac{ei_s}{4 \cdot 19} \text{ g-cal. per sec.} \quad . \quad . \quad . \quad . \quad (7)$$

where e is the voltage across the coil. The heat transmitted through a_c may be written

$$q = ca_c(T_s - T_u) \text{ g-cal. per sec.} \quad . \quad . \quad (8)$$

where T_s is the stationary temperature of the coil, while T_u is the temperature of the surroundings and c is a constant. The quantity $(T_s - T_u)$ may be determined for a given coil by measuring its resistances r_s and r_u corresponding to the temperatures T_s and T_u respectively, for

$$r_s = r_u\left\{1 + a_u(T_s - T_u)\right\} \quad . \quad . \quad . \quad (9)$$

where the temperature coefficient a_u may be expressed by

$$\frac{1}{a_u} = 235 + T_u \quad . \quad . \quad . \quad . \quad (10)$$

From equations (7) to (10) the formula

$$c = \frac{ei_s}{4 \cdot 19 a_c} \times \frac{235 + T_u}{(i_u/i_s) - 1} \quad . \quad . \quad . \quad (11)$$

is derived, where i_s and i_u are the currents which the constant voltage e will send through the coil when the latter has the resistances r_s and r_u respectively. The currents are introduced instead of r_s and r_u, the relation $(i_u/i_s) = (r_s/r_u)$ connecting the two sets of quantities.

An experimental investigation was carried out with the object of determining c for a series of coils with the same interior diameter and the same amount of wire but with different lengths l_s of the coil and with a correspondingly different number of layers. The results are given in Fig. 10. The abscissa is the power in watts, P', dissipated per cm^2 of the exterior cylindrical surface. It will be seen that c [calculated from equation (11)] is independent of the depth b_s of the winding space and is a linear function of P'. The symbols used in the figure have the following meanings: d_w = diameter of copper core of the wire, 2δ = thickness of the insulation (double cotton-covered), d_c = internal diameter of coil. The investigation was supplemented by measurement of c for a coil wound with $0 \cdot 40$-mm wire ($0 \cdot 60$ mm over covering) on a tube with a diameter $d_e = 6 \cdot 8$ cm. The value for c agrees almost exactly with that predicted from the main investigation. From the curves in Fig. 10 the following formulæ are derived:

$$c = (2\cdot 2 + 8\cdot 0P')10^{-4} \text{ (g-cal., sec., °C., cm}^2\text{, watts)} \quad (12)$$

$$T_s - T_u = \frac{P'}{4\cdot 19(2\cdot 2 + 8\cdot 0P') \,.\, 10^{-4}} \quad . \quad (13)$$

In order to convey an idea of the power necessary for the maintenance of the field, we shall consider a magnet of the type indicated in Fig. 8. The magnet, with the pole-pieces indicated in Fig. 8, is of the size employed in a 33·3-kW, 180-volt commutator with a jet of 3·8 to 4·0 mm diameter and a velocity of 6 m per sec. From curve A in Fig. 8 it is seen that the production of a field of 7 500 gauss requires about 11 200 ampere-turns. Coils for such a magnet with a 60-mm diameter iron core and an internal diameter of windings $d_c = 68$ mm were calculated. It was assumed that $T_u = 30°$ C. and that a temperature T_s of 90° C. could be allowed. Two cases were considered, namely, $e = 36\frac{2}{3}$ volts and $e = 110$ volts.

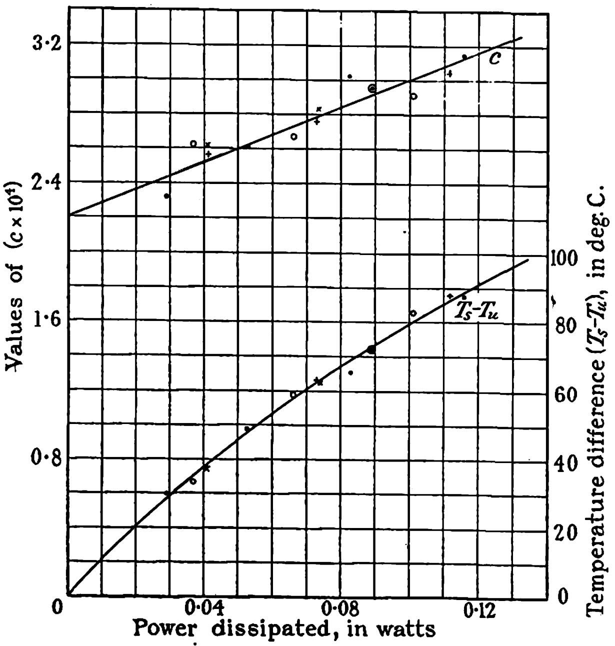

Fig. 10.

Key.

	Number of layers	b_s	l_s	d_w	2δ	d_c
		cm	cm	cm	cm	cm
●	9	1·23	42·4	0·12	0·02	9·15
+	13	1·65	27·9			
o	17	2·17	24·0			
×	21	2·73	19·0			
⊙	26	1·6	30·0	0·04	0·02	6·8

With $e = 36\frac{2}{3}$ volts the diameter d_w of the core of the wire was 1·10 mm. With double cotton covering the overall diameter d' of the wire is then 1·30 mm. The following quantities can now be calculated:

Depth of winding space, $b_s = 1\cdot 90$ cm $(d_c + 2b_s = 10\cdot 60$ cm).
Length of winding space, $l_s = 28\cdot 5$ cm.
Power consumed per coil, $P_s = 65\cdot 5$ watts, or per magnet, 131 watts.
Number of turns per coil, $N = 3\,135$.
Total length of wire per coil, $l_w \doteq 858$ m.
Total weight of copper per coil, $w = 7\cdot 26$ kg.

With $e = 110$ volts, d_w was taken as 0·65 mm, and the following figures were obtained:

$b_s = 2\cdot 32$ cm $(d_c + 2b_s = 11\cdot 44$ cm).
$l_s = 28\cdot 1$ cm.
$P_s = 69\cdot 5$ watts per coil, or 139 watts per magnet.
$N = 8\,860$.
$l_w = 2\,540$ m.
$w = 7\cdot 50$ kg.

Used with commutator No. II [Section (4)] the percentage loss with the 110-volt magnet is thus

$$\frac{139 \times 100}{33\cdot 3 \times 1\,000} = 0\cdot 42 \text{ per cent.}$$

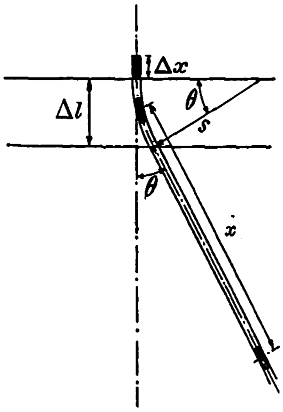

Fig. 11.

With commutator No. I [Section (4)] the loss is 0·70 per cent.

(6) Theory of the Amplitude of the Jet Wave.

We shall now show how, in a very simple way, an expression may be derived from which the excitation current necessary for the production of a jet wave of given characteristics may be obtained.

In the development of this expression we shall assume the wave to be produced by means of a current

$$i = I \sin \omega t = I \sin (2\pi t/\mathrm{T}) \quad . \quad . \quad . \quad (14)$$

We shall assume the separate particles (Fig. 11) of the jet and the wave to move quite independently of each other. We shall also suppose the field to be homogeneous. Finally, we shall in the first instance imagine the field as laminar, i.e. of an extension Δl in the direction of the jet so short compared with the wavelength that practically no change takes place in the value of the current i during the passage of a particle Δx of the jet.

The particle which passes the field at the moment t_0 experiences a mechanical force which is perpendicular to the direction of its motion and to the lines of force of the field. The force is expressed by

$$F = \tfrac{1}{10}\,\Delta x\,.\,HI \sin \omega t_0 \text{ (dynes, cm, gauss, amperes)} \tag{15}$$

H being the intensity of the magnetic field.

Under the influence of this force the particle will move along a circle the radius s of which is given by

$$(m\,.\,\Delta x\,.\,v^2/s) = F \quad . \quad . \quad . \quad . \tag{16}$$

m being the mass per cm of the jet, and v the velocity of the particle, which is that of the jet. After having passed the field with unaltered velocity v, the force being all the time perpendicular to the path, the particle will follow the tangent to the last point of the circular path, i.e. a straight line. As seen from Fig. 11, the direction of the straight path is given by

$$\sin\theta = \Delta l/s \quad . \quad . \quad . \quad . \quad . \tag{17}$$

Introducing $(1/s)$ as determined by equations (15) and (16):

$$\sin\theta = \tfrac{1}{10}(HI/mv^2)\Delta l\,.\,\sin\omega t_0 \quad . \quad . \tag{18}$$

This is the expression for the path of the particular particle. At the time $t > t_0$ we shall find the particle at a distance x from the field, say the centre of the latter, given by

$$x = v(t - t_0) \quad . \quad . \quad . \quad . \quad . \quad . \tag{19}$$

From equations (18) and (19) we finally obtain the expression for the jet wave proper by eliminating t_0. We find

$$\sin\theta = \tfrac{1}{10}(HI/mv^2)\Delta l\,.\,\sin\left[\omega\left\{t - (x/v)\right\}\right] \quad . \tag{20}$$

from which it is seen that the wave as a whole travels on with the velocity v of the jet and that its amplitude increases in proportion to the distance from the field.

Now, as a matter of fact, the fields employed in the actual jet-wave commutators are not short compared with the wavelength. As seen above they may amount to $0{\cdot}3\lambda$. It can be proved that with such fields the shape of the wave, and especially its amplitude, may be fairly accurately determined in the following way. In the first instance it is assumed that the wave will be nearly the same as would be produced if the exciting current were constant during the passage of each particle and equal to the mean value of the actual current during the passage. Furthermore, in calculating the mean value the time taken for the passage is assumed to be l/v, that is, equal to the time required for a particle of the original jet to pass the field. This mean value for the particle which at the moment t_0 passes the middle of the field is determined by

$$I_m = \frac{1}{\gamma T/2}\cdot\int_{t_0-\gamma T/4}^{t_0+\gamma T/4} I\sin\omega t\,.\,dt = \frac{\sin(\gamma\pi/2)}{\gamma\pi/2} I\sin\omega t_0 \tag{21}$$

where γ is the length of the field measured with half a wavelength $(\frac{1}{2}\lambda)$ as unit; thus $\gamma = l/(\frac{1}{2}\lambda)$. From what has been said above it is now at once seen that the deflection of the particle in question is given by

$$\sin\theta = \tfrac{1}{10}(HI/mv^2)l\,\frac{\sin(\gamma\pi/2)}{\gamma\pi/2}\sin\omega t_0 \quad . \tag{22}$$

and that the equation of the jet wave at the moment t is

$$\sin\theta = \tfrac{1}{10}(HI/mv^2)l\,\frac{\sin(\gamma\pi/2)}{\gamma\pi/2}\sin\left[\omega\left\{t - (x/v)\right\}\right] \tag{23}$$

x indicating the distance from the centre of the field to the point considered. Denoting the angular amplitude of the wave by θ_m

$$\sin\theta_m = \tfrac{1}{10}(HI/mv^2)l\,\frac{\sin(\gamma\pi/2)}{\gamma\pi/2} \quad . \quad . \tag{24}$$

It was assumed that the field was homogeneous. As shown in Fig. 9, the actual field is not homogeneous. We shall take this fact into account by substituting for the actual length of the field the effective length of field l_e as defined earlier in the paper. This may easily be calculated from the curve representing the shape of the field. We thus obtain the expression

$$\sin\theta_m = \tfrac{1}{10}\,(HI/mv^2)l_e\,\frac{\sin(\gamma_e\pi/2)}{\gamma_e\pi/2} \quad . \quad . \tag{25}$$

where $\gamma_e = l_e/(\frac{1}{2}\lambda)$.

It was furthermore assumed that the various particles constituting the jet wave moved independently of each other. One might expect that this assumption would not be correct, owing to cohesion and viscosity in the jet. The effect of these qualities of the liquid would be a "damping" of the wave which could be taken into account by applying an inverse factor of damping f' to the right-hand side of equation (25), by writing

$$\sin\theta_m = \tfrac{1}{10}f'(HI/mv^2)l_e\,\frac{\sin(\gamma_e\pi/2)}{\gamma_e\pi/2} \quad . \tag{26}$$

It can be proved, however, that with the velocities generally used in jet-wave commutators the damping is practically zero, whence $f' = 1$.

In order to illustrate this, the results of an experimental test are reproduced in Table 5.

The figures in the table refer to 6 commutators in a 6-phase series twin rectifier. The head of the jets was 177 cm, from which, by Torricelli's formula, their velocity is found to be 590 cm per sec. The frequency of the exciting current was 50; thus the wavelength was $11{\cdot}8$ cm. The mass m per cm of the jet was calculated from the diameter d of the jet and from the density ρ of the mercury. The former was determined from the diameter d_0 of the bores and from the coefficients of contraction c_c found by special measurements. The density was assumed to be $13{\cdot}4$, corresponding to a stationary temperature of about 80° C. of the mercury during the test. The effective lengths of the fields were determined from the field curves of the magnets; in all cases l' was found to be very nearly $4{\cdot}9$ mm. Finally, it should be noted that a correction of $2{\cdot}7$ per cent is applied to the values in column 5, i.e. the values calculated from equation (25). This correction takes into account the fact that the particle in the outermost path, i.e. the path which determines the amplitude, inside the imaginary homogeneous field follows an approximately circular path and thus remains there for a time which is slightly longer (in the case considered $2{\cdot}7$ per cent longer) than if it had passed the field along the path of the original jet, as assumed in equation (25).

It is seen that the actual amplitude is not smaller but, on the contrary, about 2 per cent greater than the theoretical amplitude calculated from equation (25). This, in all probability, is due to the circumstance that v is assumed about 2 per cent too large when derived from Torricelli's law. This again means that m is assumed 2 per cent too small, mv^2 is 2 per cent too high, and finally $\sin \theta_m$ is 2 per cent too small. It will be appreciated that equation (25) gives the amplitude, or alternatively the current I necessary for the production of a given amplitude, with an error not exceeding about 1 or 2 per cent.

TABLE 5.

Commutator No.	Jet current I_A	Intensity of field H	Bore of jet-piece d_0	Coefficient of contraction c_c	$\sin \theta_m$ θ_m = angular amplitude of wave		Values of			Correction factor $f' = \left(\frac{\text{col. 9}}{\text{col. 6}}\right)$
							$\tan \theta_m$	θ_m	$\sin \theta_m$	
					Calculated	Corrected	Observed	From tables		
	1	2	3	4	5	6	7	8	9	10
	amps.	gauss	cm							
1	103	4 880	0·445	0·844	0·349	0·358	0·399	21° 43′	0·371	1·035
2	118	4 450	0·446	0·840	0·367	0·376	0·418	22° 42′	0·386	1·030
3	114	4 650	0·444	0·855	0·360	0·370	0·395	21° 33′	0·367	0·990
4	101	4 995	0·450	0·826	0·357	0·366	0·396	21° 36′	0·368	1·005
5	114·5	4 810	0·451	0·836	0·380	0·389	0·443	23° 54′	0·405	1·040
6	108	4 790	0·450	0·842	0·352	0·361	0·390	21° 21′	0·364	1·010
									Average	1·018

(7) RESISTANCE AND HEATING OF THE JET WAVE.

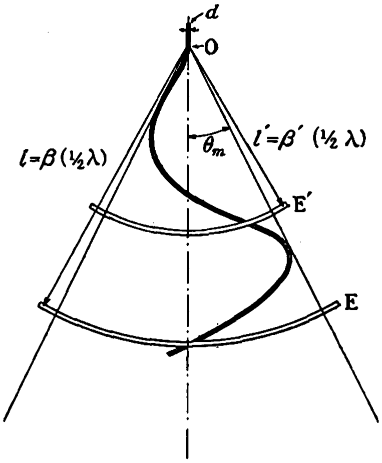
d
O
$l=\beta(\frac{1}{2}\lambda)$
θ_m
$l'=\beta'(\frac{1}{2}\lambda)$
E′
E

FIG. 12.

In the design of the commutator the resistance of the jet wave plays a great part. The resistance between the starting point, i.e. the centre O of the field (Fig. 12), and a circular electrode like E′, or the resistance between two such electrodes as E′ and E, varies periodically, though not quite harmonically, with twice the frequency of the alternating current by which the jet wave is produced. Now it has fortunately proved possible to obtain an explicit expression for the mean value, over a given period of time, of the resistance of the wave down to a circular electrode at the distance of $\beta(\frac{1}{2}\lambda)$ from the starting point. This expression is

$$k-1=\frac{\pi^2\beta^2(\sin\theta_m)^2}{6}\times\left(1+\frac{(\sin\theta_m)^2}{4}+\frac{(\sin\theta_m)^4}{8}+\frac{5}{64}(\sin\theta_m)^6+\ldots\right) \quad (27)$$

where k indicates the ratio of the mean resistance to the resistance of the corresponding length $\beta(\frac{1}{2}\lambda)$ of the original non-undulating jet. The resistance per cm of the jet in the case of mercury may be calculated as $\frac{0\cdot01}{(\pi/4)d^2}$ ohm at 80° C., d being the diameter of the jet in mm.

The resistance between two circular electrodes such as E′ and E is found by subtracting the resistance down to E′ from the resistance down to E.

In a jet carrying an electric current the temperature will rise from the point at which the current is introduced, say the nozzle, in the direction of the flow. An element of the jet will commence to heat up at the moment it enters the current-carrying portion of the jet, and it will go on heating up as long as it is traversing this portion. Its temperature must therefore increase steadily, which means that the temperature of the jet must rise in the direction of motion. The amount of heat dq stored up in the element Δx during the time dt is

$$dq = 0\cdot239\, I^2r'(\Delta x/a)dt \quad . \quad . \quad . \quad (28)$$

I being the current in amperes, r' the specific resistance of the liquid in ohms per cm³, and a the area of cross-section of the jet in cm². The corresponding rise of temperature $d\vartheta$ is given by

$$j\rho a\,.\,\Delta x\,.\,d\vartheta = 0\cdot239\, I^2r'(\Delta x/a)dt\,. \quad . \quad (29)$$

j being the specific heat and ρ the density of the liquid. During the interval dt the particle proceeds through the distance dx, where

$$dx = v \, . \, dt \quad . \quad . \quad . \quad . \quad . \quad (30)$$

v being the velocity of the jet in cm per sec. Hence the rise of temperature along a portion dx of the jet is

$$d\vartheta = 0 \cdot 239 \frac{r'}{j\rho} \cdot \frac{I^2}{va^2} dx \quad . \quad . \quad . \quad . \quad (31)$$

from which it follows that the temperature gradient (rise per cm) is

$$\dot{\vartheta} = 0 \cdot 239 \, . \, \frac{r'}{j\rho} \cdot \frac{I^2}{va^2} \quad . \quad . \quad . \quad . \quad (32)$$

With a mercury jet, $r' = (0 \cdot 958 \times 10^{-4})$, $j = 0 \cdot 033$, and $\rho = 13 \cdot 6$; hence

$$\dot{\vartheta} = (5 \cdot 10 \times 10^{-5}) I^2 / va^2$$
(deg. C. per cm, amperes, cm per sec., cm^2) (33)

Expression (31) takes no account of conductivity and the radiation of heat. Estimates of the effect of these factors show that in most cases they are practically insignificant. The formula has been tested experimentally and found to be correct within a few per cent. In order to form an idea of the heating we may consider a jet as used in a fairly large commutator, say a 30- to 40-kW commutator. With such a jet v may be 600 cm per sec., and d = diameter of jet = 0·4 cm. With these figures, $\dot{\vartheta} = (0 \cdot 540 \times 10^{-5}) I^2$. Hence with $I = 500$ amperes, $\dot{\vartheta} = 1 \cdot 35$ deg. C. per cm. If a length of 10 cm of the jet is carrying this current, the rise of temperature through the jet would thus be only 13·5 deg. C. With 1 000 amperes it would be $(4 \times 13 \cdot 5) = 54$ deg. C. A mercury jet is a conductor which will stand extremely high current densities. Thus with 1 000 amperes the density is (1 000/12·6) = 79 amperes per mm^2, and the portion of jet in question will obviously carry more than double that density before evaporation takes place.

It should be noted that the different particles of the wave suffer different heating when carrying a current. The particle following the axis of the wave undergoes the greatest rise of temperature. If with a non-undulating jet of length l_0 the latter rise is ϑ_0, the corresponding rise for the central particle of a wave produced from the jet-piece is $\vartheta_0 + \Delta\vartheta$, where

$$(\Delta\vartheta / \vartheta_0) = \tfrac{1}{3}\pi^2\beta^2\alpha'^2 \quad . \quad . \quad . \quad . \quad (34)$$

where $\beta = l_0 / \frac{1}{2}\lambda$ and $\alpha' = \sin\theta_m$. If a jet wave of wavelength 12 cm is produced from a jet-piece of length 10 cm, then $\beta = 1 \cdot 66$. With $\tan\theta_m = 0 \cdot 5$, $\sin\theta_m = 0 \cdot 447$ and $(\Delta\vartheta / \vartheta_0)$ becomes 1·83; hence the total heating is 2·83 times the heating of the non-undulating jet. With a current of 1 000 amperes the rise of temperature in the axial particles thus becomes $(2 \cdot 83 \times 54) = 153$ deg. C.

(8) THE AUXILIARY-CURRENT LOSS.

On the basis of the theory given above we are now able to calculate the current which, with a given jet, is necessary to produce a wave of given amplitude. Fig. 13 is a diagram of the upper part of the jet-wave commutator with the nozzle N, the field F and the auxiliary-current electrode E′. The latter is of the "curry-comb" type, a description of which is given in Section (12). It touches the wave along a circle the centre of which lies at the mid-point O of the field, i.e. in the starting point of the wave. In the following we shall consider the two commutators I and II specified on page 949.

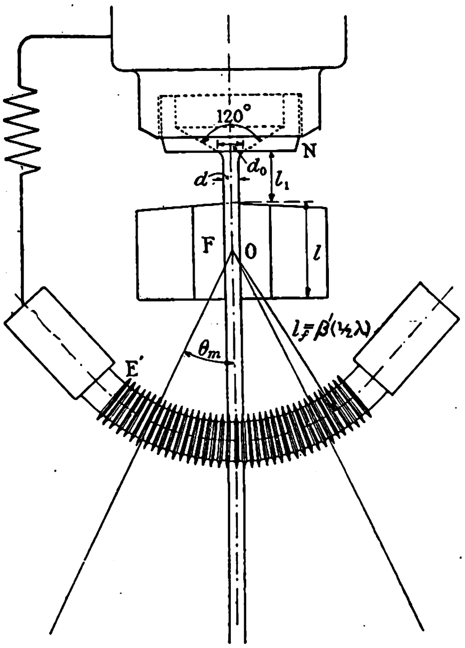

FIG. 13.

Commutator I: v = 5 metres per sec.:—

$d = 4$ mm, $\alpha' = \sin\theta_m = 0 \cdot 371$, $\frac{1}{2}\lambda = 5 \cdot 00$ cm,
$l_1 = 1 \cdot 0$ cm, $\gamma_e = 0 \cdot 5 (l_e = 2 \cdot 5$ cm),
$\beta' = l_f / (\frac{1}{2}\lambda) = 0 \cdot 8 (l_f = 4 \cdot 0$ cm), $H = 7\,500$ gauss.

Commutator II: v = 6 metres per sec.:—

$d = 4$ mm, $\alpha' = \sin\theta_m = 0 \cdot 447$, $\frac{1}{2}\lambda = 6 \cdot 00$ cm,
$l_1 = 1 \cdot 2$ cm, $\gamma_e = 0 \cdot 5$ ($l_e = 3 \cdot 0$ cm),
$\beta' = 0 \cdot 8$ ($l_f = 4 \cdot 8$ cm), $H = 7\,500$ gauss.

In both cases the mass m per cm of the jet is 1·69 g, and the resistance r per cm of the undeflected jet is $0 \cdot 810 \times 10^{-3}$ ohm, it being assumed that the density of mercury is 13·4 g per cm^3 and the specific resistance 1·017 ohm (m/mm^2), corresponding to a stationary temperature of the mercury of about 80° C. From equation (26), with $f' = 1$, the values $I = 92 \cdot 8$ amperes and 134·4 amperes are found for commutators I and II respectively. I indicates the maximum value of the auxiliary current. The effective value is obtained by dividing by $\sqrt{2}$. The effective auxiliary currents are therefore:

Commutator I: $I_{eff} = 65 \cdot 6$ amperes.
Commutator II: $I_{eff} = 95 \cdot 0$ amperes.

We now find the resistances of that part of the commutator carrying the auxiliary current. From equation (27) we find that $k - 1 = 0{\cdot}151$ and $k - 1 = 0{\cdot}223$ for the two commutators respectively.

The resistance from O to E′ is therefore:

Commutator I:
$(1{\cdot}151 \times 0{\cdot}810 \times 10^{-3} \times 4{\cdot}0) = 3{\cdot}73 \times 10^{-3}$ ohm.

Commutator II:
$(1{\cdot}223 \times 0{\cdot}810 \times 10^{-3} \times 4{\cdot}8) = 4{\cdot}75 \times 10^{-3}$ ohm.

The resistance from the nozzle to O is nearly:

Commutator I:
$(0{\cdot}810 \times 10^{-3} \times 2{\cdot}25) = 1{\cdot}82 \times 10^{-3}$ ohm.

Commutator II:
$(0{\cdot}810 \times 10^{-3} \times 2{\cdot}70) = 2{\cdot}19 \times 10^{-3}$ ohm,

the height l at the pole-piece being here identified with l_e.

Finally it is found that the contact resistance between the wave and the electrode E′ is about (4×10^{-3}) ohm, while the contact resistance between the mercury and the jet pipe through which the current is transmitted into the jet may amount to something like 10^{-3} ohm. The total resistance in the two cases is therefore about $10{\cdot}6 \times 10^{-3}$ and $12{\cdot}0 \times 10^{-3}$ ohm respectively. The power absorbed in the resistances becomes:

Commutator I: $(65{\cdot}6^2 \times 10{\cdot}6 \times 10^{-3}) = 45{\cdot}5$ watts.
Commutator II: $(95^2 \times 12{\cdot}0 \times 10^{-3}) = 108$ watts.

The first commutator serves as a 20-kW, 75-volt commutator in a 6-phase, 225-volt series rectifier, while the other is used as a 33·3-kW, 180-volt commutator in a 6-phase, 540-volt series rectifier. The percentage loss is thus:

Commutator I: $(100 \times 45{\cdot}5)/20\,000 = 0{\cdot}23$ per cent.
Commutator II: $(100 \times 108)/33\,300 = 0{\cdot}32$ per cent.

Finally, in order to take the loss in the auxiliary-current transformer and in the exterior connections into account we may increase these figures by, say, 20 per cent, thus giving the total auxiliary-current losses as

Commutator I: 0·3 per cent.
Commutator II: 0·4 per cent.

In a commutator very nearly similar to No. II, but with a jet of diameter 3·8 mm, it was found by direct measurement that the resistance in the auxiliary-current circuit was 13×10^{-3} ohm, in almost exact agreement with the above calculation.

(9) THE MAIN ELECTRODE. THE "WEARLESS" AND THE STABILIZED COMMUTATOR.

With the jet-wave commutator, commutation is accompanied by a transient arc. The latter originates from the stray fields of the transformer, the effect of these fields being in the main the same as that of two self-inductances $L_\frac{1}{2}$, inserted as indicated in Fig. 2. When the supply of the rectified current I_d is changed from, say, the left-hand to the right-hand side of the transformer, the energy stored in the left-hand inductance must be made to disappear, while an equivalent amount of energy must be produced in the right-hand inductance. The commutation spark is the direct consequence of this process, and has an important effect on the economical working of the jet-wave rectifier inasmuch as the electric energy which is transformed into heat in the spark generally represents the largest loss in the rectifier plant. On the other hand the spark has given rise to one of the main problems in the constructional development of the main electrode in that the latter, and especially the cutting device, must be capable of withstanding the corroding effect of the commutation spark. It had hitherto been considered almost impossible to solve this problem; nevertheless a complete and simple solution has been found.*

The solution consists in replacing the insulating wall P, indicated in Figs. 2 and 14 (*a*), by a knife W of conducting material, and preferably of high melting-point [Fig. 14 (*b*)]. A tungsten knife is generally employed. While with a cutting device like that of Fig. 14 (*a*) the spark occurs at the edge of the insulating wall, and so impairs the latter more or less, the spark with the tungsten knife almost always remains between the cut ends of the jet wave. It therefore only evaporates mercury which is presently again condensed in other parts of the system. With an ordinary high-power commutator for, say, 30 kW the height of the knife may be 5 mm and the width of its base about 3 mm. Such a knife will withstand the normal spark power, which may amount to 1 or 1·5 kW, for practically any length of time, and so a "wearless" commutator for mechanical rectification has been brought into existence.

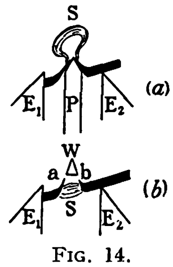

FIG. 14.

Immediately the cutting of the jet wave is completed two sparks are undoubtedly formed at "a" and "b." These sparks, however, unite almost instantly into one single spark as indicated in Fig. 14 (*b*). It has been found that if the normal spark of a large-power commutator is in some way or other forced to bridge over to the tungsten knife, then the latter is almost immediately destroyed by melting. On the other hand, it has been proved that with regular operation of the knife the latter will handle overloads of 50 or 100 per cent for considerable periods, and that it is not impaired by direct short-circuiting of the commutator.

With normal commutation the knife must be adjusted to such a position relatively to the two sides of the main electrode that these sides are short-circuited for a short time—the "interval of metallic short-circuiting" or the "overlapping interval"—during each commutation. Otherwise the circuit of the rectified current is obviously broken and a greatly increased spark loss ensues, especially if the circuit contains self-inductance. During the overlapping interval a short-circuit current i_c will generally grow up in the transformer, and this current will add to the normal rectified current I_d, thereby increasing the energy stored in the stray field and, hence, in the commutation spark. It will thus be gathered that for economical reasons it is essential to reduce i_c to as small a value as possible. Generally this is achieved by reducing the interval of overlapping but, on the other hand, this interval must not be made too small, for then the inevitable uncertainty of the process of cutting may too frequently change the overlapping into an interruption, with the effect of a heavy increase in the spark loss, especially at greater loads. Generally, however, the overlapping interval may be taken as low as 2 to 3 per cent of the half-period of the alternating voltage to be rectified. But even with such small values of the interval it has proved necessary, or advantageous, with large-capacity commutators to provide special means for reducing the short-circuit current i_c.

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* The information given in the remainder of this section has already appeared in the papers referred to in Section (1). As, however, recent experiences have thrown new light on the extremely important process of commutation, and as these experiences cannot be made intelligible without a fairly thorough representation of the facts in question, it would seem justifiable partially to re-state the latter.

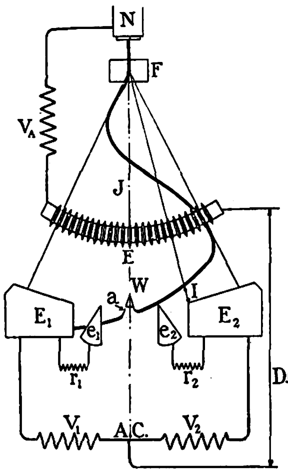


FIG. 15.

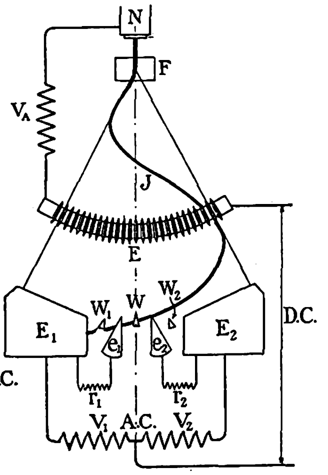


FIG. 16.

In this way the so-called "complex electrode" was introduced.

Fig. 15 represents such an electrode. Each of the two electrode sides now consists of two pieces, the main pieces E_1, E_2 and the secondary electrodes e_1, e_2. Between the two members of each side the electrode resistances r_1, r_2 are inserted. At the instant depicted in the figure the left-hand resistance r_1 is short-circuited by part of the jet wave connecting E_1 and e_1, while the right-hand resistance r_2 is inserted in the short-circuiting circuit of the transformer, reducing the current i_c. It will be noted that no new idea is involved in the device here considered, which obviously is based on a well-known principle from cell-switching practice.

In addition to the means here considered for controlling the short-circuit current, it has been found useful with large-capacity plants to add to the effective self-inductance of the transformer. This is done by inserting suitable coils in one (or in both) of the connections between the transformer and the main electrode, as indicated by $L_{\frac{1}{2}}$, $L_{\frac{1}{2}}$ in Fig. 2.

If commutation with a mechanical rectifier has not been completed—that is to say, if the spark has not vanished—before a certain moment, the normal commutation spark is changed into a permanent arc which during the next half-period, or even longer, completely short-circuits the transformer, generally throwing the rectifier out of action. The explanation of this instability is as follows: The spark lasts for a certain interval which generally extends beyond the zero-point of the voltage to be commutated. This does not matter, provided the voltage of the transformer has not, at the end of the interval, risen beyond a certain limit. If, however, this limit is passed, the voltage may be sufficient to produce a new discharge in the opposite direction in continuation of the original spark. This new discharge will be acted upon by an increasing voltage and will therefore develop into a permanent arc. This phenomenon of instability greatly endangered the development of large-capacity rectifiers until perfect stability was ensured by the simple stabilizing device indicated in Fig. 16. The commutator here shown is much the same as that in Fig. 15, the only difference being that two tungsten knives, W_1, W_2 have been inserted between the secondary electrodes e_1, e_2 and the main parts E_1, E_2. During the commutation indicated in the figure the knife W_1 will cut the wave nearly at the same moment as the main knife W, thereby inserting the resistance r_1 in series with the spark created at W. If this spark should tend to change into an arc the tendency is checked by the resistance r_1 [see Section (11)]. In order to illustrate the significance of the stabilizing device, Fig. 17, showing the constants of commutation, is reproduced. E indicates the voltage to be commutated, say the voltage across the half-phase V_1 in Figs. 15 and 16. The metallic short-circuiting commences at a time t_1 before the zero-point of the voltage. The overlapping interval is shown as τ_1 and the spark interval as τ_2. Now it was found that with a commutator with no stabilizing device, t_1—with a 200-kW, 550-volt rectifier—must be made as great as 10 or 12 per cent of the half-period in order to ensure safe commutation; while with a stabilizing device t_1 might be reduced to 3 per cent. Alternatively, commutation might be effected practically at the moment of zero voltage, which of course meant a considerably improved commutator efficiency. At the same time it was found that the commutator was made practically independent of the ordinary fluctuations in frequency.

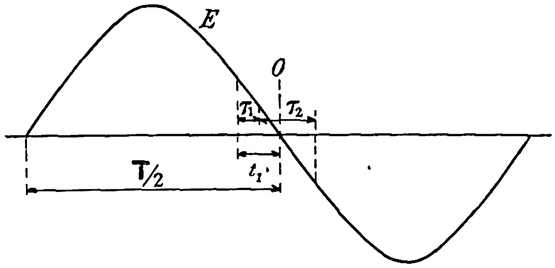


FIG. 17.

(10) DESIGN OF THE MAIN ELECTRODE.

Fig. 18 shows the component members of a high-capacity main electrode. This electrode was used in a

33·3-kW commutator in a 200-kW, 550-volt series rectifier. The jet wave was produced from a jet 3·8 mm in diameter with a velocity of 595 cm per sec. The distance from the centre of the field to the level of the secondary electrodes was $1 \cdot 95 \times \frac{1}{2}\lambda$, $\frac{1}{2}\lambda$ being 5·95 cm as the frequency was 50. The angular amplitude $a = \tan\theta_m$ (Fig. 13) was 0·50. It will be seen that the secondary electrodes consist of two steel wedges and that the inner members of the two main sides E_1 and E_2 are likewise given the shape of wedges. The wings of E_1 and E_2 consist of so-called " curry-combs," a description of which is given in Section (12).

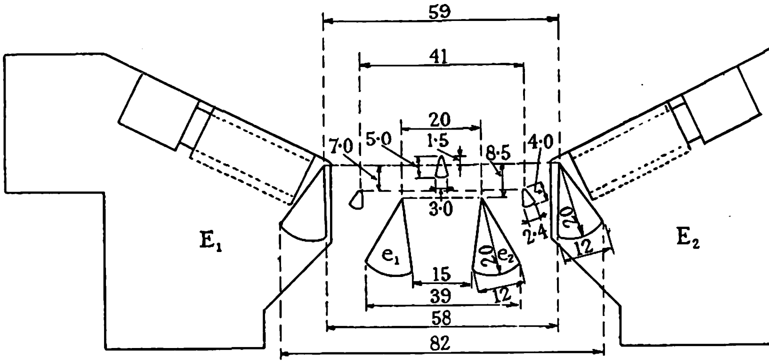


FIG. 18.

All dimensions in mm.

The following indicates how a main electrode for operation with a given jet wave is designed. In order to simplify the problem we will confine ourselves to the case of an electrode without secondary electrodes.

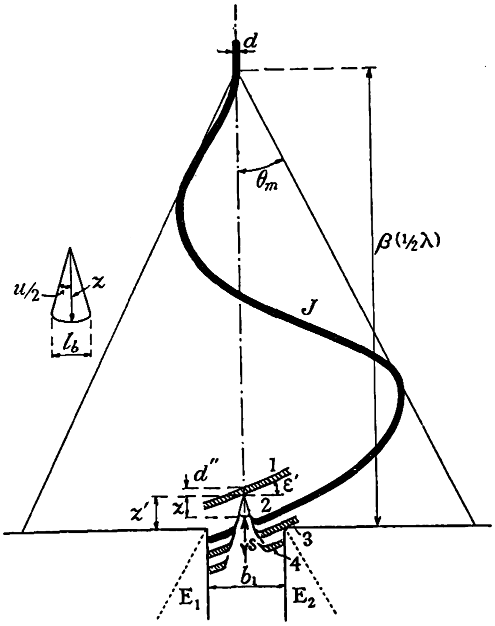


FIG. 19.

In Fig. 19 part of the jet wave is shown in a series of positions (1, 2, 3 and 4) during commutation. In position 3 the metallic short-circuiting is just commencing. In position 4 it is assumed that the strings between the wave and the knife break after having reached a length s'. The overlapping interval τ_1 is thus the time required for the wave to travel from position 3 to position 4. With the notation of the figure it is seen that

$$\tau_1 = \frac{z + s'}{v} - \frac{z'}{v} - \frac{b_1}{2v}\tan\varepsilon' + \frac{d''}{v} \quad . \quad . \quad (35)$$

Now in the theory of the jet wave it is found that

$$d'' = d\frac{\sqrt[4]{(1 + \pi^2\beta^2a'^2)}}{\pi\beta a'} \quad . \quad . \quad . \quad (36)$$

where $a' = \sin\theta_m$, and β is the distance from the centre of the field to the main electrode measured in half wavelengths. Furthermore,

$$\tan\varepsilon' = \frac{1}{\pi\beta a'} \cdot \quad . \quad . \quad . \quad . \quad . \quad (37)$$

Introducing the values of d'' and $\tan\varepsilon'$ (see Fig. 19) in equation (35), we obtain

$$\frac{\tau_1}{\mathrm{T}/2} = \frac{z + s'}{\lambda/2} - \frac{z'}{\lambda/2} - \left(\frac{b_1}{\lambda/2} \cdot \frac{1}{2\pi\beta a'}\right) + \left(\frac{d}{\lambda/2} \cdot \frac{\sqrt[4]{(1 + \pi^2\beta^2a'^2)}}{\pi\beta a'}\right) \quad . \quad (38)$$

This formula generally serves for the determination of the level z' of the knife-edge which is required for obtaining a given value of τ_1 with a given electrode and a given jet wave. It can, however, only be used for this purpose provided s' is known. Hence it was necessary to carry out elaborate investigations regarding the dependency on the various factors of the breaking-length of the string. The result of these investigations is given in the formula

$$s' = (0 \cdot 244 \times 10^{-3})v^2dz\frac{\sqrt[4]{(1 + \pi^2\beta^2a'^2)}}{\pi\beta a'}\tan^2\frac{u}{2} \quad (39)$$

where all dimensions are in cm. With three very nearly equal commutators C_4, C_5 and C_6, for which $b_1 = 2 \cdot 0$ cm, $z = 0 \cdot 5$ cm, $l_b = 0 \cdot 3$ cm, $a' = 0 \cdot 447$, $\beta = 1 \cdot 95$, $v = 595$ cm per sec., $\frac{1}{2}\lambda = 5 \cdot 95$ cm, and $d = 0 \cdot 380$ cm, the values of $(\tau_1/\frac{1}{2}\mathrm{T})100$ stated in Table 6 were found by direct measurement, while equations (38) and (39) give a value of 5·0.

The agreement is very satisfactory. It should, however, be noted that the length of the string s', and hence τ_1, are not constant, but depend very markedly on the temperature of the knife. Generally, when cold, the knife exhibits extremely high values for s' and τ_1. The values in Table 6 are "cold" values, and equation (39) corresponds to a cold knife. When heated after normal operation for some time the values of $(\tau_1/\tfrac{1}{2}T)100$ were found to be 2·6, 2·0, and 3·7 for the three commutators respectively. Generally, changes of up to 2 or 3 per cent of the half-period must be expected in the value of τ_1, which means that the "cold" value of τ_1 should not be taken as less than 2 or 3 per cent, in order to avoid too frequent interruptions.

TABLE 6.

Commutator	Ratio $\left(\frac{\tau_1}{T/2}\right)$
	per cent
C_4	4·7
C_5	6·4
C_6	5·3

(11) MANIFOLD CUTTING. PARALLEL AND SERIES AGGREGATES. STATISTICS OF THE JET-WAVE COMMUTATOR.

During recent investigations the explanation of the *modus operandi* of the stabilized electrode in Fig. 16 was doubted. If the jet wave is cut by, say, the knife W_1 before the spark below W is extinguished—and such are generally the conditions—a spark appears below W_1, short-circuiting the resistance r_1. Possibly, therefore, the resistance is not alone responsible for the increase of stability, or is not even of any great importance. This doubt gave rise to an experiment which led to a new and simpler main electrode, which is shown in Fig. 20. Here the secondary electrodes and the resistances are dispensed with, and are replaced by a series of tungsten knives, introducing manifold cutting. With 3 symmetrically arranged knives simultaneous cutting by 2 knives may be obtained, and it at once proved that stability equal to that of the electrode in Fig. 16 is achieved. With a 5-knife electrode (Fig. 20) the wave is cut simultaneously by 3 knives; and with an electrode of this description in a 33·3-kW, 180-volt commutator the stability was increased to such an extent that t_1 (Fig. 17) might be reduced to zero or even made negative. Obviously, the arrangement of spark-gaps in series affords a simple and most effective means of stabilizing the commutation process. Recognition of this fact is likely to lead to results of great consequence. In the first instance it is evident that the higher stability opens up the possibility of producing commutators for higher voltages, e.g. for 500 or even 1 000 volts. For the present, 3- and 5-knife electrodes are used co-ordinately with the older electrode of Fig. 16 in high-capacity commutators for voltages up to 180.

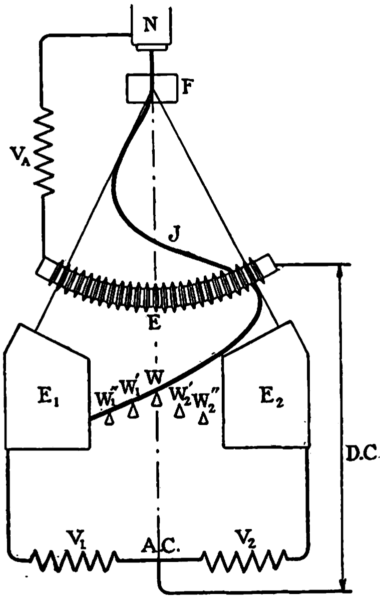


FIG. 20.

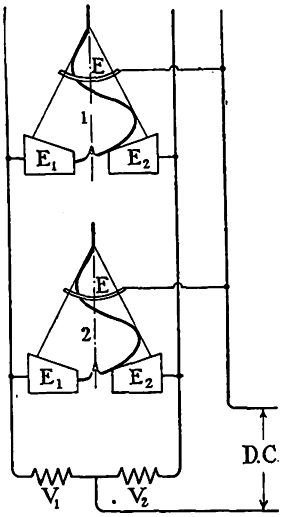


FIG. 21.

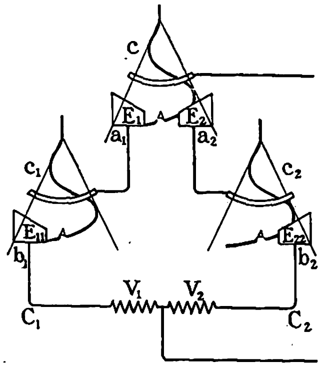


FIG. 22.

In order to commutate larger currents or powers than can be handled by a single commutator, two or more commutators may be operated in parallel in the simple way indicated in Fig. 21. It should be understood that the jets of such aggregates may be fed from a joint reservoir, but each jet must as a rule have its own jet-pipe. Furthermore, the fields may be produced by means of a single magnet. With suitable design of the joint members the aggregate assumes the character of a unit commutator, the capacity of which may be raised to several hundred kilowatts. It has proved feasible to produce simple commutators which have two jet waves instead of one playing on a single main electrode of ordinary design.

Again, several commutators may be connected in series for the commutation of extra-high voltages. The principle is illustrated in Fig. 22. It will be noted that during every alternate half-period the rectified current is carried by c_1 and c through E_{11} and E_1, while during the remaining half-period the same current passes through c_2 and c via E_{22} and E_2. Obviously, any number of commutators like c_1 may be inserted in series in the branch b_1a_1, and it is seen that all the spark-gaps of the series-connected commutators are in series during the commutation. Moreover, as the principle of manifold cutting may be used in each of the several commutators, the possibility of commutating extremely high voltages by means of aggregates like that of Fig. 22 is evident.

In connection with the problems of manifold cutting and of aggregates of parallel or series-connected commutators, the statistics of the jet-wave commutators have been studied. The subject of this investigation is the overlapping interval τ_1. While the foremost boundary (the left-hand in Fig. 17) is well defined owing to it being determined by the moment of arrival of the jet wave at the edge of the electrode-side [or the secondary electrode (compare Fig. 15 or 16)], the rear boundary of τ_1 is characterized by a marked uncertainty μ_1 owing to the fact that the boundary is determined by the breaking of the strings between the knife and the wave. Now it is of interest to learn how, first, the width of the resultant overlapping interval τ_1 and, secondly, the value of μ_1, are affected by the number of commutators connected in parallel, or commutators or knives operated in series.

TABLE 7.

Number of commutators n	Ratio $\frac{\Delta\tau_{1n}}{\mu_1}$	Ratio $\frac{\mu_{1n}}{\mu_1}$
2	0·516	0·808
3	0·778	0·727
4	0·926	0·689
5	1·061	0·654
6	1·160	0·629
7	1·240	0·609
8	1·309	0·593
9	1·365	0·577
10	1·420	0·572

In the first instance it will be noted that if two or more commutators are operated in parallel (Fig. 21), the overlapping (short-circuiting of the transformer) lasts as long as any of the commutators exhibit overlapping, while with series-connected commutators the overlapping only exists until one or more of the commutators commence cutting. Hence it will be understood that with parallel connections the average value of τ_1 will be increased, while with series connections it will be reduced. The increase and decrease $\Delta\tau_1$ is, *ceteris paribus*, numerically the same with the same number of commutators. On the other hand, the value of μ_1 is reduced in both cases and the reduction is the same with the same number of commutators. A few numerical values originating from the investigation referred to are given in Table 7. $\Delta\tau_{1n}$ represents the increase (or decrease) of τ_1 with n commutators in parallel (or series), while μ_{1n} stands for the corresponding decrease of μ_1. In the table both quantities are expressed in relation to the mean value of μ_1 with one commutator.

(12) THE AUXILIARY ELECTRODES. STRAY CURRENT AND STRAY FIELD.

The electrodes E′ and E (Fig. 2), used for the introduction of the auxiliary current and for the tapping of the rectified current, are called the auxiliary electrodes. Of the several types which have so far been developed a few have been described in the papers referred to in Section (1), especially the so-called "curry-comb electrode" and the wedge electrode. The former, which is now generally used in large-capacity commutators, is the one indicated in Figs. 13, 15 and 16. The curry-comb is produced in the following manner. On the surface of a cylindrical piece of steel a series of equidistant ribs with sharp edges are turned, or a sharp angular thread is cut. The cylinder is then bent into an arc of a circle with a radius equal to the distance from the field to the electrode in its proper position. The two curry-combs of which the electrode generally consists are separated by a gap through which the jet wave passes. The width of the gap is so adjusted that the ribs will cut, say, a few tenths of a millimetre into the wave. Under these circumstances there will, with the proper jet wave, be safe contact between an unimpaired wave and the electrode, and comparatively heavy currents of several hundred amperes may be passed from the latter into the wave. The deformation to which the electrode gives rise is, at the same time, relatively small. The dimensions in mm of a normal curry-comb for tapping 200 or 300 amperes may be taken from Fig. 23. With a jet wave produced from a jet of diameter 3·8 mm and with an angular amplitude $\alpha = \tan\theta_m = 0{\cdot}5$, the width of the slit between the component combs was from 1·8 to 2·0 mm.

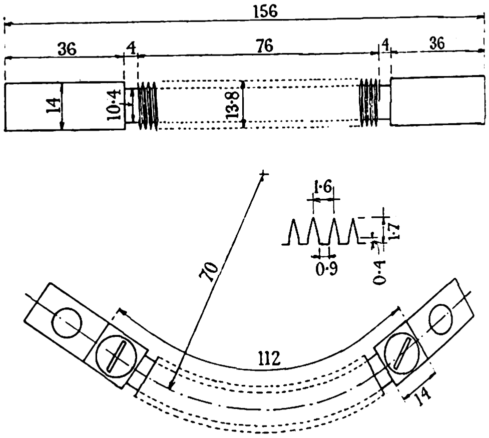


FIG. 23.

All dimensions in mm.

In the problem of the tapping of the rectified current a peculiar difficulty had to be faced. In Figs. 15 and 16 the auxiliary current is transmitted into the jet wave by means of the curry-comb through which the rectified current is tapped from the jet wave. This arrangement, with a single joint electrode instead of two, as in Fig. 2, has proved adequate as long as the rectified current is small compared with the auxiliary current. Generally, however, this is not the case, and a complication arises which may be explained thus.

Between the jet wave and the tapping electrode, say a curry-comb electrode, there will always be a contact resistance. In Fig. 24A, E indicates an auxiliary electrode used both for the transmission of the exciting current, supplied by the transformer V_A, and for the rectified current I_d. The contact resistance referred to is indicated as R. Owing to the latter resistance the fraction $\frac{R}{R+R_0}$ of the rectified current, the so-called "stray current," will pass through the part "c d b" of the auxiliary-current circuit, R_0 being the resistance of this part. This is detrimental if the stray current is not small compared with the auxiliary current, for the stray current is a direct current and, by interaction with the constant field generally used in the production of the wave, it will therefore give rise to a deflection of the whole jet wave proportional to the rectified current. The consequence is illustrated in Fig. 24B, which shows that alternate commutations will be advanced and retarded, respectively. Retardation of the commutation, however, means a danger of instability, while too early commutation involves an increase of the spark loss. The stray field of the magnet has just the same effect as the stray current had. The latter is perceptible at a rather considerable distance from the field and, if the tapping electrode is arranged close to the latter, the part of the wave which carries direct current will pass the constant stray field. Thus a deflection is caused, and unfortunately this will, as indicated, be in the same direction as that caused by the stray current.

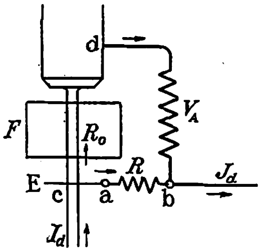


FIG. 24A.

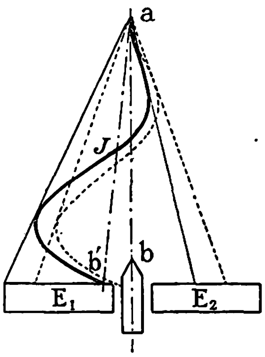


FIG. 24B.

Obviously, the effectively way to avoid the stray-current and stray-field complications is to employ separate electrodes for the auxiliary and the rectified current, and to mount the electrode for the latter close to the main electrode and well outside the stray field. With curry-comb electrodes, however, this scheme introduces a new difficulty, since the deformation of the wave—especially of the top of the wave—caused by the upper comb is apt to make the contact between the wave and the tapping electrode less definite. This is very unfortunate, for if contact was broken with the rectifier on load an arc appeared and at once destroyed the curry-comb. For a long while, therefore, the tapping electrode was a joint electrode and the stray-current phenomenon was counteracted in various ways. Thus the stray current was reduced by the introduction of resistance in the auxiliary-current circuit. The auxiliary-current loss was, of course, increased thereby, but as this loss is comparatively small, as seen above, a certain increase might be tolerated. The auxiliary current was led in through one end of the joint electrode, while the rectified current was tapped out of the other. The two components of the electrode were sometimes insulated from each other and each component used for its current. Generally, however, connection was maintained between the two components through a suitable resistance in order to ensure safer contact relations. Finally, the main electrode was often turned through a small angle about the centre of the field in the direction of the deflection of the wave in order partially to compensate for this deflection. By such means the six 20-kW, 75-volt commutators in a 120-kW, 220-volt rectifier for practically constant load were made to operate satisfactorily. As, however, the problem of producing 33·3-kW, 180-volt commutators for a 200-kW, 550-volt rectifier destined for tramway-traction service had to be faced, and as it was realized that such commutators would have to withstand overloads of up to 100 per cent or more, the measures indicated above were obviously insufficient. Hence separate electrodes had to be introduced. Generally the commutators referred to above were operated in pairs of two connected in parallel, and with this arrangement the deformation was less dangerous, for, if the contact failed on one of the two parallel commutators, the tapping electrode of the other would take over the whole current and no arc would appear. As a matter of fact the 200-kW, 550-volt rectifier indicated was operated on the tramway feeders for about 2 months without any trouble. Nevertheless, it was unsatisfactory that the commutator with two combs could not be used alone, and the problem of overcoming the trouble due to the deformation was therefore again taken up, and was solved in two entirely different ways.

In one solution the teeth of the outer ends of the combs of the tapping electrodes were made higher than the rest, so that the slit between the component combs became narrower at the ends, where the deformation was most liable to take place, than at the middle, where no deformation occurred. This construction is known as the "stepped curry-comb." In an electrode which was otherwise identical with that shown in Fig. 23, the two values of the width, with the jet wave indicated above, were 2·0 and 1·2 mm respectively, and the extension of the middle was about half the length of the comb. With this electrode the deformation caused by the auxiliary-current electrode proved harmless.

In the other solution referred to, the single tapping electrode was replaced by an aggregate of two twin combs arranged at a distance from each other of about a quarter of a wavelength. With this distance the teeth on the ends of the combs may be removed, for if the wave were to make contact with these teeth in one of the twin combs it would at the same time make safe contact with the centre teeth of the other, and so the end teeth, with the indifferent contact, are not essential. The arrangement was tested in the 200-kW, 550-volt rectifier mentioned above, and was found to be reliable.

(13) THE COMPLETE COMMUTATOR. RESISTANCE AND OVERLOAD CAPACITY.

For the reasons stated above, the jet-wave commutator of to-day is generally a curry-comb commutator with separate curry-comb electrodes for the exciting and rectified currents. The following is a review of the main properties of this type of commutator.

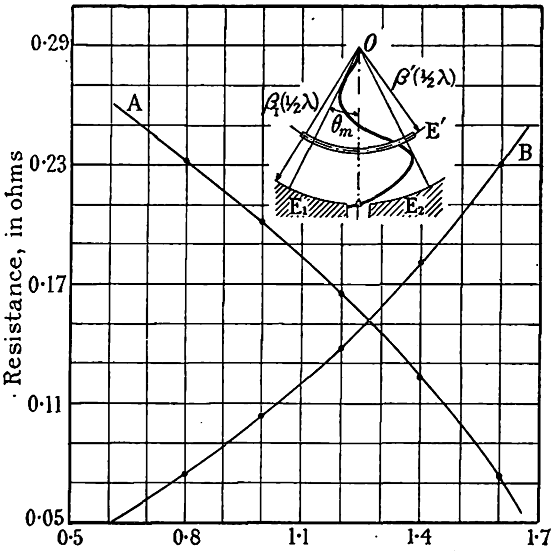


FIG. 25.

We shall first consider the resistance of the commutator, i.e. the resistance between the circular tapping electrode and the main electrode. The surface of the latter also is nearly circular, and the resistance of the commutator is therefore roughly equal to the resistance of the jet wave between two circular electrodes, which resistance may easily be calculated by means of equation (27). (Compare the calculation of the resistance of the auxiliary-current circuit.) In Fig. 25, curve A shows how the resistance varies with the position of the tapping electrode in the case of a wave for which $d = 1 \cdot 0$ mm, $\alpha' = \sin\theta_m = 0 \cdot 447$, and $\frac{1}{2}\lambda = 6$ cm. The main electrode is kept at a distance $\beta_1(\frac{1}{2}\lambda) = (1 \cdot 83 \times 6) = 11$ cm from the centre of the field. The resistance per cm of the jet is taken to be $12 \cdot 75 \times 10^{-3}$ ohm, corresponding to a stationary temperature of the mercury of 80° C.

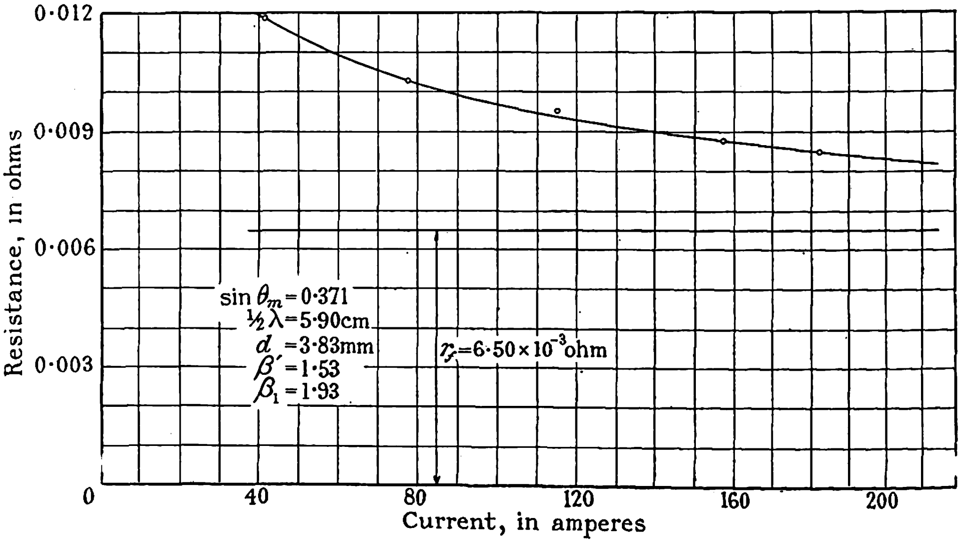


FIG. 26.

Now the resistance calculated from the theory of Section (7) does not represent the whole resistance of the commutator. There are still the contact resistances between the wave and the two electrodes the main electrode E_1 E_2 and the tapping electrode E′ furthermore, the resistance in the connections and the connecting bolts to be taken into account. In Fig. 26 the variation with the load of the total resistance of the commutator proper (not including the connections) is shown for a commutator with the constants indicated in the figure (compare Fig. 25). The resistance alters rather considerably with the load, owing in the main to the contact resistance between the wave and the tapping electrode. The commutator has a capacity of 33·3 kW at 180 volts and the normal load current is thus about 185 amperes. From theory the wave resistance was found to be $6 \cdot 50 \times 10^{-3}$ ohm. Thus at full load the contact resistance is 2×10^{-3} ohm. The resistance of the connections can, in a commutator of the type indicated, be reduced to 1 or $1 \cdot 5 \times 10^{-3}$ ohm, so that the amount to be added to the resistance of the wave is, say, $3 \cdot 5 \times 10^{-3}$ ohm.

From the curves in Figs. 25 and 26 we may now find the total resistances of the two representative commutators considered. We shall suppose the first commutator to be furnished with a wave for which $d = 4 \cdot 0$ mm, $v = 5$ m per sec., $\frac{1}{2}\lambda = 5$ cm, $\alpha' = \sin\theta_m = 0 \cdot 371$; and we shall assume $\beta' = 1 \cdot 42$ and $\beta_1 = 1 \cdot 83$. From Fig. 25 it is seen that the wave resistance for $d = 1$ mm and $\alpha' = 0 \cdot 447$ is 120×10^{-3} ohm with $\beta' = 1 \cdot 42$. This resistance is reduced in the ratio 1 : 16 owing to the larger diameter, in the ratio 5 : 6 owing to the smaller velocity, which implies a smaller wavelength, and in the ratio $\{0\cdot371/0\cdot447)^2 \times (1\cdot037/1\cdot055)\} : 1 = 0\cdot675 : 1$ due to the smaller amplitude. The wave resistance thus becomes

$$(120 \times 10^{-3} \times \tfrac{1}{16} \times \tfrac{5}{6} \times 0\cdot675) = 4\cdot2 \times 10^{-3}\,\text{ohm}$$

The total resistance of the commutator is therefore $(4\cdot2 + 3\cdot5) \times 10^{-3} = 7\cdot7 \times 10^{-3}$ ohm. As the current at full load is $(20 \times 10^3)/75 = 267$ amperes, the main-current loss becomes $\{(7\cdot7 \times 10^{-3}) \times 267^2\} = 547$ watts, and the percentage loss very nearly 2·7.

In the case of the second commutator we shall assume a wave having $d = 4\cdot0$ mm, $v = 6$ m per sec, $\alpha' = \sin\theta_m = 0\cdot447$; also $\beta' = 1\cdot17$ and $\beta_1 = 1\cdot83$. From Fig. 25 we find the wave resistance to be $(170 \times 10^{-3})/16 = 10\cdot6 \times 10^{-3}$ ohm. The total resistance of the commutator is thus $14\cdot1 \times 10^{-3}$ ohm. The rectified current at full load is 185 amperes, and thus the main-current loss $\{(14\cdot1 \times 10^{-3}) \times 185^2\} = 482$ watts, i.e 1·45 per cent, or about 1·5 per cent of the d.c. load.

The two commutators are both very nearly identical with normal constructions tested in practical rectifiers. Hence we are justified in stating for the main-current loss:

20-kW, 75-volt commutator: 2·7 per cent.
33·3-kW, 180-volt commutator: 1·5 per cent.

Jet-wave commutators and rectifiers will withstand a considerable overload. Thus with a 16·6-kW, 75-volt commutator in a 100-kW, 225-volt series rectifier plant it was found that the load could be raised for a considerable time to 50 per cent above the normal value (220 amperes per commutator) and the commutator would withstand complete short-circuiting. More systematic investigations were carried out with the 33·3-kW, 180-volt commutators of a 200-kW, 540-volt series rectifier plant. The normal current load per commutator was here about 185 amperes. The load could, however, be kept at 300 amperes per commutator for 20 or 30 minutes at a time with practically no irregularity of operation. If the current was increased to 400 amperes arcing of the commutators set in, but the arcs were checked by the stabilizing device and no damage was done to the commutators.

It is easy enough to see why instability must occur when the load per commutator is raised above a certain limit. The spark interval τ_2 becomes too long, i.e. the voltage across the transformer assumes such large values before the spark is extinguished that a discharge in the opposite direction sets in.

It is interesting to note that the growth of the spark-interval τ_2 can be predicted with fair accuracy on the basis of an investigation on the commutation spark. It has been found that the way in which the current through the spark diminishes may be represented by the expression

$$i = i_0\epsilon^{-yt^3} \quad . \quad . \quad . \quad . \quad . \quad (40)$$

where

$$y = \frac{c'}{P_{g.100}} \quad . \quad . \quad . \quad . \quad . \quad (41)$$

Here $P_{g.100}$ means the spark power with 100 sparks per sec., while c' is a numerical constant. In plants similar to those indicated above, c' may have a value of about $4\,000 \times 10^9$, P_g being measured in watts. We are now able roughly to calculate the time $t_{\frac{1}{2}}$ during which the current falls to half its original value. It is determined by the equation

$$t_{\frac{1}{2}} = \sqrt[3]{\left(\frac{\log_\epsilon 2}{y}\right)} = \sqrt[3]{\left(\frac{\log 2}{4\,000 \times 10^9}\right)} \times \sqrt[3]{(P_{g.100})}$$

In Table 8, P_d indicates the d.c. outputs in kW corresponding to the currents 92, 185, 277 and 370 amperes per commutator in the overload experiment with the 200-kW, 540-volt, 6-commutator rectifier indicated above. It will be seen that the spark interval rises from about 10 to about 17 per cent of the half-period ($\frac{1}{2}$T) when the load is increased from 100 to 400 kW, it being assumed that τ_2 is nearly equal to $2t_{\frac{1}{2}}$. The spark starts nearly at the moment of zero voltage; hence with 400 kW, or nearly 400 amperes, per commutator the spark is not extinguished until the voltage across the transformer has reached a value $E_0 \sin\{(17/100)\,180\} = E_0 \sin 30\cdot6°$, or about $\frac{1}{2}E_0$, where E_0 is the maximum value of the transformer secondary voltage. In the case considered the latter was about $(420 \times \sqrt{2})$ volts, or nearly 600 volts. Hence at the end of the spark interval the spark-gap is subject to a potential difference of at least 300 volts. The increase by 7 per cent of the half-period of τ_2 in Table 8 is equivalent to a lowering of the main electrode by 7 per cent of a half-wave. Such a lowering would inevitably give rise to instability with the commutator in question. It should be noted that the figures of the example only represent rough estimates, and furthermore that the case considered is actually that of a simple single-knife electrode.

TABLE 8.

D.C. output P_d	Spark power $P_{g.100}$	Ratio $\left(\frac{t_{\frac{1}{2}}}{\frac{1}{2}T}\right)$	Ratio $\left(\frac{\tau_2}{\frac{1}{2}T}\right)$
kW	watts	per cent	per cent
100	830	5·2	10
200	1 670	6·6	13
300	2 500	7·6	15
400	3 333	8·3	17

(14) THE SPARK LOSS. THE EFFICIENCY OF THE COMMUTATOR AND OF THE RECTIFIER.

As indicated in Section (9), the commutation spark originates from the stray fields of the transformer. The latter fields, as stated, may to some degree be considered as equivalent to inductance coils $L_{\frac{1}{2}}$, $L_{\frac{1}{2}}$ (Fig. 27) inserted in the connections from the transformer V_1V_0 to the main electrode E_1E_2.

The spark power, which determines the spark loss, does not depend solely on the inductance $L_{\frac{1}{2}}$ and on the magnitude of the rectified current. During the interval of metallic short-circuiting τ_1 (Fig. 17) a short-circuit current i_c will rise in the transformer [compare Section (9)] and add to the intensity of the spark. On the other hand part of the energy may be absorbed in the electrode resistances, which may thus act as spark-damping devices. Finally, the voltage across the terminals of the transformer may in some cases, with large values of t_1 (Fig. 17), give rise to an increase of the spark power, while in other cases the voltage may have a highly damping effect, e.g. if the spark interval stretches essentially beyond the zero-point of the voltage. All these relations are considered in the theory of commutation which is, however, outside the scope of the present paper. Here it need only be mentioned that if we neglect the effects of the electrode resistances r_1, r_2 (Fig. 27) and of the transformer voltage, the spark power, with completely smoothed-out rectified current, should be

$$P_g = 2p \times L_{\frac{1}{2}} \times (I_d + i_c)^2 \quad . \quad . \quad . \quad (42)$$

where $2p$ is the number of commutations per sec. From this equation it is seen that the spark power does not become zero for zero rectified current owing to the current i_c. Generally, however, the latter is made comparatively small, so that it tends to be negligible at large loads. Therefore one may find, especially if commutation takes place close to the point of zero voltage, that the spark power with increasing load tends to a value given by

$$P_g = 2pL_{\frac{1}{2}} \times I_d^2 \quad . \quad . \quad . \quad . \quad (43)$$

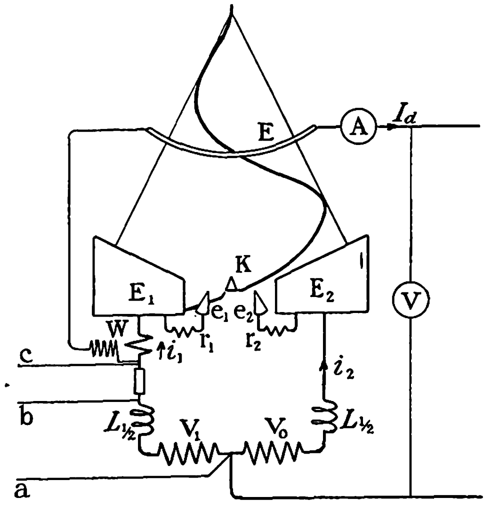


FIG. 27.

This statement, however, is only to be taken as roughly representing the actual conditions, which are generally rather intricate.

We shall therefore base our statements with regard to the spark loss on direct observations obtained from a series of plants of various descriptions. With such plants elaborate investigations of the spark loss in its dependency on the load have been carried out by means of the instruments indicated in Fig. 27, where W indicates a wattmeter. A similar instrument may be imagined in the right-hand connection between the transformer and the main electrode. The sum of the readings of the two instruments gives the total loss originating from (1) the spark (P_1); (2) the resistance of the jet wave (P_2); and (3) the electrode resistances (r_1, r_2), (P_3). From knowledge of the wave resistance, which may either be calculated or measured directly, the main-current loss P_2 may be determined. From measurement of the effective currents flowing in r_1 and r_2 the loss in these resistances is found. Thus the spark loss may be found by subtracting P_2 and P_3 from the total loss. Two instances are now given.

The first deals with a 100-kW, 230-volt series rectifier furnished with 6 commutators (3 pairs in series). The rectifier was fed from a 150-kVA, 6 100/182-volt, 50-cycle transformer. The jet waves had the constants $d = 3 \cdot 8$ mm, $v = 6$ m per sec., $\frac{1}{2}\lambda = 6$ cm, and $\alpha' = 0 \cdot 371$. A joint curry-comb electrode placed at a distance $1 \cdot 42(\frac{1}{2}\lambda)$ from the field was used for the transmission of the auxiliary current and the main current. The main electrode was at a distance of nearly $1 \cdot 83(\frac{1}{2}\lambda)$ from the centre of the field. In Fig. 28, curves representing as percentages the losses P_1, P_2 and P_3 (and in addition the voltage-drop Δe_r), are given. Of special interest here are the percentage spark loss P_1 and the loss P_3 in the electrode resistances, these losses being in the main independent of the commutator and the wave. It will be seen that less than 1 per cent energy loss is involved in stabilizing the commutator by means of the resistances. The percentage spark loss is by no means negligible at low loads. This, of course, is due to the short-circuit current. At full load (240 amperes) it amounts to nearly 5 per cent.

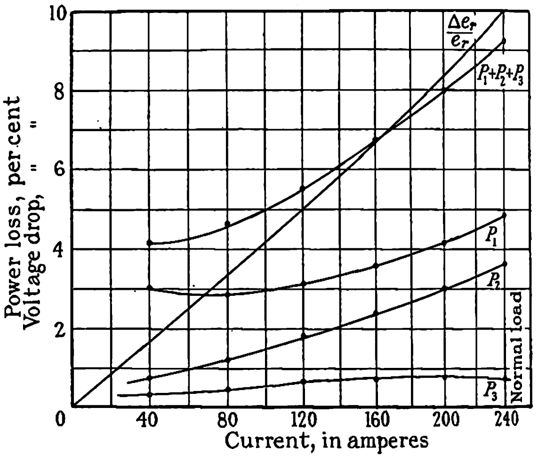


FIG. 28.

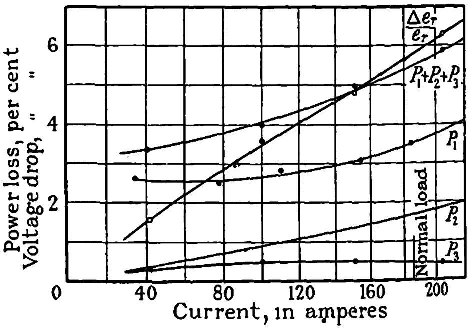


FIG. 29.

The second example originates from a 200-kW, 550-volt series rectifier—the same as was used in the 100-kW, 230-volt plant. It was run on a 400-kVA, 10 250/450-volt transformer. In Fig. 29, curves for P_1, P_2 and P_3 for the commutators of this plant are given. The curves are obviously of the same types as in the former case but the percentage losses are somewhat smaller. While with the 230-volt rectifier no damping coils were inserted in the places indicated by $L_{\frac{1}{2}}$, $L_{\frac{1}{2}}$ in Fig. 27, the 550-volt rectifier was furnished with two coils of $0 \cdot 1 \times 10^{-3}$ henry in each of the 3 pairs of commutators.

We have now considered all the losses of a jet-wave commutator and so are able to draw the efficiency curves of various commutators and rectifiers—for the efficiency of the complete rectifier is of course identical with that of the component commutators. We shall confine ourselves to the two commutators I and II considered in Sections (4), (5), (8) and (13). At normal (maximum) load the losses are then

Commutator I (20-*kW*, 75-*volt*):

$d = 4 \cdot 0$ mm, $v = 5$ m per sec., $\frac{1}{2}\lambda = 5$ cm, $a' = 0 \cdot 371$

	Per cent
Pump loss	0·57
Auxiliary-current loss	0·30
Magnet loss	0·70
Total constant losses	1·57
Main-current loss	2·7
Spark loss Electrode-resistance loss	to be deduced from Fig. 28.

Commutator II (33·3-*kW*, 180-*volt*):

$d = 4 \cdot 0$ mm, $v = 6$ m per sec., $\frac{1}{2}\lambda = 6$ cm, $a' = 0 \cdot 447$

	Per cent
Pump loss	0·51
Auxiliary-current loss	0·40
Magnet loss	0·42
Total constant losses	1·33
Main-current loss	1·5
Spark loss .. Electrode-resistance loss	to be deduced from Fig. 29.

Figs. 30A and B show the efficiency curves for the two cases. As indicated, the spark loss and the electrode-resistance loss have been deduced from the curves in Figs. 28 and 29, and are thus based on direct observations. The latter is true with regard to all the other losses, as these have been calculated on the basis of formulæ amply controlled by observations. The efficiency curves in Figs. 30A and B may therefore be taken to represent that which can at the present time at least be achieved.*

The efficiency curves for the rectifier plants from which Figs. 28 and 29 originate are not reproduced because they would be rather misleading, owing to the constant losses being to some extent abnormally large with these plants. Thus in the 200-kW, 550-volt plant (Fig. 29) they are

	Per cent
Pump loss	1·40
Auxiliary-current loss	0·56
Magnet loss	0·49
Total constant losses	2·45

The explanation is that the pump [compare Section (4)] was designed for more than twice the quantity required by the actual rectifier and, in addition, for a greater head. Furthermore the magnetic field was only about 5 000 gauss instead of 7 500 gauss, owing to the commutation chamber consisting of ordinary cast iron instead of being a non-magnetic casting. The auxiliary current must therefore be taken as about 50 per cent larger, with the effect of a 100 per cent larger loss.

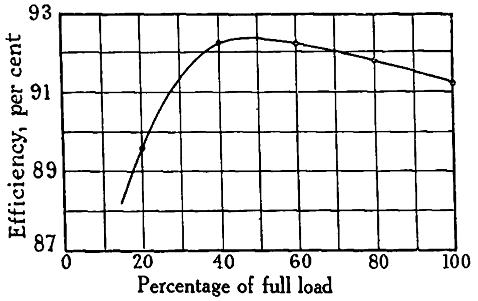


FIG. 30A.—Efficiency curve for 20-kW, 75-volt commutator.

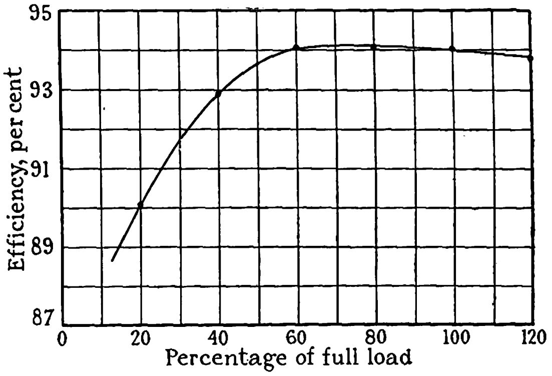


Fig. 30B.—Efficiency curve for 33·3-kW, 180-volt commutator.

(15) THE COMPLETE RECTIFIER AND THE RECTIFIER PLANT.

The so-called 6-phase series rectifier, which is considered here exclusively, consists as indicated of 3 commutators (or aggregates of commutators) connected in series. The component commutators are generally mounted in a joint chamber [compare the papers referred to in Section (1)]. The chamber is kept filled with hydrogen because this gas alone of all gases (barring, perhaps, helium) is able to absorb the energy of the spark within the time available for absorption to take place. The ratio of the duration of a spark in hydrogen

---

[*] It should be noted that the losses given are expressed as percentages of the d.c. output. If the total percentage loss is P_x, the percentage efficiency η, i.e. 100 times the ratio (output/input), is determined by

$$\eta = \{100 - P + (P^2/100)\} \text{ per cent}$$

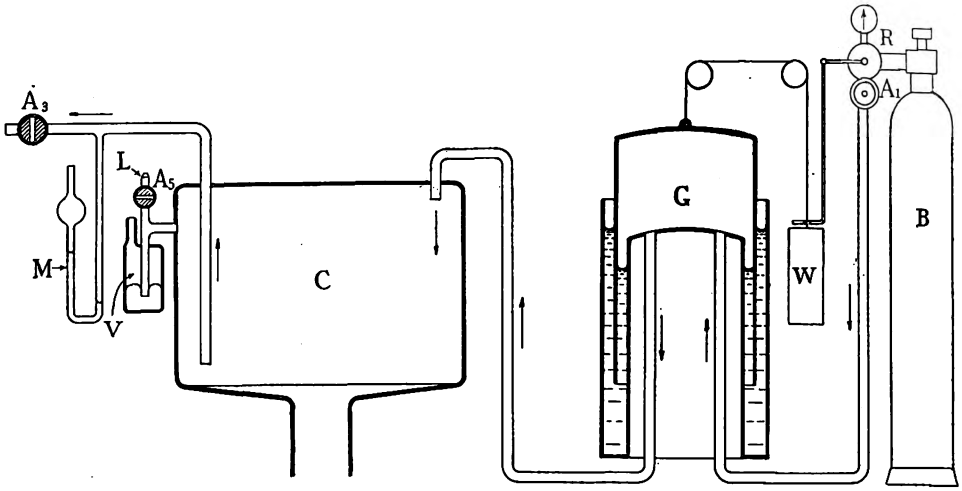

A₃
L
A₅
M
V
C
G
R
A₁
W
B

FIG. 31.

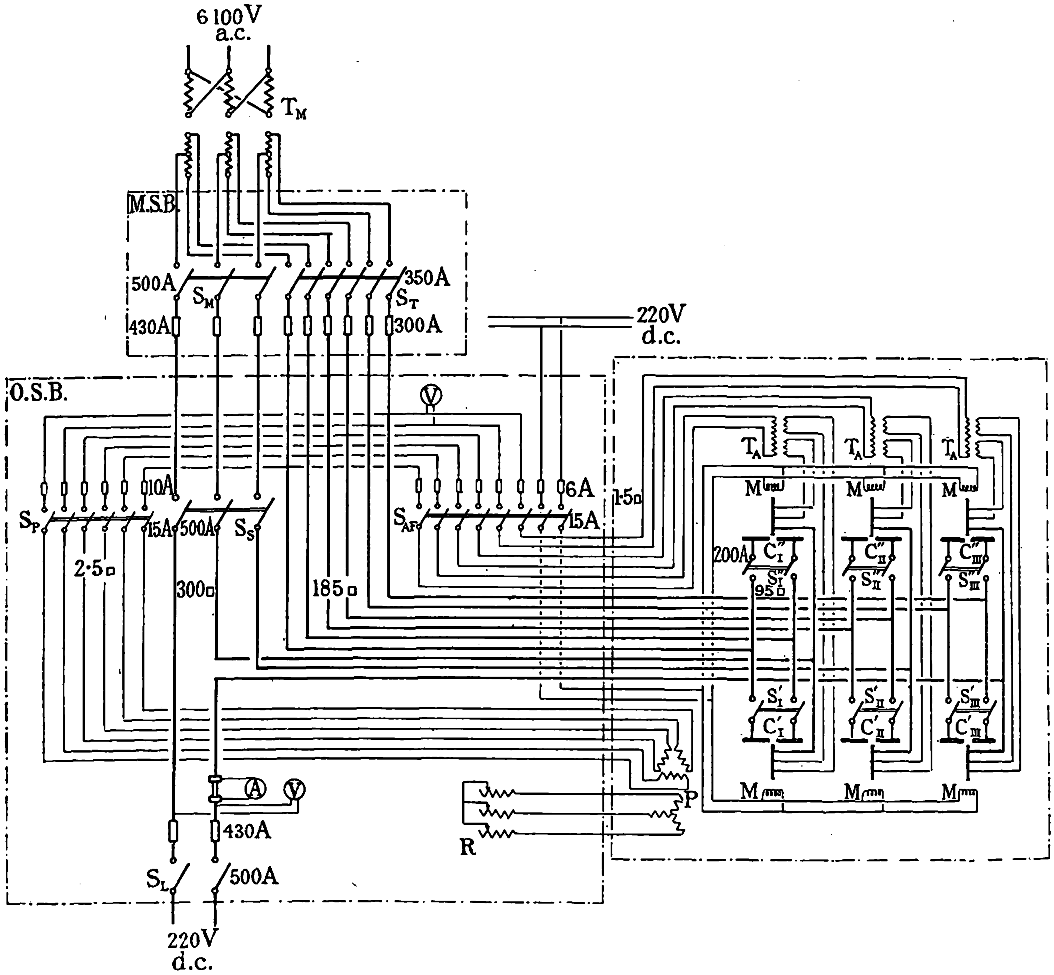
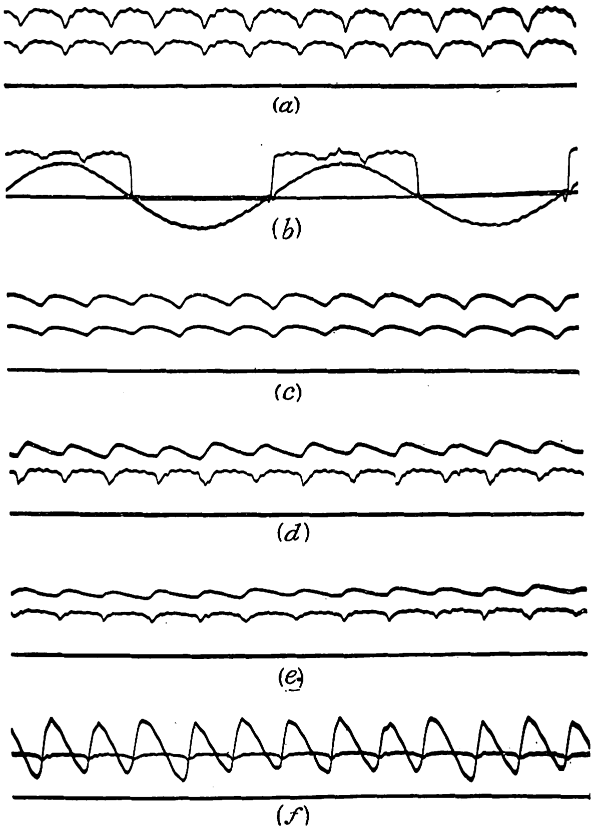

6 100V
a.c.
T_M
M.S.B.
500A
S_M
350A
S_T
430A
300A
220V
d.c.
O.S.B.
V
T_A
T_A
T_A
M
M
M
10A
6A
1·5Ω
S_P
15A
500A
S_S
S_AF
15A
2·5Ω
300Ω
185Ω
200A
C″_I
S″_I
95Ω
C″_II
S″_II
C″_III
S″_III
S′_I
C′_I
S′_II
C′_II
S′_III
C′_III
A
V
P
M
M
M
R
430A
S_L
500A
220V
d.c.

FIG. 32.—Diagram of connections of rectifier plant in the Northern Cable and Wire Works, Copenhagen.

T_M = Main transformer 150 kVA, 3-phase, 6 100/182 volts.
M.S.B. = Main switchboard.
S_M = Main switch for mid-points of transformers.
S_T = Main switch for terminals of transformers.
O.S.B. = Operating switchboard.
R = Starting resistance for pump motor P.
S_P = Switch for pump motor.

S_{AF} = Switch for auxiliary transformer T_A and field magnets M.
S_S = Switch for series connection of commutators.
S_L = Switch for connection to load.
S'_I, S''_{II}, S'_{II}, S''_{II}, etc. = Switches for connection to commutators C'_I, C''_I, C'_{II}, C''_{II}, etc.

and atmospheric air or nitrogen is something like 1:10. A few words may be said here concerning the maintenance of the constant excess pressure of about 5 cm of water which is thought appropriate for the hydrogen in the commutation chamber. The arrangement is shown in Fig. 31, where C is the chamber and B is the bottle (0·040 m^3) from which the hydrogen is supplied. It is furnished with a reduction valve R, which is opened if the container of the gasometer G sinks below a certain level. The gasometer is especially suited for smoothing out the changes in pressure which, without G, would arise from changes in the load on the rectifier. By adjustment of the weight W the regulator may easily be set to a given excess pressure read on the water manometer M. If the supply from B is too small, W will rise, and its motion may, as indicated, be used for opening the reduction valve, thus preventing a deficiency of supply. If the cylinder B becomes empty, W will continue rising and may, when G has sunk below a certain level, close an alarm-bell circuit. It may be noted that the loss of hydrogen to which inevitable leakages give rise may easily be made quite negligible.


(a)

(b)

(c)

(d)

(e)

(f)

FIG. 33.

The jet-wave rectifier was developed in the municipal power station of Copenhagen, the H. C. Oersted Works. The rectifier here used had a capacity of 200 kW at 550 volts, and the transformer was a 400-kVA, 6 300-volt Siemens-Schuckert transformer. After the completion of the work of development, two complete plants were tested under ordinary working conditions. The first, a 100-kW, 230-volt plant, was erected at the Northern Cable and Wire Works, Copenhagen. The plant was here used for running d.c. motors either alone or in parallel with the various d.c. sources of the works (a 200-kW rotary convertor, a 500-kW motor generator, and a 500-kW turbo-generator). It was kept under observation for 9 months and during this time behaved to the satisfaction of all concerned. From this plant, a diagram of which is shown in Fig. 32, the characteristics represented in Fig. 28 originate. A series of oscillograms are reproduced in Fig. 33. Fig. 33 (*a*) shows the rectified voltage (upper curve) and current with non-inductive load, while Fig. 33 (*b*) indicates the current in one of the secondary half-phases of the transformer, together with the voltage across the same. The latter figure shows that commutation takes place exactly at the zero point of the voltage. Fig. 33 (*c*) refers to the same circuit as Fig. 33 (*a*), the only difference being that a small choking coil was inserted in the d.c. circuit inside the terminals of the rectifier. Fig. 33 (*d*) and (*e*) show the current and voltage with motor load without and with the choking coil. Finally, Fig. 33 (*f*) indicates the current and voltage of the rectifier plant operated in parallel with a 500-kW turbo-generator. The latter maintains a perfectly smooth voltage, and so the ripples on the voltage of the rectifier must give rise to considerable fluctuations in the rectified current.

The other of the two plants indicated above is a 200-kW, 550-volt plant which is still in operation. The rectifier proper is the same as was used in the former test. The plant is erected in the Nordsjællands Elektricitets-og Sporvejs-Aktieselskabs power station at Skovshoved, just outside Copenhagen, and is used to drive the electric street cars on the lines of that company. From this plant the curves of Fig. 29 originate, and with it the overload and short-circuiting experiments indicated in Section (13) were carried out. The plant has been kept under observation for several months and operates with complete satisfaction, handling without difficulty the disturbances which must be reckoned with in a substation for traction purposes.

Some interesting experiences with this plant may here be stated. The substation in which the rectifier was erected was supplied with power from a 50-kV main covering a good deal of the southern part of Sweden and the eastern part of Denmark. At a certain juncture very interesting large-scale experiments were carried out on this main, the latter being several times short-circuited through arcs for from 1 to 3 secs. The result was to throw practically all rotary convertors out of operation, but the jet-wave rectifier continued to operate during the short-circuits, though with greatly reduced voltage, and continued working after the short-circuits had ceased and the normal voltage returned. The street cars were thus practically uninfluenced by the severe disturbances on the main, and it was probably not even noticed that experiments were being carried out.

Later, the effect on the rectifier of direct short-circuiting of the street-car feeder proper, and thus of the d.c. circuit of the rectifier, was investigated. Three feeders, each with its overload circuit-breaker, were operated in parallel by the rectifier, and one of the feeders was short-circuited. The effect on the rectifier was hardly perceptible, and the operation of the two parallel feeders was by no means affected. The short-circuit current per commutator was estimated to be 1 000 amperes, i.e. more than 5 times the normal load current.

From these tests it may be concluded that the jet-wave rectifier has been developed into a perfectly reliable d.c. source, allowing, of course, for such transient irregularities as are likely to occur in the course of the development of any new apparatus.

A few words about the current and voltage relations of the rectifier plant may not be out of place. These relations are represented in Fig. 34, where I_s indicates the current in a secondary half-phase of the transformer, while I_p is the current in the primary phase-winding and I_l the current in the a.c. line. The current diagrams are drawn on the assumption of a completely smoothed-out rectified current and the stray-field reactance of the transformer is neglected. Furthermore, the magnetizing current of the transformer is considered to be negligible. In the figure, different transformers and connections have been considered. In (A) an ordinary 3-phase transformer is assumed. With the primary phases star-connected, the full line represents the primary current. This connection cannot, however, be used with the series rectifier owing to the fact that the primary and secondary ampere-turns of each leg of the transformer do not compensate each other. The result is that a periodic flux with 3 times the frequency of the alternating current is set up in the iron, causing greatly increased spark losses in the rectifier. The normal connection of the primary windings is the mesh connection, with which perfect compensation takes place and the primary current assumes the shape indicated by the dotted curve. In (B) the relations with 3 single-phase transformers are shown, while (C) corresponds to a 3-phase transformer with the primary windings in mesh and with zig-zag secondary half-phases.

Fig. 34 originates from a complete discussion of the current and voltage relations with the many different rectifiers which can be built up from jet-wave commutators. From the discussion the following figures are taken. With the normal transformer-connection [(A), primary phases mesh-connected] the transformer should be chosen for a load 1·34 times the normal d.c. load of the rectifier. The heating of the transformer will then be nearly that for which it is designed as an a.c. source in a circuit without inductance. The power factor of the line will be reduced in the ratio 0·955 : 1.

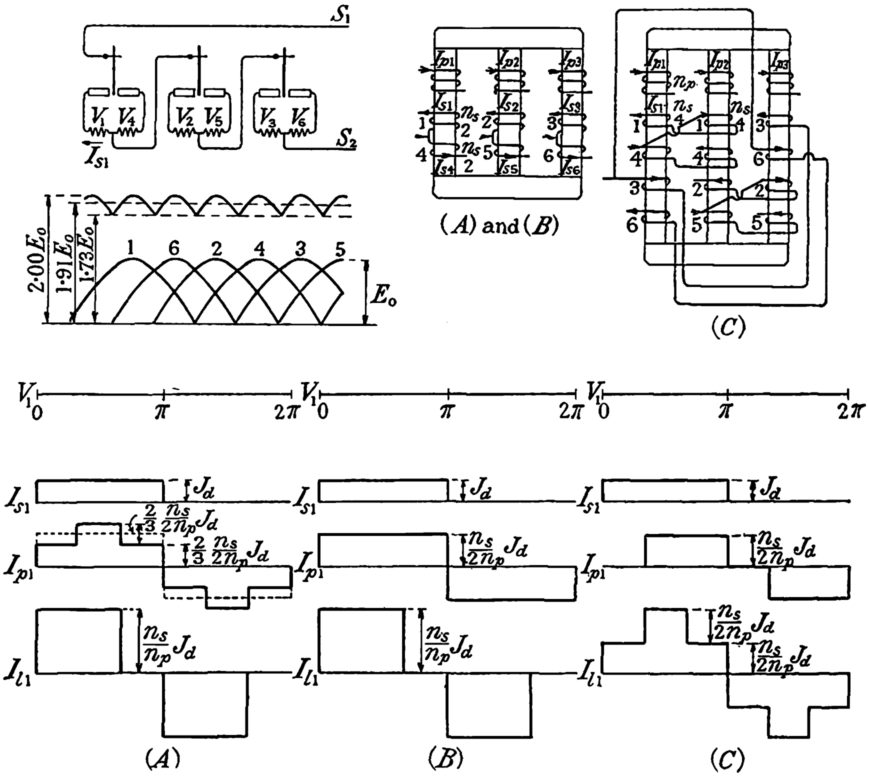


FIG. 34.

n_p = number of turns per phase of primary winding. n_s = number of turns per phase of secondary winding.
J_d = rectified current, in amperes.

(16) CONCLUSIONS AND ANTICIPATIONS.

The new rectifier has hitherto been produced for outputs up to 200 or 300 kW (with 6 commutators) and for voltages from 220 to 550 volts. It is hoped that the present paper will leave no question as to the practicability of rectifiers for larger capacities. Obviously, jet-wave rectifiers of any size may be produced on the basis of the theoretical and experimental knowledge at hand in connection with the constructional members available. With regard to such very large systems it may be anticipated that the efficiency will be slightly raised and that the amount of mercury required per kW will diminish. An interesting question is whether the interval for the d.c. voltage can be extended; and there is no doubt that it can. It will be noted that the efficiency of a 230-volt rectifier can be made nearly as high as that of a 550-volt plant with practically the same commutator. With a special main electrode the resistance of the commutator can be very considerably reduced, and as it is the resistance which is the predominant factor with low-voltage rectifiers it may be concluded that economical rectifiers for 110-volt, or probably even 55-volt, direct current may be constructed. On the other hand, the only reason why 550 has hitherto been the limiting voltage in the development is the accidental circumstance that rectifiers of this voltage could easily be tested on traction service. Obviously, if an economical 200-kW, 500-volt rectifier is developed, a 600-kW, 1 500-volt rectifier of at least the same efficiency is equally practicable, in that 3 commutators per phase can be used in series. But as a matter of fact there is nothing to indicate that it will prove necessary to build a 1 500-volt rectifier from commutators of (1 500/9), i.e. 167 volts. Commutators for much higher voltages can undoubtedly be produced, so that most likely a 1 500-volt rectifier can be made from 3 commutators for 500 volts each and possibly a 3 000-volt rectifier from 3 commutators for 1 000 volts each. With such a rectifier the main-current loss will, with commutator of the same capacity, be reduced to one-third of that in a 500-volt rectifier, i.e. the efficiency will be raised by more than 1 per cent.

Rectifiers of 1 500 or 3 000 volts are, however, not our final goal. The author is convinced that the jet-wave commutator affords a practical means for the production of very high d.c. voltages, say, 100 kV or more, and, on the basis of certain observations, would venture to predict that a 100-kV rectifier can be made from 100 very simple jet-wave commutators connected in series.

In connection with the question of high-voltage production it is interesting to note that the jet-wave rectifier is capable of transforming d.c. into a.c. energy under certain conditions. This, as will be seen, opens up the possibility of producing a d.c. transformer by means of which the high d.c. voltage suitable for energy transmission may be stepped down to a value suitable for motor operation and electric illumination.

Finally, a few words may be said with regard to the important question of the cost of production of the rectifier. The majority of the readers of this paper will probably admit that the jet-wave rectifier in its present shape is, comparatively speaking, a very simple system consisting of a few inexpensive parts adaptable to mass production. The most expensive material employed is, of course, the mercury. The amount necessary approximates at the present moment to 0·5 kg per kW for the larger rectifiers. A further and very essential reduction may, however, be anticipated. It should be noted that absolutely no loss of mercury takes place and that ordinary commercial mercury is perfectly suitable for the purpose. The substitution for mercury of some other metal or alloy of low melting point has been carefully considered, and this could probably be done. While it is impossible to give exact figures for the cost of production at the present stage, it seems safe to say that in this respect the new rectifier will easily compete with other available means of a.c. rectification.

DISCUSSION BEFORE THE INSTITUTION, 13TH FEBRUARY, 1930.

Mr. W. W. E. French: I wish to speak on the commutation in the jet-wave rectifier and to explain it in a way which, although quantitatively incorrect, does provide a qualitative analysis of the process. When approaching the problem, I recalled the earlier conceptions in which the ideal is straight-line commutation, the current in the short-circuited armature coil having a zero value at $\tau/2$, the mid-period of commutation. Although an appreciable amount of inductance in the coil is permissible, provided that a complete reversal of current can be produced within the period of commutation, the condition in which the current has not commutated after the time τ, must be avoided, because it gives rise to a spark. τ, the time of commutation, must be larger than the time-constant of the coil. In the jet-wave commutator, the author has completely broken with this tradition. He deliberately invites the spark and provides for its control, and he does not find it necessary that the current should commutate within the overlapping or short-circuit period. The apparatus used for controlling the spark is constructed of materials such as tungsten-steel and mercury which are immune from the harmful effects of the short-circuit current, and a cooling and spark-quenching atmosphere of hydrogen is provided. Provided that the spark is accurately controlled no danger from reactance voltage need be feared. There is first the overlapping period when the short-circuit current arises, then the instant at which the mercury jet is cut by the knife—when the spark is rapidly formed and extinguished. After the short-circuiting or overlapping period (see Fig. 17 of the paper) the events of commutation become, in effect, a switching process and can be explained by means of the well-known arc characteristics. The equivalent circuit of the author's stabilized commutator (see Fig. 15 of the paper) is shown in Fig. A, and the total circuit characteristic is obtained by superposing the typical curves of the mercury arc on the characteristics of the main circuit (1).* The effect of the shunt circuit characteristic (2) is to bend the curve, as indicated in the figure by the dotted part of the curve. As the current (I_a) dies down in the process of commutation, it attains a certain value below which it cannot fall unless the arc extinguishes, which must take place at point P, as shown in the figure. When this has occurred the current I_a is reduced exponentially to zero, according to the time-constant of the circuit involved. It is necessary to investigate whether extinction takes place within the period allotted for the whole of the commutation. Within this period the main voltage $E \sin \omega t$ should not have risen to such a value as to restart or maintain the arc. The various time intervals (t), at which the instan-

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* See also RÜDENBERG: "Elektrische Schaltvorgänge," p. 200.

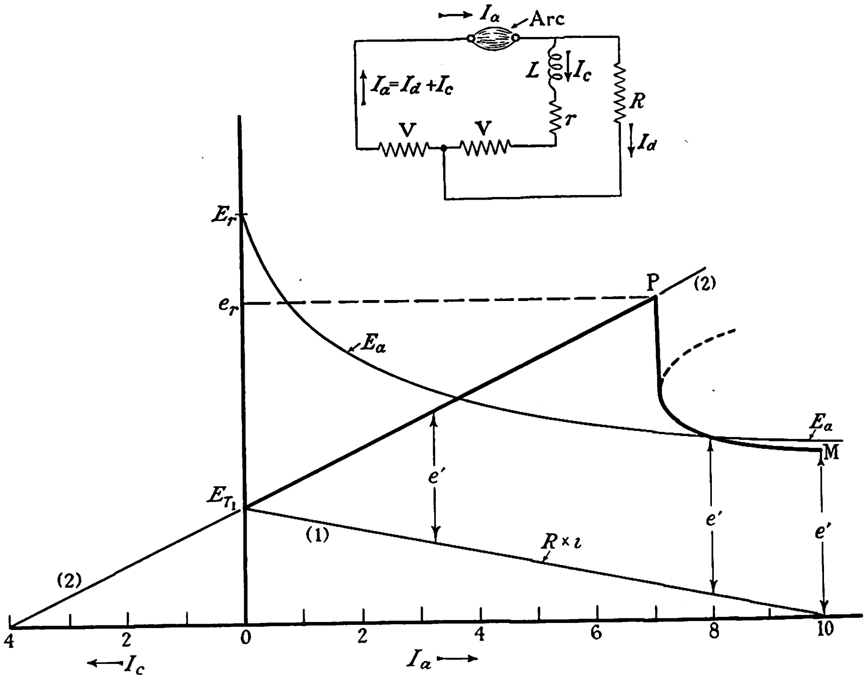
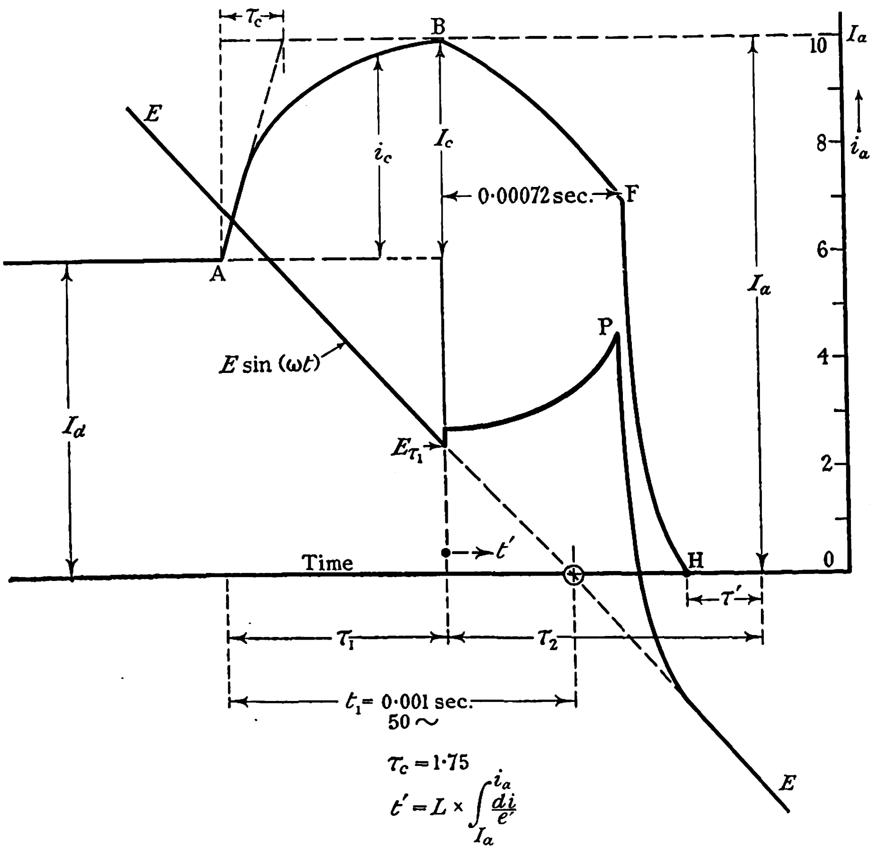

I_a
Arc
$I_a = I_d + I_c$
L
I_c
R
V
V
r
I_d
E_r
e_r
P
(2)
E_a
E_a
M
E_{T_1}
e'
e'
e'
(1)
$R \times i$
(2)
4
2
0
2
4
6
8
10
I_c
I_a

FIG. A.


τ_c
B
10
I_a
E
i_c
I_c
8
i_a
0·00072 sec.
F
6
A
I_a
P
$E \sin(\omega t)$
4
I_d
E_{T_1}
2
t'
Time
H
0
τ'
τ_1
τ_2
t_1 = 0·001 sec.
50 ∼
E

$\tau_c = 1{\cdot}75$

$$t' = L \times \int_{I_a}^{i_a} \frac{di}{e'}$$

FIG. B.

taneous values of the current I_a and the instantaneous voltage values of the total circuit characteristic occur, can be obtained by successive integrations of the area 10–M–P–E_{τ_1}–10, in Fig. A. The results are plotted in Fig. B, where the integral for t' is given. E is part of the wave $E \sin \omega t$ which is to be rectified and I have taken $\tau_1 = 0 \cdot 1 \times T/2$. "O" indicates the zero passage of the voltage wave (see Fig. 17 of the paper). At the commencement of τ_1, the overlapping period (metallic short-circuit), the short-circuit current rises exponentially according to τ_c, the time-constant of the circuit, to the value I_c at B. Now the arc sets in, and the arc current I_a dies down, the intervals t' being determined as explained. The total circuit characteristic of Fig. A is plotted correspondingly for the same time intervals as the currents I_a. The arc breaks at P, after which the current dies down exponentially and the voltage changes to $(-E)$, as shown in Fig. A. At no instant during the period τ_2 or $(\tau_2 - \tau')$ is the impressed voltage $E \sin \omega t$ in excess of the total circuit characteristic, and large enough to restart or maintain the arc. It will be observed that the commutation period could have been started later by the time interval τ'. Excessive increase of frequency would shift "O" to the left with a given setting of the commutator, and with excessive fall of the frequency "O" would move to the right, which could, in either case, bring the values of the impressed voltage above those of the total circuit characteristics and endanger safe and stable commutation. But it is quite clear that, within the normal working frequency-changes, there is a safe margin of operation for the jet-wave rectifier. I have also attempted to explain stable commutation by multiple cutting, that is commutation without the stabilizing resistance r (see Fig. 20 of the paper). It has been assumed, in order to establish some kind of working basis, that two arcs exist simultaneously and so two arc characteristics in additive superposition have been shown in Fig. C and E_{τ_2}M becomes the total circuit characteristic, which now belongs to a simple series circuit as shown in Fig. C. Otherwise the procedure of Fig. D is much the same as explained in Fig. A. But it will be observed that since in the calculation of the time-intervals the time t' is inversely proportional to e', the period after the overlapping interval must be considerably shortened. This is the case, and the time-interval τ' (Fig. D) is now almost twice as great as previously and commutation could have been started considerably later with complete safety. In addition, it will be seen that the total circuit characteristic E_{τ_1}P lies very much higher than in Fig. B; for this reason alone, commutation could be easily started very near to zero passage of the voltage $E \sin \omega t$, which is in full agreement with the author's statement. I understand that the jet-wave rectifier can also be used as an inverted rectifier, and I would ask the author if he could give some idea of the efficiency of commutation under these conditions.

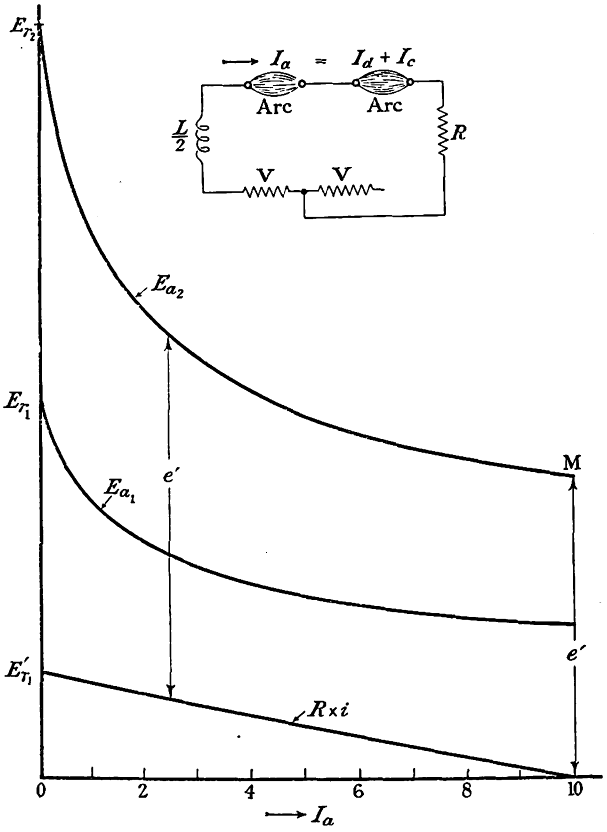


FIG. C.

Prof. W. M. Thornton: Although other accounts of this interesting development have been given none of them, I think, has dealt so fully with its design and the problems met with and overcome during the 15 years throughout which the author has been at work upon it. I only wish to encourage the author when I say that the rotary convertor, utilizing as it does the alternating voltages generated in every electromagnetic machine, is at first sight a more direct attack upon the problem of rectification; but even now—40 years or more since it was introduced—papers and books are still published to explain its action. It is perhaps unfortunate that Fig. 1 (*c*) shows the jet flowing upwards, though there is no reason why this should not happen. I take it that in Fig. 2 the lead S_1 is always negative and S_2 is positive. Accordingly, the auxiliary alternating current which deflects the jet by its reaction upon the fixed magnetic field must have a definite phasing-out relation to the current in V_1 or V_2; this relation depends on the magnetic polarity of the field F. It would perhaps be better to refer to the rectifier as a double-phase rather than as a 2-phase instrument (as in the first paragraph), for there is no 90-degree phase relationship between V_1 and V_2. I should like to ask the author whether any distortion has been perceived in the jet, say from circular to elliptical section, while passing through the field, for it is clear that the mercury, itself a conductor, will be polarized as it cuts the field—one side of the jet becoming positively, the other negatively, charged—and a current may flow across the jet. The voltage across the latter is, in any case, about 10 millivolts for a diameter of 4 mm. If a current could flow along a diameter and then divide and return by each side (as an eddy current), its density should be about 350 amperes per cm². This current is independent of the diameter, for as the latter becomes greater the voltage and the resistance increase in the same ratio. I may point out that the surface tension of mercury is extremely sensitive to external conditions and if at any point, either from the above action or in a parallel orifice, surface conditions suddenly change there is a tendency to change the curvature of the surface. At the top of page 948 there is a reference to the possibility of the occurrence of an explosion of hydrogen through air being drawn in. Hydrogen-air mixtures are not explosive so long as the proportion of hydrogen is above 75 per cent, and a relatively large volume of air would have to be drawn in for this to be possible. The resistance of the jet is as low as or lower than that of a rotary machine of corresponding power, and the efficiency, as shown in Fig. 30, is of much the same order, or rather higher. In order to understand Figs. 14, 15 and 16 the wave should be regarded as falling bodily. The device of the cutting points is very ingenious and satisfactory. The ripples in the current wave (Fig. 33) are not unduly great in view of the fact that when machines of such low resistance are used in parallel a small difference in voltage produces large pulsations of current. It is the old problem of a single-phase rotary convertor used for charging batteries, in which case the d.c. pulsation may be nearly 100 per cent of the mean current. I estimate that a difference of 2 to 4 volts in 500 may produce the pulsation shown. This is a practical consideration which may have to be given attention, for it does not affect ordinary mercury-vapour rectifiers where the resistance of the arc circuit stabilizes the current-flow. The regulation is very good, the mechanical stability of the apparatus on short-circuit has been proved, there are no inertia effects and the only questions which appear to be in doubt are those of cost. The quantity of mercury does not seem to be unduly great in comparison with the size of the plant. 7·5 litres or 2 cwt. are required for a 250-kW machine and a quantity of this size is often locked up as a catalyst in operations of, say, chemical manufacture. Every new idea is a direct asset to the industry, and I hope that the author will find engineers willing to give this one an extended trial on a commercial basis. I hope that its suitability for extra-high-tension systems will be considered. A system of rectifiers in series would, no doubt, be necessary for the purpose and there is a definite need for such equipment in cases where short-circuits would probably destroy other forms of apparatus.

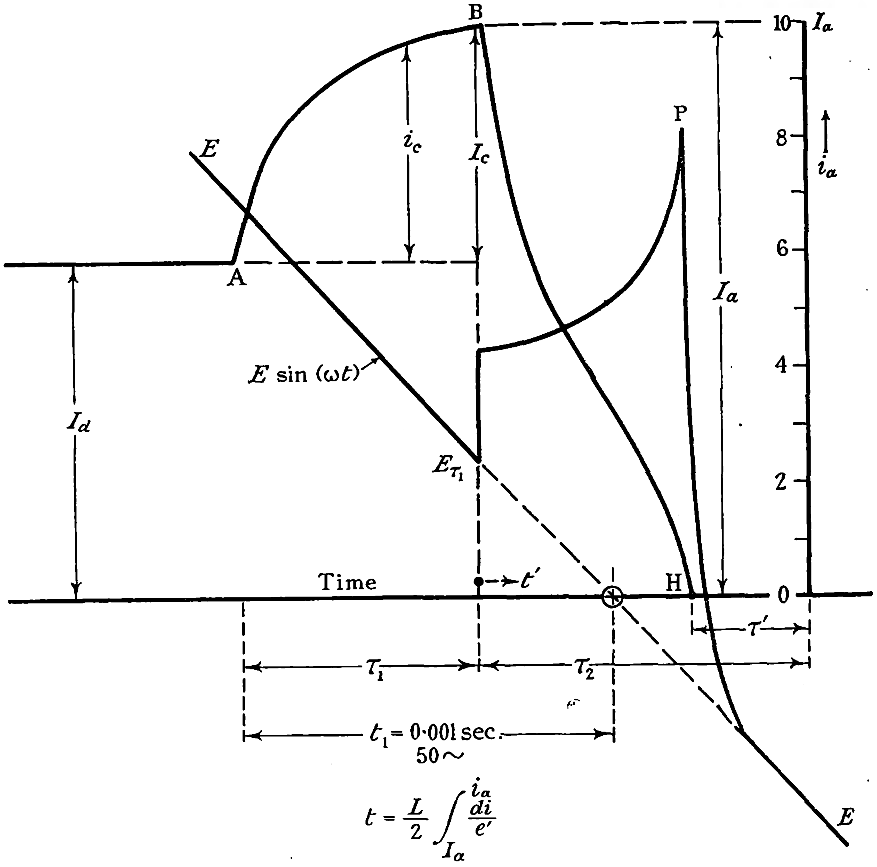


FIG. D.

Mr. A. T. Bartlett: The subject of power rectifiers is one which, in spite of its neglect by English engineers, is, I think, destined to play an important part in the developments of the near future. Several years ago a full description of the author's jet-wave rectifier was brought to my notice, and I formed an unfavourable opinion of it. My judgment was then, and to a large extent still is, that mercury or other types of rectifiers could not compete with rotary machines unless the voltage and power were high. The author was at that time using only about 150 volts per jet, whilst I believed a voltage of 600 to 1 000 to be the least which would justify the use of a rectifier. I fully appreciated that when a rectifier was required for low voltage the author's device was more suitable than the mercury-arc rectifier, as it had under these conditions a much higher efficiency, there being a constant potential-drop of about 20 volts in the latter. In the theory of his device the author has had to deal with the dynamics of common matter, and the task is very much easier than is the case with the mercury-arc rectifier. With regard to overload, the author states, on page 963, that a jet which will normally carry 185 amperes can stand a maximum of 300 amperes for 20 to 30 minutes, but that arcing sets in at 400 amperes. Such an overload current is very low in comparison with those which mercury-arc rectifiers are now being called upon to stand. Equipment of this type is now being supplied under contract to give 50 per cent overload for 2 hours, 120 per cent for 30 minutes and a maximum of 200 per cent; an arc rectifier the normal current of which is 200 amperes will therefore stand a peak load of 600 amperes—an overload which far exceeds that of any other rectifying plant. The arc rectifier can stand a prolonged overload, assuming that the heat produced is the only limiting factor, because the losses in it depend only upon the first power of the current, while in the jet-wave rectifier and rotary machines the loss is proportional to the square of the current. The author mentions a 300-kW rectifier as an example of the capacity of the plants which have hitherto been produced. Although this output is large in comparison with those of his earlier machines, it is not comparable with the sizes in general use to-day. Does the jet-wave apparatus require a large floor space? I have seen a 4 270-kW rectifier working at 1 500 volts on a floor space 9 ft. square. No statement of the initial cost of the equipment is given, and I should be pleased to have some information on this point. The author appears to be somewhat optimistic when he states that, although the highest pressure yet dealt with has been 550 volts, he hopes to be able to work with 100 jet-wave commutators giving a total of 100 kV. I find it difficult to visualize such a large number of jets at work with adequate insulation. Perhaps one of the most important statements in the paper is that referring to the possibility of the rectifier operating in the reverse direction, that is, transforming d.c. energy into a.c. energy. I should like to know whether this has ever been carried out in practice and, if so, what kind of wave-form is obtained. If the author can rectify to anything approaching 100 kV and can then convert the direct current to alternating current satisfactorily he has accomplished something for which we have all been hoping for many years, and such an achievement would revolutionize the methods of distribution of power. I should like to know whether the effects of a short-circuit are comparable with those of the back-firing of a mercury-vapour rectifier. Is there, in such a case, much destruction of the light mechanical parts, such as the knives, etc., which are used in the jet-wave machine?

Mr. S. A. Stevens: Will the author explain how it was that he first thought of using this principle? Had the cathode-ray oscillograph anything to do with it? With regard to high-tension apparatus, could not a small current at a high voltage such as is required by X-ray tubes be obtained on this principle, using water instead of mercury, or is the surface tension of water too low? We have been shown three separate rectifiers for a 3-phase supply. Could not one rectifier be used with a rotating field to cause the jet to oscillate in three dimensions instead of in one plane? Again, could an electrostatic field replace the magnetic field? In the description of the apparatus it has been assumed that the d.c. load is a pure resistance. Most loads have considerable reactance; what will be the effect of this? Can hydrocarbons be used instead of hydrogen in the commutation chamber, as was done in Poulsen arc wireless transmitters? The problem seems to be similar. What effect has the pressure of the gas? It is possible that a high pressure would be an advantage. At the moment of commutation the apparatus resembles the arc wireless transmitter. Can it give rise to similar high-frequency oscillations? Its use might seriously interfere with telephone and wireless circuits. I notice that the efficiency, as shown by the curve, falls off at low loads in the characteristic manner of d.c. motor-generators, although I believe the curves of mercury-vapour rectifiers maintain a higher general level.

Prof. E. W. Marchant: A mercury column which is conveying a current tends to break up when that current exceeds a certain value. This was shown in one of the photographs, and if it were to occur inside the rectifier this effect might cause excessive arcing. In the event of a short-circuit I imagine that the jet itself would break, so that there should not be much trouble involved in breaking a circuit which is connected to it externally. I am indebted to Mr. R. O. Street of the University of Liverpool for a calculation which he has made of the effect of the inward pressure on a jet of mercury carrying current, due to the interaction between the magnetic field produced by the current itself and the electric current in the jet. The effect is like the pressure on the surface of a tube due to some external source and increases as the jet becomes thinner. The "pinch" effect produced by it is often observed if a thin layer of mercury at the bottom of a narrow trough is used as a regulating resistance; if the layer becomes very thin it will break at that point owing to the "pinch" effect, and the process of making and breaking will continue indefinitely. Mr. Street finds that if there were no surface tension in the jet such a jet would be unstable when carrying current, that is, the jet would always tend to break into drops as soon as there was the slightest irregularity in it. Taking the ordinary figures for the surface tension of mercury the jet is stable, but the greater the current passing through it the less stable it becomes. If the current through the jet is 100 amperes and its diameter is 0·4 cm the force at the surface is about two-thirds of that due to surface tension, and the jet is just stable. If the current exceeds this value, however, the jet will immediately break up. This is probably the explanation of the fact that when the jet-wave rectifier takes an excessive current, owing to a short-circuit or some other cause, the circuit breakers controlling it do not come out. The jet itself acts as a circuit breaker and disconnects the load from the supply.

Mr. R. O. Street (*communicated*): It has been shown by Rayleigh * that a circular jet is not unstable for oscillations which alter its cross-section, and is unstable for longitudinal disturbances the wavelengths of which exceed the circumference of the jet. If the jet is of conducting matter, such as mercury, and is carrying an electric current, it is now shown that the electromagnetic forces decrease the stability of the jet. Only the simplest case is considered, in which the axis of the jet remains approximately straight, and in which the cross-section differs but little from a circle. Consider a section of the jet of radius R. At a point within it at a distance r from the axis, the magnetic force is $2(Qr^2/R^2)/r$ or $2Qr/R^2$, where Q is the total current, which is assumed to be uniformly distributed across the section. The force per unit length on a filament of cross-section δS parallel to the axis is thus

$$\left(\frac{Q\delta S}{\pi R^2}\right)\frac{2Qr}{R^2} \quad \text{or} \quad \frac{2Q^2 r\delta S}{\pi R^4}$$

inwards. The electromagnetic force is thus $2Q^2r/(\pi R^4)$ per unit volume, and this can be regarded as derived from a potential $Q^2r^2/(\pi R^4)$ per unit volume. If the equation of the surface of the jet is $r = a + \xi$, where ξ/a is small, the value of this potential per unit volume at the surface is $Q^2/[(a + \xi)^2\pi]$, or approximately

$$\frac{Q^2}{\pi a^2}\left(1 - \frac{2\xi}{a}\right)$$

If the mean speed of the jet remains uniform throughout its length, the oscillations will be independent of this speed, and so it may be taken to be zero. Assume, then, for the velocity potential in the fluid

$$\phi = CI_s(kr)\cos s\theta \cos(kz - \sigma t)$$

where the axis OZ is the axis of the jet in its undisturbed position, and (r, θ) are polar co-ordinates in a plane perpendicular to OZ. The constant C is small, $I_s(kr) \equiv (-i)^s J_s(ikr)$, where $i^2 = -1$, and J_s is the Bessel Function. The radial velocity at the surface is $\partial\xi/\partial t$; and as it must equal the radial velocity of the fluid there, $-\partial\phi/\partial r$, it follows that

$$\xi = [Ck/\sigma]I_s'(ka)\cos s\theta \sin(kz - \sigma t)$$

The effect of the surface tension T is to produce an inward force

$$T\left(\frac{1}{r} - \frac{1}{r^2}\frac{\partial^2\xi}{\partial\theta^2} - \frac{\partial^2\xi}{\partial z^2}\right)$$

or approximately

$$T\left(\frac{1}{a} + \frac{s^2 + k^2a^2 - 1}{a^2}\xi\right)$$

per unit area at the surface. Hence the pressure equation at the surface gives

$$\frac{Q^2}{\pi a^2}\left(1 - \frac{2\xi}{a}\right) + T\left(\frac{1}{a} + \frac{s^2 + k^2a^2 - 1}{a^2}\xi\right) = \rho\frac{\partial\phi}{\partial t} + \text{constant},$$

neglecting the square of the velocity. Substituting for ϕ and ξ, and equating the variable parts, we find

$$T(s^2 + k^2a^2 - 1) - \frac{2Q^2}{\pi a} = \frac{\rho\sigma^2a^2}{k}\frac{I_s(ka)}{I_s'(ka)}$$

If the oscillations are to be stable, all the constants must be real. The right-hand side of this equation is then always positive. Hence the condition for stability is

$$s^2 + k^2a^2 - 1 > 2Q^2/(\pi aT)$$

Case (I).—Oscillations in planes perpendicular to the axis.—Here $k = 0$, so that the condition for stability is

$$s^2 > 1 + 2Q^2/(\pi aT)$$

The displacement given by $s = 1$, which is a lateral displacement without deformation of the circular section, is now unstable. When there is no current flowing the equilibrium is neutral for displacements of this type. If Q is sufficiently large, other (integral) values of s may give unstable modes. Taking $Q = 100$ amperes $= 10$ C.G.S. units, $a = 0{\cdot}2$ cm and $T = 550$ dynes per cm, the value of $2Q^2/(\pi aT)$ is about $0{\cdot}6$; so that for values of s greater than unity the oscillations are stable. If, however, the current becomes as great as 220 amperes, the radius being the same, the oscillations corresponding to $s = 2$ are unstable. These oscillations make the cross-section of the jet elliptical.

Case (II).—Oscillations in planes through the axis.—Here $s = 0$, and the cross-sections remain circles but of varying radii. The condition for stability now gives

$$k^2a^2 > 1 + 2Q^2/(\pi aT)$$

or, using the same figures as before, $ka > 1{\cdot}3$. Thus the wavelength $(2\pi/k)$ must be less than $0{\cdot}8$ times the circumference of the section. It should be noted that if the current is not distributed uniformly over the section, the effect will be to modify the coefficient of Q^2 somewhat. For example, if the current at distance r from the axis is assumed to be proportional to r^n, where n is positive, the coefficient of Q^2 has to be multiplied by $(2 + n)/(2 + 2n)$. The conditions for stability are then slightly modified in form, but are not altered essentially.

[The author's reply to this discussion will be found on page 978.]

NORTH MIDLAND CENTRE, AT LEEDS, 11TH FEBRUARY, 1930.

Mr. W. W. E. French: I am taking part in the London discussion (see page 969) and I therefore propose to confine my present remarks to general considerations. While the fundamental principle—the jet-wave itself—was first conceived in 1907, the complete rectifier did not appear as an engineering fact in the Northern Cable and Wire Works until about 1925. The jet-wave rectifier was demonstrated in this country for the first time in

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* RAYLEIGH: "Scientific Papers," vol. 1, pp. 366 and 377, and vol. 3, p. 594.

1927, in the Electrical Engineering Department of the University of Leeds. A 200-kW rectifier for experimental and demonstration purposes has been installed in Bradford during the last week, and it is hoped that it will go into traction service within the next few days. This achievement, I hope and believe, will stand in the future to the credit of our Chairman, Mr. T. Roles. Thus, after 20 years of patient work, the author is satisfied that he has produced a rectifier which will do its work successfully, and I am sure that the reticence of the inventor is in itself an indication that it will be a good and reliable apparatus. I believe that the development of rectifiers is the beginning of a new era for the "Cinderella" of electrical engineering—direct current. A little consideration leads to the discovery, or rediscovery, that direct current is the most universally applicable form of electrical energy available, and it is certainly the most elastic in its industrial application. In this connection I need only remind you of electric traction, and recall the persistent efforts which have been made for the past 18 years to design a good a.c. motor for traction service. This period has ended in the vindication of the high-tension series d.c. motor for 1 500 to 3 000 volts. It is, I believe, now universally accepted that the series d.c. motor is the traction motor *par excellence*. Generally speaking, through the introduction of the commutation pole the operation of the d.c. machine has been perfected, and since reactance voltage is no longer the limiting consideration and heating only is the limit in the design problem, the d.c. machine can be built almost as cheaply as the induction motor, the only exception being the squirrel-cage type. The much-abused commutator has been adopted in a.c. machines for speed control and for power-factor correction even by the most ardent advocates of alternating current. The great obstacle to the extension of d.c. engineering has been the inflexibility of the d.c. distribution system. The alternating-current transformer substation is a simple, convenient and reliable means of providing feed points and regularizing the voltage on far-flung networks. Hitherto, the provision of equally serviceable feed points has been the difficulty with direct current since the substations or feed points must contain rotating machinery, which is expensive and needs constant supervision. During the past 10 years, however, mercury-arc and jet-wave rectifiers have been developed and brought to a high pitch of perfection, and it seems to me that the jet-wave rectifier, with its immunity from the harmful effects of short-circuits, is an important apparatus. It will, I think, prove to be suitable for use in the kiosk type of substation so much needed in the d.c. distribution system. In view of the present perfection of rectifiers, it appears to me that the wholesale scrapping of d.c. machinery is becoming progressively less justifiable. It is my considered opinion that if the present users of d.c. power realized the extent of the unnecessary expense and inconvenience to which they and the nation as a whole are put, they would rise in revolt and, I think, in justifiable revolt. I should like to refer to the comparative expenditure on copper in the various systems. In the statements for relative weights it is rarely mentioned that the section of the conductor increases in inverse proportion to the square of the power factor. Taking the most unfavourable condition for direct current, namely the 2-wire unearthed system, and the most favourable for 3-phase power, that is the 4-wire and the 4-wire earthed neutral, the relative weights for the same power and the same transmission losses are 100, 86·6 and 58·6 for the d.c. 2-wire, the 3-phase 4-wire and the 3-phase 4-wire earthed neutral, respectively. But if we introduce and consider a power factor of 0·80 a figure which is a common average, the corresponding figures are 100, 136 and 92, respectively. If I had taken an earthed return on the direct-current system, the relative weight figure would have fallen to well below that of the 3-phase system, which always has been considered to be inherently more economical in the outlay of copper. Another matter to which I would refer is that the total current and voltage change in an a.c. system is $2\sqrt{2}$, that is to say 2·82, or 282 per cent. This change takes place 100 times per second, or 8 640 000 times per day. In which of the two systems, I would ask, are the electrical stresses likely to be the larger? In the d.c. system, with no change at all (apart from a slow load change), or in the a.c. system, which has a change whose magnitude is 282 per cent—a change which takes place more than 8 million times per day? With regard to the possibility of high-tension d.c. transmission, I believe it is here that the jet-wave rectifier will establish its superiority over any system which I now know in commercial use, because the jet-wave commutator is pre-eminently suitable for the production and generation of high d.c. voltages. The paper states that it is possible to deal with 500 volts per jet, and in my opinion this is a conservative estimate as 1 000 volts can be safely negotiated in the jet if the manifold cutting device is used. Assuming that a 100-kV set is required, it appears from what I have said that 100 jets would suffice. If a jet can carry a normal current of about 200 amperes there at once arises the possibility of a 20 000-kW set which would occupy a small space compared with its output. For the same voltage transaction the "Highfield" transverter would require well over 2 000 sections or commutation bars. From what I saw at the Wembley Exhibition a 20 000-kW "Highfield" transverter would be an enormous machine: the one shown there was designed for about 2 000 kW, and it occupied a considerable space. According to the author, the jet-wave rectifier will not only convert alternating to direct current but will also perform the reverse process, as is naturally to be expected if the apparatus is a true commutator, and the device can thus be used as an inverted rectifier. Up to the present, high-tension direct-current transmission has suffered, apart from the problem of the generation of high-tension direct current, from the difficulty of inverse rectification. This obstacle has now been removed by what I would call the jet-wave inverter, and there is, to my mind, no valid reason why high-tension direct-current transmission should not become an accomplished fact within a very short space of time, if only the same technical and financial energy as has been given to the development of the a.c. systems is devoted to it. It will be, I think, superior to a.c. transmissions of 300 miles and over, and at least equally good for smaller distances. I should like to ask for some further information regarding voltage regulation, and also regarding the possibilities of automatic operation of the rectifier. I should further be interested to know whether the commutation problem is more difficult when the jet wave is used for inverted rectification.

Prof. E. L. E. Wheatcroft: I can find little to criticize in the author's calculations, but I should like to refer to the resistance of the jet [sections (6) and (7)]. If I have read the calculations of the wave-form correctly the front of the wave is essentially circular and, as the author himself said in commenting on the photograph, the stretching of the mercury jet from the straight line is $2\frac{1}{2}$ times the actual original length. If the average length has a ratio of $2\frac{1}{2}$, the "stretch factor" of the extreme end will probably be about 5 times. It is remarkable that the mercury can be stretched to a ratio of 5, and this can, I take it, only take place provided that the cross-section is correspondingly reduced. Does formula 27 (page 954) allow for the apparent reduced cross-section of the jet, as well as for the increase in length? From the point of view of the current, I imagine that the cross-section of the jet is not circular as it travels along, but that it is altered to an elliptical form by the twisting effect of the magnetic field. Three factors must, therefore, enter into the calculation of the effective resistance. The increased length (i.e. the curvature of the path), the decreased cross-section and the alteration of the shape of the cross-section must all be considered. From the point of view of design, this was the only topic on which I could find any basis for discussion. With regard to operation, I should like to refer to the oscillograms on page 967, and to what might be called the pseudo-oscillograms on page 968. The particular feature of this rectifier as distinct from mercury arcs is, I think, the clean-cut way in which the wave is switched over from one polarity to the other. The angle of overlapping between the two half-waves is kept down to a minimum by the designer—a feature which has the definite advantage of reducing the losses inside the rectifier itself and thus improving the efficiency. Its one disadvantage, however, is that the wave-form of the alternating part of the current is essentially of a very square shape. This is shown on page 967, Fig. 33 (*b*), which is an actual oscillogram. The effect of the square wave on the alternating line-current is seen in any of the parts of Fig. 34, where the current has essentially a form very far removed from that of a sine wave.

Mr. F. S. G. Hinings: The principle of the jet-wave rectifier presents some good features which differ radically from those of any other rectifier. With regard to the constant velocity of the jet, the statement on page 946 suggests that the pumping system may be a source of weakness, since the velocity in this system has to be kept within fine limits. In other words, the correct velocity in the pipe system seems to be at a point of almost unstable equilibrium, since departure from this velocity in either direction will cause serious, if not disastrous, failures. I should like to ask the author whether it will not be possible at this part of the apparatus to fit some protective device dependent on the velocity, and so ensure the isolation of the plant should the pumping system fail or be unable to maintain the correct velocity. On page 948 mention is made of air bubbles in the jet; such air could only be present through a defect in the piping of the system. Could this not be overcome by running the pumping system under an oil seal? With regard to the statement on page 967: "It may be noted that the loss of hydrogen to which inevitable leakages give rise may easily be made quite negligible," what are these leakages, and why do they occur? Leakages of hydrogen are dangerous, and this fault may militate against the use of the rectifier in certain places. The experience of the author with regard to short-circuiting, given on page 967, is very important as regards continuity of supply, especially in traction and railway services. The author indicates that the development stage is not wholly passed, and I should therefore be interested to know whether further developments are in his mind and, if so, whether they are radical, or only refinements of the existing systems. Such information is important from a commercial aspect, as people will not buy apparatus that is still in the early stages of development. On page 968 it is stated, regarding the various connections of transformers, that the star connection on the primary cannot be used with the series rectifier, owing to the fact that periodic flux is set up. I think that this remark would apply more especially to the 3-phase shell type than to the core type. Star-star connection with a tertiary winding and the normal connection as mentioned by the author are suitable. On page 969 the author states that he is convinced that the rectifier will produce direct current at pressures of 100 kV or more. This is a bold statement, and Mr. French seems to be confident that jet-wave rectifiers can be used in series to obtain 100 kV. I should like to ask the author whether he would propose to use the transformers in cascade, or to employ a number of transformers in parallel on the supply side with increasing insulation on the low-tension side. It would be interesting to have information as to the method of solving the transformer problem. Apart from the rectifier problem for this high voltage, the transformer problem would require special attention and, so far as one can see, it can only be solved economically by the principle of the cascade winding. In any case, for such high pressures the installation would be very bulky and expensive. The following points with regard to the jet-wave rectifier are open to criticism: (1) the length of life of the commutating knives; (2) the risk of explosion (there is a risk, and one would like to know more about it); (3) the insulation of the live parts when used in series for high voltages; (4) the small tolerance of cycle variation for any particular frequency; and (5) the limitation of output due to the heat generated in the jet.

Mr. A. N. Aikman: As yet it is too early to visualize the full extent of the utility of the jet-wave rectifier, for complete technical data, together with confirmation as to the reliability of the parts which make up the complete unit, are necessary if a correct estimate of its value is to be made. Of the auxiliaries—the excitation, pump, and hydrogen supply—the latter is, in my opinion, the weakest link, and its use precludes automatic working, a necessary feature of any new traction station. Whilst the spark-quenching potentialities of hydrogen are somewhat remarkable, the danger of explosion which attends the use of the latter must not be overlooked. In view of the numerous openings to the main body of the rectifier, the question of making all the joints leak-proof is of great importance, and it would be of interest to learn what is the best type of packing for this purpose. Any leakage in the packing may create conditions resulting in an explosion. The efficiency curve is much flatter than for the rotating machine, but it does not reach the higher figure usually given for a rotary convertor. Actually, the numerous leads between the transformer and the rectifier can be expected to result in a considerable drop in the commercial efficiency, just as in the case of rotary convertors; experience has shown that these have little gain in efficiency over, say, a motor convertor, although the individual efficiency of each machine is considerably higher. Having seen the jet-wave rectifier now under test in this country, I would suggest that finality in the arrangement is by no means reached and that attempts to simplify the control and arrangement of the low-tension switchgear are desirable. How often do the curry-combs require adjustment, and is the mercury liable to oxidation, thus necessitating frequent cleaning? Some explanation of the shaded area in Fig. 9 seems to be necessary.

Mr. F. N. Rendell-Baker: As a supply engineer, I am naturally interested in this rectifier. At present, systems are changing over from direct current to alternating current—a very costly process—and in this connection, having worked a 460-kW rectifier for the last 2 years, I have been led very seriously to consider whether supply authorities are justified in spending so much money on the change. Mr. French has already referred to direct current, and has rightly drawn attention to the comparative merits of d.c. and a.c. distribution. The rectifier which I have been operating is not of the same make as the one described by the author, but it appears to me to be rather more simple. In view of the use of motors, pumps, etc., any one of which may break down, I am afraid that the jet-wave machine may give trouble. It is interesting to note that the mercury rectifier requires just 5½ seconds to switch on. Years ago I was interested in motor convertors and remote-control substations, but it is well known that relays and similar devices are expensive, and some of them are not self-controlled. In my opinion, there should be no difficulty in going forward with the development of d.c. distribution using rectifiers. I would not consider the use of rotary plant in preference to rectifiers after my experience during the last 2 years. I think that the d.c. side of electrical engineering has been too easily passed over in order to go on to the more modern a.c. distribution with all its supposed efficiency, and I am of opinion that the same results can be obtained with much less cost by d.c. distribution. I think there is little doubt that Mr. Chattock has proved this to be the case with the many rectifiers which he installed at Birmingham. The cost of rectifiers at the present time is between £5 and £6 per kW. The rectifier at Halifax with which I am associated is self-controlled by a time switch, and it is inspected once a month. Can such results be obtained with any rotary substation? The rectifier is always found to be in order: it goes on load at 5.30 a.m. and cuts off at 11 p.m., for tramway operation. It has been working now for 2 years, and it once ran for 2½ months without a stop. With regard to the question of the spark on the jet-wave rectifier, this is by no means negligible at low loads, and the author gives its value as nearly 5 per cent. This appears to me to be rather a large quantity, as the efficiency of the rectifier substation at Halifax at a quarter of normal load is 90 per cent.

Mr. R. M. Longman: I am glad to know that d.c. supply is not yet obsolete, and that new ideas are still being introduced to assist it. I gather that the efficiency of the rectifier is in the neighbourhood of 95 or 96 per cent, but if transformers are necessary as well this figure will be reduced and the cost increased. With due respect to Mr. French's faith in the jet-wave rectifier and its use in the inverted fashion, I recommend the author to concentrate his energies on applying the equipment to d.c. supplies for lighting, power and traction. It is likely that d.c. networks will be kept going by means of such recent inventions as the mercury-arc rectifier and, now, the jet-wave rectifier. One of the reasons for effecting the change-over from direct current to alternating current is the fact that the condition of cables prevents them from carrying direct current. On the other hand, Mr. French states that a.c. cables are subject to changes in electrical stress which occur 8 million times per day; when cables have been changed over from direct current to alternating current, however, they have been able to stand these stresses, and such cables have operated satisfactorily for many years. There are numerous difficulties in the way of conversion by means of jet-wave rectifiers to high-voltage direct current for transmission. Mr. Hinings has referred to difficulties in connection with the transformers which are apparently necessary, and the only advantage to be derived from direct current when once the high voltage has been obtained is that transmission lines are simpler and cheaper. With regard to the experiment (page 967) of having a few heavy short-circuits on the high-tension lines in order to observe the effect upon the system, it is stated that the jet-wave rectifier carried on but that the remainder of the converting plant was thrown out of action. I am glad that some people are able to make such tests, although in this country it is difficult to carry them out unless they are made to appear as complete accidents. Practical experience of this new rectifier is, of course, what is required.

Mr. R. G. Ward: Are any great difficulties, such as require expert attention, experienced when starting up the apparatus, and does this operation take a long time? Regarding noise, is the apparatus of the type which has to be placed in a cellar or sound-proof chamber? Does the apparatus generate a large amount of heat when working, thus making it necessary to have a cooling device to keep the rectifier within reasonable limits of temperature? Also, is it a difficult matter to adjust the apparatus? The author's remarks suggest that some of the adjustments are of a very fine character and I should like to know whether, when once these are effected, there is any possibility of the machine getting out of adjustment. Some information as to the extent of the running repairs would be welcome, as these appear to me to form one of the principal items in connection with such a piece of apparatus as this, and on them depends its successful working. I should like to support Mr. French in his praises of direct current, as I feel sure that what he said was quite correct. Speaking from practical experience, I have not yet been able to satisfy myself that direct current has any rival for the purposes of speed variation and regulation on motors for driving machine tools and similar apparatus.

Mr. W. A. Crocker: It has been my privilege to help the author and his assistant in the installation of the 200-kW plant in Bradford, and I hope the author will allow me to explain a few of the practical points raised by previous speakers. With regard to automatic operation, after only 3 days' experience the whole installation appears to me to be remarkably simple. Mr. Rendell-Baker has mentioned that the switching-on period for a mercury-arc rectifier is about 5½ seconds, and my estimate of the time required for the operation on the jet-wave rectifier is practically the same. The necessary operations are to close the high-tension switch (making sure that the hydrogen content is correct), and then to start the mercury pump. The motor-generator immediately energizes the d.c. magnets and the mercury is raised to a certain head in the stand-pipe, where there is a reservoir and a float. This, incidentally, clears up Mr. Hining's point as regards making sure that there is a proper circulation of mercury, for the float could be fitted with a couple of contacts to ensure the existence of this head before the procedure is continued. The mercury jet is sent into wave form immediately, and it is then only necessary to close the low-tension main circuit-breaker and the main d.c. circuit-breaker. There are thus but few operations, and I consider that it compares favourably with a motor-convertor or rotary convertor in this respect. With regard to leakage of hydrogen, this appears to be one of the difficult problems, for the leakage takes place, I understand, through the pores of the cast-iron chamber as well as through the joints. The author is concerned with this problem, and he has considered spraying the chamber with molten nickel. The hydrogen leakage is made up from a cylinder which passes a small amount of gas, day and night. The oxygen content of the chamber must not exceed 5 or 6 per cent, otherwise the mixture is explosive, although the only effect of an explosion is to blow out the mica windows of the chamber and temporarily to deafen anyone present. In practice, it is easy to limit the content of oxygen to 1 per cent, this being the percentage in the commercial product, and such a proportion is quite safe as regards risk of explosion. Unless the leakage of hydrogen and the corresponding replacement is very small, this amount of oxygen will oxidize the mercury and necessitate frequent cleaning of the whole of the mercury circuit—pump, stand-pipes and chamber. It will be necessary, therefore, either to reduce the leakage or the oxygen content of this hydrogen.

Mr. I. S. Mackenzie: I should like to bear out what Mr. Rendell-Baker has said. Such experience as I have had of mercury-vapour rectifiers has been quite satisfactory. I do not entirely agree with Mr. French's opinion of the merits of direct current. I have a great many motors at Staveley and, whilst admitting the figures as to distribution, I submit that the cost of maintaining d.c. motors, even of the most modern types, is far greater than the cost associated with a.c. motors. We must move forward, however, and I believe, as did Dr. Ferranti, that there is a great future before high-tension d.c. transmission. It may take a long while to work out all the details of insulation, to overcome transformer difficulties, etc., but I think that these will be overcome, and I feel that perhaps Dr. Ferranti was right in this matter, as in so many others. If so, d.c. transmission at hundreds of thousands of volts will be the rule, with freedom from the present surge troubles.

Mr. T. Roles: The question raised by Mr. French and others with regard to the use of direct current is interesting. Years ago, when I was at Poplar, the then chief engineer decided to put down a high-tension direct-current system to meet a certain set of circumstances. It was in respect of its details rather a novel system, and Lord Kelvin, who came down to see some of his instruments which were not altogether giving satisfaction, evinced much interest in the scheme and ventured the opinion that direct current would eventually be the form of electrical energy most generally used. From his remarks on this occasion it was gathered that he had no great faith in the future of 3-phase and other alternating-current systems of electricity. It is interesting to note how, during different periods, the vogue has changed from d.c. to a.c. systems and from a.c. back to d.c. systems. I am therefore in agreement with the remark that we should not be too quick to abandon direct current. In many cases, however, it is necessary to consider changing over because of the expense involved in supplying the d.c. network. The use of rectifiers, therefore, becomes an economic question, and their adoption will largely depend upon their efficiency and the cost at which they can be supplied. Direct-current apparatus is extremely useful in cases where the demand is for ease of speed regulation. Although alternating-current motors which do very well in this respect have now been developed, the direct-current motor is, I consider, still pre-eminent for variable-speed work. Such being the case, the future of this rectifier will be followed closely. As Mr. French and others have stated, a 200-kW rectifier of this type has been installed in Bradford, and within the past few days it has been coupled up and switched into circuit. Fortunately, I have a number of assistants who are very keen on carrying out pioneer work, and they, I am sure, will give the apparatus every attention. I therefore think that the author will have no cause to regret its having been installed in a substation of the Bradford Corporation Electricity Department.

THE AUTHOR'S REPLY TO THE DISCUSSIONS.

Prof. J. Hartmann (*in reply*): The discussions have raised a multitude of questions, most of which may, however, be co-ordinated in groups dealing with more or less definite problems. In general, therefore, my reply will take the form of a series of brief treatments of these problems. I am glad that the discussion gives me this opportunity of supplementing the paper itself—dealing with the design of the rectifier—with information which, while it cannot well be grouped under this heading, has an important bearing on the jet-wave rectifier as an engineering proposition. I refer especially to the possible future applications of the jet-wave principle.

The Electromagnetic Pressure inside a Jet carrying an Electric Current.

Prof. Marchant has raised the question of the effects of the current on the stability of the jet, and Mr. Street has dealt with it in a valuable contribution to the discussion and may add an experimental result from my laboratory.

The internal pressure set up by the mutual attraction of the layers of a current-carrying cylindrical jet of radius r_0 at the distance r from the axis of the jet is expressed by

$$p_r = \frac{I^2}{100\pi r^4}(r_0^2 - r^2)\text{(dynes/cm}^2\text{, amps., cm)} \quad . \quad (a)$$

I being the value of the current in amperes. The average value taken over the cross-section of the jet is

$$p_a = \frac{I^2}{200\pi r_0^2}\text{(dynes/cm}^2\text{, amps., cm)} \quad . \quad . \quad (b)$$

With a cylindrical jet the internal pressure to which the surface tension C gives rise is

$$p_c = \frac{C}{r_0}\text{(dynes/cm}^2\text{, cm)} \quad . \quad . \quad . \quad . \quad (c)$$

The effect of both pressures is to reduce the velocity of the jet, the pressures p_a and p_c acting against the (geometric) head of the jet. A proof of this is given in Fig. E. Here the ordinate is the square of the volume V discharged per sec., while the abscissa is the geometric head. With a cylindrical jet the curve corresponding to a currentless jet should intersect the axis of the abscissa at a point determined by the counter-pressure (*b*), i.e. at the point $\Delta h_c = (C/r) \,.\, 1/(\rho g)$, ρ being the density of the liquid. As a matter of fact it has been proved that Δh_c assumes this value, which means that the surface tension of a liquid can be determined by means of such an experiment.* The horizontal distance between the two parallel curves of Fig. E is due to the electromagnetic counter-pressure. In the case considered the diameter of the jet was about 0·13 cm. From the exact value of the diameter of the orifice the value 0·235 cm was calculated for $\Delta h_a = p_a/(\rho g)$ by means of equation (*b*). The observed value is 0·239 cm.

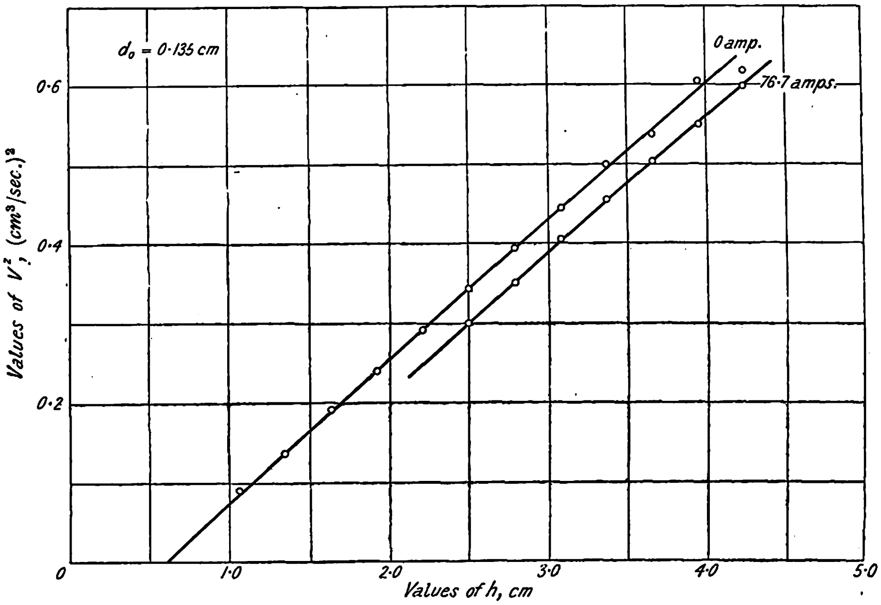

FIG. E.—Effect of electromagnetic pressure on the discharge of liquid in a jet.

Now in order to see whether the electromagnetic pressure is likely to break up the jet wave, let us consider the wave of an ordinary 33·3-kW, 180-V, 50-cycle commutator. This wave may have the constants $d_0 = 3\cdot 8$ mm, $a'(= \sin\theta_m) = 0\cdot 447$ ($\lambda = 12$ cm), and the main electrode may be placed at the distance $\beta = 1\cdot 8$ from the centre of the field. In the theory of the jet wave it is shown that the area of cross-section S of the jet wave in the axis is determined by

$$S = \frac{S_0}{\sqrt{[1 + \pi^2(a')^2\beta^2]}} \quad . \quad . \quad . \quad . \quad (d)$$

S_0 being the cross-section of the non-undulating jet. In the case considered $S = 0\cdot 367$, $S_0 = 4\cdot 16 \times 10^{-2}$ cm² for $\beta = 1\cdot 8$, i.e. just above the knife of the commutator. With 100 per cent overload the current which this part of the jet will have to carry is about 400 amperes. The electromagnetic pressure in it is thus, by equation (*b*), $p_a = 16 \times 10^4/(200 \times 4\cdot 16 \times 10^{-2}) = 1\cdot 92 \times 10^4$ or 1·45 cm of mercury. If there be a not too pronounced contraction on the wave, due for instance to the teeth of the curry-comb, pressure differences of about this order may occur between adjacent parts of the wave. *A priori* it would seem unlikely that such differences could break down the wave in the course of the few thousandths of a second during which they are in play, and as a matter of fact they do not. It would appear to be of great interest to study the question of the development of a deformation under the influence of pressure differences due either to surface tension or to the " pinch " effect of the current. The otherwise highly interesting analyses of Lord Rayleigh and Mr. Street do not, as far as I can see, throw light on this question.

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* "The Influence of Surface Tension on the Efflux of a Liquid in Jet Form," *Physical Review*, 1922, vol. 20, p. 728.

The main jet and the jet wave are thus not likely to be destroyed either by the heating or by the "pinch" effect of the current. Other elements, occasionally used, are more sensitive, e.g. the so-called jet-comb electrodes. In this electrode a " comb " of tiny jets was employed for tapping the rectified current. With a comb of jets of 0·75 mm diameter and a velocity of 250 cm per sec. it appeared that the rectified current could not be raised above 200 amperes without causing the comb-jets to evaporate. This effect could be predicted, for from formula (32) on page 955 a rise of temperature per cm of 414 deg. C. with the current in question is derived, and the length of the comb-jets was about 0·8 cm, giving a rise of temperature of 330 deg. C., nearly the boiling temperature. The effect of evaporation was very definite and manfested itself in a sudden increase of the pressure-drop of the commutator when a current between 200 and 220 amperes was reached. Further, the evaporation and pinch effects undoubtedly make themselves felt in the commutation process, as they both tend to break down the " strings " between the wave and the knife at the extreme end of the interval of metallic short-circuiting.

Deformation of the Jet-Wave due to Mechanical Disturbances.

It is a well-known fact that a liquid jet is highly sensitive to any contact. This explains the great difficulties met with in the development of the auxiliary electrodes, especially the tapping electrode. These difficulties were, however, finally overcome completely through the invention of the curry-comb and certain other electrodes. Otherwise the jet wave is an extremely stable system. From instantaneous photographs of waves used in the ordinary high-capacity commutators it is seen that such waves continue far beyond the part utilized. Hence, under ordinary conditions, the question of the stability of the jet and the wave has, as a matter of fact, but little bearing on the practical commutator. If, however, for any reason high-frequency vibrations, say of 1 000–2 000 cycles per sec., are likely to be set up in the jet-producing system, a different state of affairs exists, for the jet is highly sensitive to such vibrations. The effect of the vibrations has been thoroughly studied by means of instantaneous photographs. Three cases are illustrated in Fig. F(1, 2 and 3). The vibrations are in the direction of the axis of the jet pipe, and as a rule only such vibrations are dangerous. On the non-deflected jet, Fig. F(1), they give rise to prominences and contractions. When the jet is deflected by means of a constant field *F*, interacting with a direct current, the jet assumes the grotesque aspect shown in Fig. F(2). On the inner side a regular series of protuberances appear, the height of which increases steadily with the distance from the field. They of course originate from the prominences on the undeflected jet, these prominences suffering a smaller deflection than the contracted parts owing to their greater mass. In the jet-wave, finally, the same protuberances are seen on the inner side of the wave-tops [Fig. F(3)] and here only. It will be understood that the deformations in Fig. F(3) may endanger the safe contact between the wave and a curry-comb electrode. High-frequency vibrations, especially in the direction of the jet pipe, should therefore be avoided. So far, however, it has never been necessary to take any precautions against them, not even with rectifiers set up in a room together with other rotating machinery such as turbo-generators. On the other hand, high-frequency vibrations are the only disturbances to be feared when a rectifier is mounted in a railway carriage (see page 985).

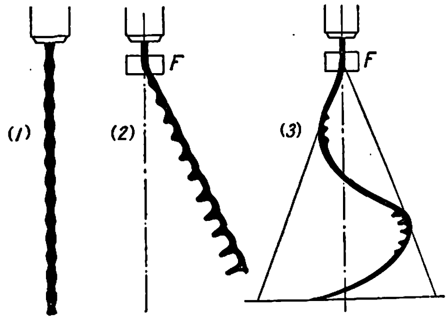

FIG. F.—Effect of high-frequency vibrations on jet and jet-wave.

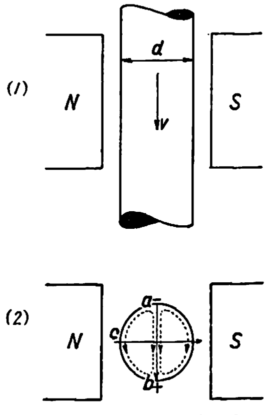

FIG. G.—Electromotive forces induced in the jet.

In connection with this subject I may answer a question raised by Prof. Thornton. Let us consider a disc-shaped element of the jet between two cuts perpendicular to the axis. During the passage of the field of this disc an e.m.f. is set up as shown in Figs. G(1 and 2). If the diameter of the jet is d cm, its velocity v cm per sec. and the field intensity H gauss, the e.m.f. between the points " a," " b " is

$$e = 10^{-8} \times dvH \text{ volts.}$$

With $d = 0{\cdot}4$ cm, $v = 500$ cm per sec., $H = 10\,000$ gauss, $e = 20 \times 10^{-3}$ volt. If two light contact-pieces are so arranged that they touch the jet at the points "a" and "b," the e.m.f. can easily be measured by means of a simple millivoltmeter. The jet with the contact-pieces thus constitutes a magnetometer. The latter has been developed in connection with the rectifier and, due to the small dimensions of the moving conductor, i.e. the disc, it has proved an excellent means for the survey of abruptly varying fields. The question raised by Prof. Thornton is whether circulating currents such as those indicated by the dotted curves in Fig. G will not flow. Obviously they will not, for the sum total of e.m.f.'s induced in any circuit situated in the plane of the disc is nil or, in other words, the e.m.f. along the diameter "a b" is exactly counterbalanced by the e.m.f. in any curved line from "a" to "b," say the line "a c b."

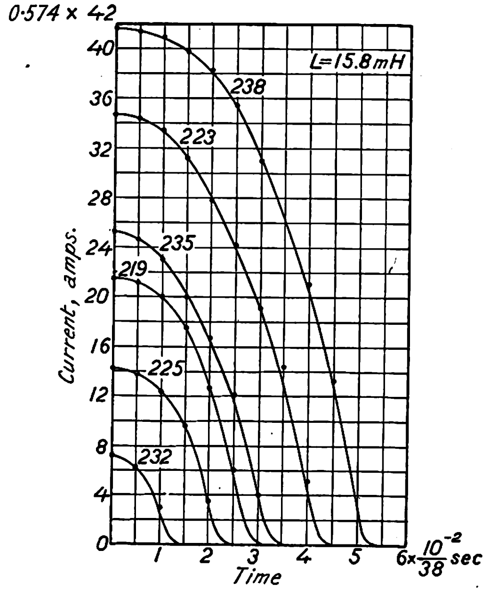

FIG. H.—Spark-current curves.

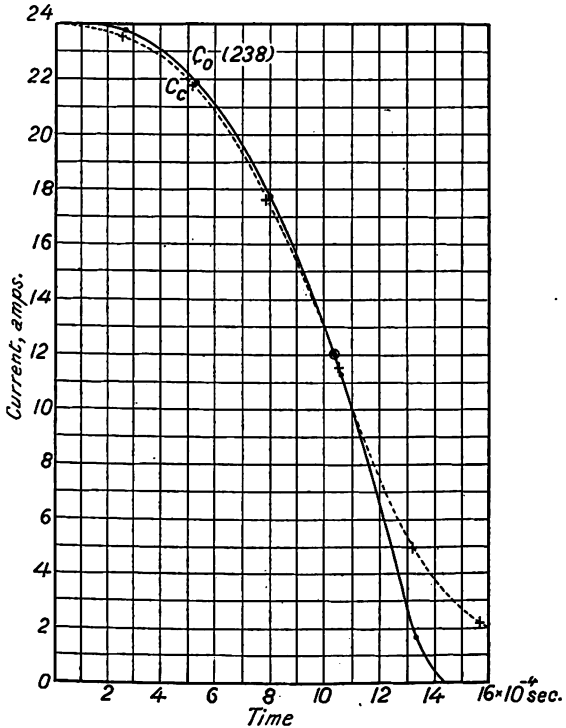

FIG. J.—Representation of the spark-current curve by $i = i_0 \varepsilon^{-yt^3}$.

Theory of Commutation.

Mr. French has, by his qualitative analysis based on a knowledge of the current/voltage characteristic of the commutation spark or arc, introduced into the discussion the question of the commutation. The theory of commutation has only been hinted at in the paper because it has but slight bearing on the problems of the design, and because the whole question of this theory is such a vast one that it requires—and deserves—special treatment. The subject is, however, hardly ripe as yet for such treament, since rather elaborate investigation is still pending. It may, however, prove of some interest to survey the problem in order to see how it may be tackled. Some years ago an investigation on the commutation spark was carried out by means of the jet-wave commutator. Some of the experimental results were obtained with an artificial circuit containing a constant e.m.f. and an ironless self-inductance. Oscillograms of the current through the commutation spark and of the voltage across the same were taken, and at the same time the spark power was measured by means of a wattmeter. Similar observations were taken with a com-

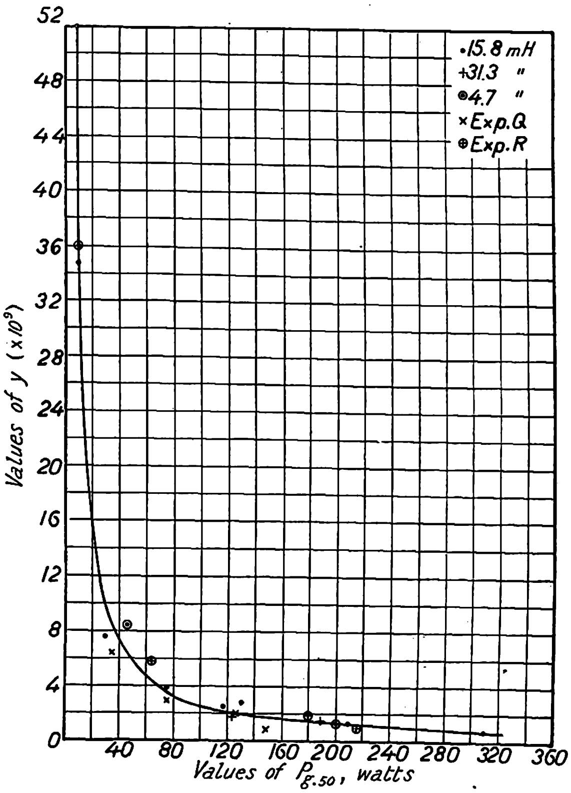

FIG. K.—Relation between spark-current constant, y, and spark power.

TABLE A.

A					B				
$P_{g.50}$	y		$y \cdot P_{g.50}$		$P_{g.50}$	y		$y \cdot P_{g.50}$	
watts					watts				
20	14·0		280		200	7·00		1 400	
40	7·2		288		400	3·80		1 520	
60	4·9		294		600	2·80		1 680	
80	3·5	$\times 10^9$	280	$\times 10^9$	800	2·14	$\times 10^9$	1 710	$\times 10^9$
100	2·6		260		1 000	1·75		1 750	
150	1·5		225		1 200	1·33		1 590	
200	1·2		240		1 400	1·05		1 470	
250	1·0		250						
			265×10^9					$1\,588 \times 10^9$	

mutator in a 6-phase series rectifier. Attention was drawn to the fact that the spark-current oscillograms were normally of a characteristic regular shape, as illustrated in Fig. H. Attempts were made to find an analytic expression suitable for the representation of the current, and it was found that the formula

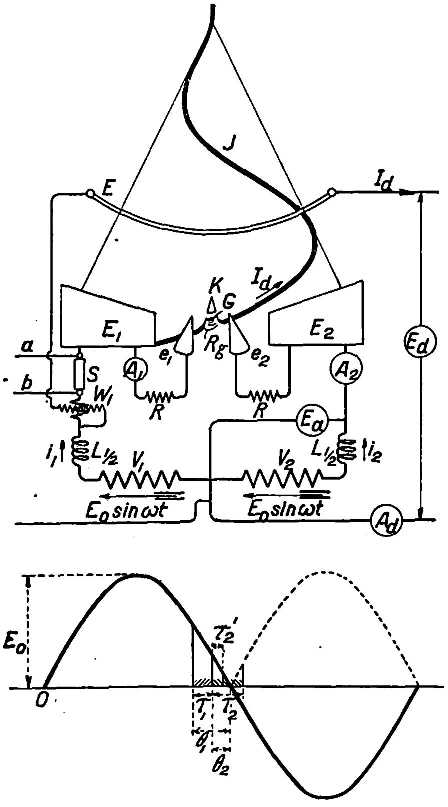

FIG. L.—Commutation diagram.

$$i = i_0 \epsilon^{-yt^3} \quad . \quad . \quad . \quad . \quad . \quad . \quad (e)$$

where i_0 is the initial value of the current, gave a good approximation, as will appear from Fig. J. Here C_0 is the actual oscillogram, while C_c is a curve of the type (e) determined in such a way that C_c and C_0 coincide for $i = \frac{1}{2}i_0$. The constant y characterizing the oscillogram was co-ordinated with the spark power $P_{g.50}$ corresponding to 50 commutations per sec. and a very simple relation was found, namely

$$y = \frac{c}{P_{g.50}} \quad . \quad . \quad . \quad . \quad . \quad (f)$$

c being a constant. In Fig. K a graphic representation of the y–$P_{g.50}$ relation is given, and in Table A (A) the numerical test of equation (f) is made.

The same simple law was found to hold good with oscillograms from a 33·3-kW, 180-V commutator in a 100-kW, 550-V rectifier [Table A (B)]. The value of $y \cdot P_{g.50}$, however, differs widely from that of the small plant. Obviously c depends on the characteristics of the plant, but the connections have so far not been explored.

The knowledge reviewed above was made the basis of a theory of commutation. In the first instance certain general relations may be derived from it. Thus, for instance, if we cut the wave by two knives instead of one, we get two sparks, each with half the spark power. Hence we conclude that the constant y for each spark must be twice that of a single spark. This means that the spark interval τ_2 is reduced in the ratio $\sqrt[3]{2}$ (= 1·26) to 1. With three knives the factor of reduction should be $\sqrt[3]{3} = 1 \cdot 44$, and so on. Again, an attempt was made to predict the spark power with a given plant, it being assumed that the numerical value of the constant c was known for that plant. The commutator in Fig. L was considered, and an expression was derived for the spark power P_g. It should be understood that during the interval τ_2' the right-hand resistance is inserted in series with the spark G, while during the rest of the spark-interval τ_2 this resistance is short-circuited. During the interval τ_2 the current relations in the short-circuited secondary transformer are obviously determined by

$$2E_0 \sin \omega t - L_{\frac{1}{2}} \frac{di_1}{dt} + L_{\frac{1}{2}} \cdot \frac{di_2}{dt} = i_1 R_g - i_2 R \quad . \quad (g)$$

R_g being the resistance of the spark.

If the rectified current I_d is completely smoothed out, then

$$i_1 + i_2 = I_d \quad . \; . \quad . \; . \; . \quad (h)$$

By eliminating i_2 we get

$$2E_0 \sin \omega t - 2L_{\frac{1}{2}} \,.\, di_1/dt = i_1 R_g + (i_1 - I_d)R \quad . \quad (j)$$

The spark power is now

$$P_g = 2p \int_0^{\tau_2} i_1^2 R_g \, dt, \quad . \; . \; . \; . \; . \; . \quad (k)$$

$2p$ being the number of commutations per sec. Hence

$$P_g = 2pL_{\frac{1}{2}}\bar{i}_1^2 + 2p \,.\, 2E_0 \int_0^{\tau_2} i_1 \sin \omega t \, dt$$
$$- 2pR \int_0^{\tau_2} (i_1 - I_d) i_1 \, dt \quad . \quad (l)$$

where $\bar{i}_1$ is the value of i_1 at the commencement of the spark interval. This value is $I_d + i_c$, where i_c is the short-circuit current which has been increasing during the overlapping interval τ_1. Expression (l) is of some interest. The first term on the right-hand side is twice the electro-kinetic energy stored up in the inductance shown on the left in Fig. L. The second term denotes the increase of the spark power due to the transformer voltage. It may be negative if the greater part of the spark interval is situated to the right of the zero point of the voltage in Fig. L. The third term represents the reduction of the spark power due to the electrode resistance R, in which a certain part of the electro-kinetic energy may be absorbed. It is, however, not certain that the reduction is positive, as will appear from equation (l). At no load, $I_d = 0$, it is always positive, i.e. the resistance always tends to extinguish the arc in this case.

Now, in order to predict the spark power, $\bar{i} = I_d + i_c$ must be known. It is a simple matter to derive expressions for i_c and therefore for $\bar{i}$. During the overlapping interval τ_1 the current relations are determined by equations (g) and (h), the term $i_1 R_g$ being omitted from the former. For the commutator in Fig. L the following expression is derived:—

$$\bar{i} = I_d + \frac{E_0}{R/2}\left[\sin\left(\pi \frac{\vartheta_1 - \tau_1}{\mathbf{T}/2} + \phi\right) \right.$$
$$\left. - \epsilon^{-\frac{\pi}{\tan\phi} \cdot \frac{\tau_1}{\mathbf{T}/2}} \sin\left(\pi \frac{\vartheta_1}{\mathbf{T}/2} + \phi\right) \right] \Big/ \sqrt{[1 + \tan^2 \phi]} \quad (m)$$

where $\tan \phi = \dfrac{\omega L_{\frac{1}{2}}}{R/2}$.

Then, again, the determination of P_g [eqn. (l)] requires a knowledge of the variation of the spark current i_1 with time. The latter, however, depends mainly on the spark power to be determined. Hence the problem must be solved by approximation. This was done in the following way.

The first term $P_{g.0} = 2pL_{\frac{1}{2}}\bar{i}_1^2$ [cf. eqn. (l)] was used as an approximate value for P_g. From this the expression

$$i_1 = \bar{i}_1 \epsilon^{-yt^3} \quad . \; . \; . \; . \; . \; . \quad (n)$$

where

$$y = \frac{c}{P_{g.0}} \quad . \; . \; . \; . \; . \; . \quad (o)$$

was derived and taken to represent the variation of the spark current with time. Then the two last terms of (l) were calculated by numerical integration and so a first value of P_g was found. By replacing $P_{g.0}$ in (o) by this value and by repeating the numerical integrations a new and improved value for P_g could be computed. It was generally found, however, that the first and second values of P_g were practically identical. The method was tested on a series of commutations for which the spark losses were observed. The knowledge of the commutation constants τ_1 and τ_2' was hardly good enough for a complete test, but at any rate a certain agreement was established. Moreover, the method was found to be suitable for an *a priori* survey of the variation of the spark power with the commutation constants and the constants of the electric circuit, such as $\tan \phi$. The method furnishes not only a value of P_g but also an approximate picture of the variation of the spark current, namely that of equation (n) (with y calculated from the value found for P_g). It should be noted that the method depends on a knowledge of one numerical constant only, the constant c, which, as mentioned, seems to be characteristic of the plant, i.e. of the transformer constants.

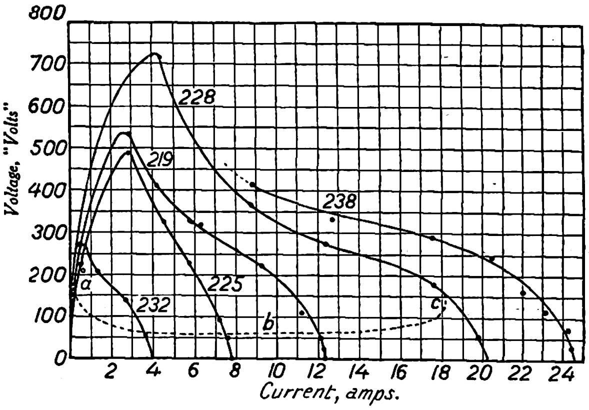

FIG. M.—Voltage/current characteristics.

It is interesting to contrast Mr. French's method with that indicated above. His is based on a knowledge of the voltage/current characteristic of the commutation spark. This characteristic is, however, by no means common to all sparks or plants. It is just as individual as the current/time curve (the spark-current oscillogram). For the sparks which were considered in Fig. H the voltage/current characteristics are represented in Fig. M. Attempts have been made to derive a general expression for these characteristics. If this is achieved the commutation problem can be solved graphically and, possibly, analytically. It may be mentioned that systematic experimental investigations have now been planned as a basis for the complete solution of the commutation problem with the jet-wave commutator.

The Jet-Wave Inverter, the Jet-Wave D.C. Transformer and the Jet-Wave Frequency-Changer.

Mr. French desires information with regard to the inverse rectifier, "the inverter" and related jet-wave apparatus. When used in the ordinary way, the rectifier conveys electrical energy from the a.c. mains to the d.c. busbars. If, however, the voltage of the latter is raised above that of the rectifier, energy will be transmitted in the opposite direction, the complete electric system being reversible, if it is not made irreversible by suitable means. Preliminary investigations on inverse rectification have been carried out with a laboratory plant of about 7 kW and it has been proved that, apart from the direction of the various currents, the current relations are identical with those of the same system used for rectification. There is, however, a very interesting difference between the rectifier and the inverse rectifier, and this is illustrated in Fig. N. If, with a rectifier, the commutation could be delayed until after the voltage had changed its sign [Fig. N(2)], a reduced spark loss would ensue owing to part of the electro-kinetic energy being absorbed by the transformer voltage. The scheme cannot, however, as a rule be realized, because the delay would make the commutation unstable. With the inverse rectifier or "inverter" the current is in the opposite direction with regard to the transformer voltage [Figs. N(3) and N(4)]. It means that part of the electro-kinetic energy is normally absorbed during the overlapping interval and that the commutation should be precipitated in order to reduce the spark loss [Fig. N(4)]. There is nothing to prevent this; on the contrary the process of commutation is made more stable. The inverse rectifier therefore provides an effective spark damper.

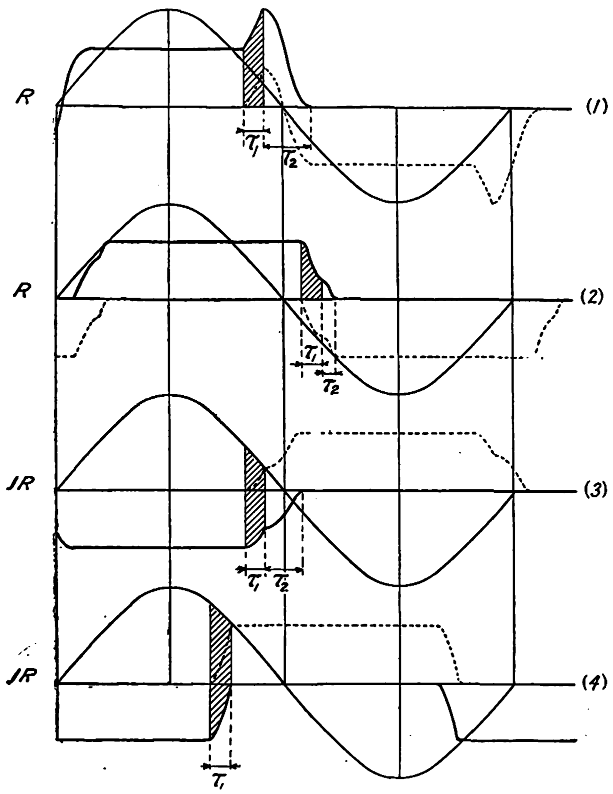

FIG. N.—Commutation with rectifier (1 and 2) and with inverse rectifier (3 and 4).

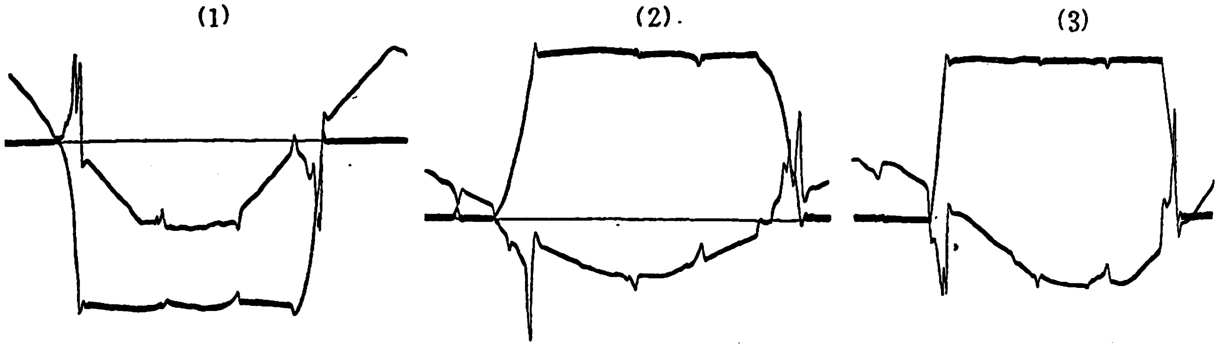

FIG. O.—Oscillograms of rectifier and inverter.

This spark-damping is seen in the oscillograms, Fig. O, which all represent the current flowing in a secondary half-phase of the transformer of the 6-phase series system. Fig. O(1) corresponds to rectification ($I_d = 25$ amperes, $E_d = 242$ volts) with t_1 (Fig. 17) equal to 2 per cent of the half-period. In Fig. O(2) inverse rectification ($I_d = 25$ amperes, $E_d = 202$ volts) with $t_1 = 2$ per cent is represented. Finally Fig. O(3) again corresponds to inverse rectification ($I_d = 25$ amperes, $E_d = 202$ volts), but now t_1 is 12 per cent. It is clearly seen that the current falls off much more steeply in Fig. O(3) than in Fig. O(2), owing to a pronounced reduction of the commutation spark.

When inverse rectification is possible it is safe to say that step-up or step-down transformation can also be carried out by means of jet-wave commutators. This application has been studied on a small scale and found to be a promising technical proposition. Fig. P is a diagram of a 6-phase system. The 3-phase transformer is furnished with 3 sets of windings per phase, the S_I–S_{II} and P windings in Fig. P. Two 6-phase series jet-wave systems I and II are connected to the S_I and S_{II} windings of the 3 phases as shown. The P windings are connected in delta to an auxiliary 3-phase source N which is also assumed to supply the exciting currents for the two sets of commutators. In the d.c. transformer plant the primary d.c. source E_I now supplies energy to N, the 6-phase system I acting as an inverse rectifier. N, however, again supplies the same energy to the secondary side of the d.c. transformer (E_{II}), the 6-phase system II acting as a rectifier. It will thus be seen that the source N and the windings P need only be designed for a small fraction of the power dealt with in the transformation. The transformation ratio is determined by the ratio of turns of the S_I and S_{II} windings, as in the case of the ordinary a.c. transformer.

If the commutators II in Fig. P are removed, the rest of the plant constitutes an inverter, i.e. a d.c.–a.c. transformer. The frequency of the a.c. voltage produced is determined by that of the auxiliary a.c. source N. The system here considered is the inverter in its most general form, while the ordinary rectifier plant, used inversely, is only suited for the transmission of energy from a d.c. line to an a.c. line under voltage. With the latter system the transformer flux necessary for the transmission of the energy may be regarded as being produced partly by the a.c. voltage. In the general solution of the inverter problem the flux is to a certain degree produced by the auxiliary a.c. source N, Fig. P, and it is possible to choose any frequency whatever.

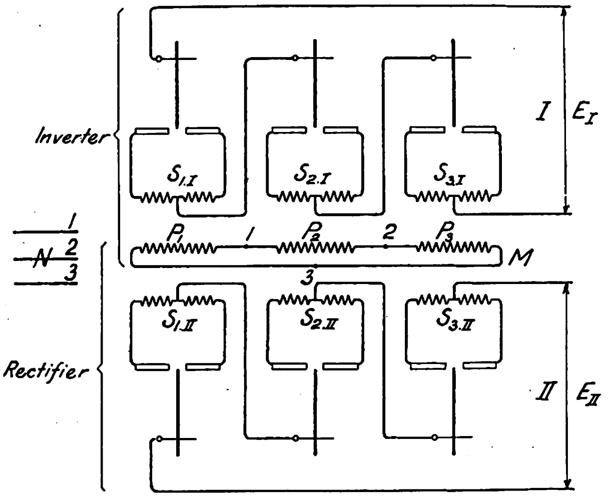

Fig. P.—Diagram of d.c. "transformer."

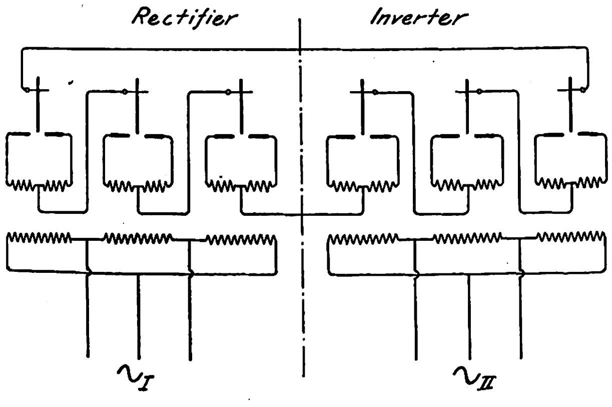

Fig. Q.—Frequency-changer.

Finally, it will be gathered that a frequency-changer may be produced by means of a rectifier in combination with an inverter. By means of the rectifier, the action of which is governed by the primary a.c. voltage, this voltage is changed into a d.c. voltage. The latter is again changed into an a.c. voltage by means of the inverter. If the frequency-changer is to form a bridge between two networks of different frequencies $\sim_I$ and $\sim_{II}$, the frequency-changer assumes the simple symmetrical form shown in Fig. Q.

An argument which has been advanced against the scheme of d.c.–a.c. transformation indicated above is that the wave-shape of the a.c. voltage deviates considerably from that of a sine curve. This is generally true, as will be understood, for instance, from Fig. 34 of the paper. By means of special transformer connections, however, the wave-shape can be made to approximate more closely to a sine curve. Another method is to use 12-phase instead of 6-phase commutator systems.

High-Tension D.C. Transmission.

This scheme has been referred to by Mr. Bartlett, Mr. Hinings and Mr. Longman. Its realization requires means for the production of a high d.c. voltage (e.g. 100 kV) and means for stepping it down. Owing to the comparatively high voltages for which the jet-wave commutator can be built, I am of the opinion that it yields the simplest available means for the production of such high d.c. voltages. I fail to see why the transformer problem, which, it is true, has so far not been seriously discussed, should prove so difficult as Mr. Hinings seems to think. I am also confident that the jet-wave principle will furnish the necessary means for dealing with the high d.c. voltage when once produced. On the whole I consider the applications of the jet-wave principle to the proposed scheme of high-tension d.c. transmission to be very promising, since this principle seems to furnish nearly all that is necessary to enable the scheme to be carried out.

The Jet-Wave Rectifier as a Means for Railway Traction.

So far the chief applications of the jet-wave rectifier have been to tramway traction and to the operation of motors in a factory, and, apart from a few slight objections, it has undoubtedly proved suitable for these purposes. As far as I am able to judge, a very promising future field of application is that of railway traction, because the jet-wave rectifier is reversible and because it seems suitable for installation in trains. I assume that the best system for railway electrification is that in which the electrical energy is transmitted to the train in the form of high-tension alternating current, transformed in the train itself to direct current at, say, 1 500 volts, and utilized in a d.c. series motor. This scheme can in all probability be realized by means of the jet-wave rectifier, but it seems doubtful whether the mercury-arc rectifier will operate safely in a running car. At any rate the latter rectifier is not reversible. The reversibility of the jet-wave rectifier implies that regenerative braking can be used. According to electric railway authorities * this form of braking may result in a saving of approximately 15 per cent of the total power required and, especially in connection with heavy passenger or freight service on mountain grade sections, in considerably increased safety, reduced wear on equipment, and increased comfort to passengers. I have not yet been able to install a jet-wave rectifier in a running railway carriage, but the effect of the accelerations by which the jet is likely to be influenced in the train has been carefully discussed, and it has been found that the accelerations or decelera-

* Cf. A. S. Rickey: "Electric Railway Handbook" (New York, 1924).

tions caused by starting, braking, passing of sidings, or driving in curves, are quite harmless, or at any rate easy to counteract by means of springs. The same is true for the vertical accelerations set up by irregularities in the rail joints. The only point on which there may still be a slight doubt is the possibility of the high-frequency vibrations referred to earlier in my reply, but if they occur they can undoubtedly be eliminated by springs in connection with some damping device.

The Jet-Wave Rectifier in Automatic Substations.

Mr. Ward raises the question of the attention required for starting up the jet-wave rectifier. This gives me an opportunity of furnishing some information with regard to this starting and also with regard to the use of the rectifier in automatic substations, a field of application for which the rectifier would seem especially suitable.

With an ordinary non-automatic plant the rectifier is started in the following way: (1) The oil switch is closed; (2) the pump is started; (3) when the mercury has reached the normal height in the reservoirs the combined exciting-current and magnetizing-current switch is closed; and (4) the commutators are connected to the main transformer by closing either a separate switch for each commutator or a common 6-pole switch. The complete starting of the rectifier can be performed in from 10 to 15 sec. when done in this way, and it requires no kind of expert attention. It is, however, interesting to note that the whole operation can be done by simply pressing the button of the oil switch, provided certain simple automatic devices are employed, and, furthermore, provided the rectifier can remain permanently connected to the d.c. busbars. The first effect of connecting the plant to the a.c. mains is that the pump is started, and at the same time the small d.c. generator supplying current to the magnets, if such a generator is used, is also started. (The power necessary for the operation of the pump and generator is so small that a simple squirrel-cage asynchronous motor without any starting device may be employed.) When the mercury has reached the normal height in the reservoirs the exciting-current circuit is automatically closed by the mercury proper and, as the magnets are already excited, the rectifier will start to supply current to the d.c. busbars. As a rule it does not matter, with rectifiers of moderate size, how large the load is at the moment the rectifier starts operation. If the pump motor should fail, all that will happen is that the d.c. voltage will disappear. When, owing to a deficiency in the supply, the mercury sinks in the reservoir, the exciting-current circuit will first be broken, the immediate effect of which will be that the jet will no longer undulate. This means that, owing to the design of the main electrode, the a.c. side of the plant is automatically cut off from the d.c. side. The same effect is produced by the failure of the exciting current or the magnetizing current of any of the three commutators or set of parallel commutators of a 6-phase series rectifier.

Considering now the question of automatic plants, it would seem, from what has been stated, that the arrangements must be simpler with the jet-wave than with the mercury-arc rectifier, in that plants of the latter type must generally include automatic devices for the starting, exciting and vacuum-pump elements. Also, as artificial cooling is not necessary with the jet-wave rectifier, the corresponding automatic starting devices are also eliminated. Generally the jet-wave plant is now provided with a 3-pole overload circuit breaker inserted in three of the 6 wires between the main transformer and the three commutators. This circuit breaker protects the plant not only against short-circuits on the d.c. side, but also against internal short-circuits. So far it has been found necessary only to use quite ordinary types of circuit breakers and not (as with the more delicate mercury-arc system) special high-speed breakers. In automatic plants the overload circuit breaker—like the corresponding breaker in the mercury-arc plant—must be combined with a relay for switching it in again a definite number of times after an interruption has occurred. In d.c. lighting plants an automatic regulation of the d.c. voltage must of course be provided with both types of rectifiers. The jet-wave rectifier plant is, as already stated, reversible, while the arc rectifier plant is not. In cases where this quality is not desirable, the jet-wave rectifier plant must be furnished with an automatic reverse-current switch.

The Jet-Wave Rectifier compared with the Mercury-Arc Rectifier.

The jet-wave rectifier and the mercury-arc rectifier have been compared several times in the course of the discussion, notably by Prof. Thornton, Mr. Bartlett and Mr. Rendell-Baker. I think Mr. Bartlett is perfectly right in saying that it has been much easier to gain insight into the nature of the jet-wave rectifier than into that of the mercury-arc rectifier. The jet-wave rectifier is a purely mechanical device, and is much simpler than its competitor. Knowing the difficulties to which the development of the former system has given rise, I therefore fully appreciate the achievement of those who made the mercury-arc rectifier the practical engineering proposition it certainly is to-day. I admit that, at present, the capacity of the latter rectifier is greater than that of the jet-wave rectifier. I am, however, convinced that the jet-wave rectifier, when its manufacture has been rationalized, will soon gain upon its competitor and finally overhaul it. I trust I have made it fairly clear that there is nothing to prevent practically all sizes of jet-wave rectifiers for practically all voltages being made, and I shall endeavour to sum up the facts upon which I base my opinion with regard to the final outcome of the competition between the arc rectifier and the jet-wave rectifier (or rectifiers of substantially the same qualities).

The efficiency of the jet-wave rectifier is, at medium voltages (550 volts), practically identical with that of the arc rectifier, while at lower voltages it is higher. Hence, while an economical rectifier of the arc type cannot be built for voltages below 220, and with difficulty for even that voltage, economical jet-wave rectifiers can be produced for voltages down to 110 and most likely for still lower voltages. In this connection it may be mentioned that serious consideration has been given to the possibility of developing low-voltage jet-wave rectifiers for the chemical industries. In connection with the question of efficiency I should like to say a few words about the glass-bulb rectifier. I suppose that Mr. Rendell-Baker's experiences refer to this type of rectifier, which undoubtedly yields a wonderfully simple means for a.c. rectification, although in my opinion a rather costly one. The price of a glass-bulb rectifier plant for 550 volts, 400 amperes (the size of the jet-wave rectifier installed in Bradford) is stated in the catalogue of a leading Continental manufacturing company to be 12 880 reichsmarks (£630), not including the main transformer or means for voltage regulation. The plant comprises two glass bulbs, each for 200 amperes and 501–600 volts. The two bulbs cost £124 6s., to which must be added a transport insurance of 10 per cent, or £12 8s. The total price is thus £136 14s. Now the average life of such bulbs is on an average 8 000–10 000 hours. Using the latter figure we find that 3·27d. must be set aside per hour for renewal. Let us assume that the plant is running on full load. Then the d.c. energy produced per hour is about 200 kWh. At 0·35d. per kWh for the a.c. energy, the raw material for the production of the 200 kWh of d.c. energy has cost 5s. 10d. Hence the 3·27d. represents a percentage loss in the production amounting to $3 \cdot 27 \times 100/5 \cdot 8 \times 12 = 4 \cdot 6$ per cent. This loss may be given other names, but actually it is equivalent to a reduction of the efficiency by 4·6 per cent. With the jet-wave rectifier there is no corresponding loss.

I have tried to convey an idea of how simple a matter the operation of a jet-wave rectifier is. As stated, the rectifier can be started within 10 sec., even with the present low-tension switchgear, which Mr. Aikman quite correctly thinks can be simplified. The simplicity in operation of the rectifier has been considered a prominent feature of the new apparatus by all who have had experience of it, and it has been suggested that it lends itself better than the arc rectifier for use in automatic substations. I fail to see why the quite harmless circumstance that hydrogen is used as a medium of commutation should preclude automatic working, as suggested by Mr. Aikman. Again, by all who have had experience in its use the jet-wave rectifier has been considered well able to stand all kinds of rough treatment. As far as I can see, it is superior in this respect to the arc rectifier, the operation of which is still in a rather obscure way threatened by the phenomenon of backfiring. Mr. Bartlett states that the modern arc-rectifier equipment is called upon to stand larger overloads than those claimed in my paper for the jet-wave rectifier. This is true, but what percentage overload a plant will stand obviously depends solely on what is taken to be the normal load. With 33 per cent reduction of the nominal value of this load the overload capacity of any plant will be doubled, and with the jet-wave rectifier this reduction would leave the efficiency at full load unaltered.

In a comparison between the mercury-arc and the jet-wave rectifier great stress must be laid on the fact that the latter is a reversible system. This quality, which the mercury-arc rectifier in its ordinary form does not possess, opens up great fields of applications for the jet-wave principle—as already indicated in my reply.

It may be questioned whether the arc rectifier or the jet-wave rectifier is the simpler, but I know that the manufacture of large jet-wave rectifiers is now, and will be especially in the future, a very much simpler process than that of arc rectifiers. Therefore the cost of production cannot fail to be much smaller for the former than for the latter. It has been mentioned in the discussion that a 200-kW/550-V jet-wave rectifier plant has recently been installed at a substation in Bradford. This rectifier was manufactured under very unfavourable conditions in Copenhagen, in a workshop not in the least equipped for the purpose. The whole low-tension switchgear, together with the auxiliary transformer, had to be bought at the full list price from various firms. Notwithstanding these drawbacks the whole plant, apart from the main transformer but including the low-tension switchgear, has cost us only what a glass-bulb mercury-vapour plant of the same size delivered by one of the leading Continental firms would have done. Since that time the jet-wave rectifier has been greatly simplified. The rather expensive slide arrangement for setting the main electrodes has been discarded and the velocity of the jet changed from 6 to 5 metres per sec., which results in a reduction of the mercury content of the rectifier by about 30 per cent. It would therefore seem that the commercial production of the new rectifier is almost sure to be a good business proposition.

Various Subjects.

The discussion contains a great number of suggestions and questions, with some of which I shall now deal. Prof. Thornton suggests that the large pulsations in the current supplied by the jet-wave rectifier when operated in parallel with a constant-voltage source are characteristic of this rectifier while they are absent from the mercury-arc rectifier as " the resistance of the arc circuit stabilizes the current flow." I fail to see how any resistance could have such an effect, and I am convinced that the current fluctuations are practically identical in the two rectifiers. Mr. Bartlett states that he based his early unfavourable view in regard to the jet-wave rectifier on the fact that I was " at that time using only about 150 volts " per jet whilst he believed " a voltage of 600 to 1 000 to be the least which would justify the use of a rectifier." I regret that his views are based on a complete misconception. It is true that, at the time referred to, commutators for 183 volts only were used, but as our aim was to construct a 550-volt rectifier for tramway traction, and as such a rectifier must consist of 3 commutators in series, each commutator had to be designed for 550/3 = 183 volts. It would seem that Mr. Bartlett has confused the two terms " commutator " and " rectifier " in my paper.

The floor space required by large-power jet-wave rectifiers is likely to be $0 \cdot 125\ \text{m}^2$ per 100 kW.

Mr. Stevens asks me how I came upon the idea of the jet-wave principle. The first jet-wave apparatus was a periodic interrupter. In February 1907 I was working at certain problems in connection with the radiation of electricity from needle points, and found that none of the interrupters for inductor operation known at that date was satisfactory. A few months before, when taking my degree of Master of Science at the University of Copenhagen, I had been set the problem of determining the mass-charge ratio of the particles of a cathode ray by the method of magnetic deflection. In searching for a new principle for an interrupter it now occurred to me that the analogical deflection of a mercury jet in a magnetic field could probably be used for this purpose, and a preliminary estimate at once showed that the scheme was quantitatively sound. Such was the origin of this idea. All the constructive suggestions given by Mr. Stevens have been considered and some of them have been realized. Thus a rotating-field commutator has been built. A serious drawback with this commutator is, however, that the exciting current for the production of the wave must be a direct current of rather great intensity, though of course of small voltage, and such a current is comparatively expensive. I am doubtful whether the use of a water jet-wave and the application of an electrostatic field for the production of the wave would be sound propositions. An inductive load is on the whole an advantage in that reactance in the d.c. circuit means a smoother rectified current but no increase of the spark-loss (cf. description of commutation process). Hydrocarbon (illuminating gas) has been used as a medium for the commutation, but its use has now been discontinued on account of the carbon deposits to which it gave rise. Experiments have been carried out with hydrogen at pressures up to about 20 atmospheres. The pressure has of course no effect on the spark loss. Probably the spark interval τ_2, Fig. 17, decreases with increasing pressure, which would mean a greater stability. This question, however, has not yet been finally settled. It appears that the commutation spark does not give rise to any serious radio disturbances and, as regards the disturbances to be expected from the rectified current proper in telephone circuits, it would seem that they must be of the same intensity and character as those due to currents from a mercury-vapour rectifier, seeing that the currents from the two types of rectifier are practically identical.

Prof. Wheatcroft asks whether all changes occurring with the jet when transformed into a jet wave have been taken into account in the building-up of the formula for the resistance of the latter. I trust they have, but I confess that I fail to see how " the alteration of the shape of the cross-section " can have any appreciable effect on the resistance. The complete theory of the jet wave has been given in a treatise issued by the Danish Royal Society,* to which treatise I would refer inquirers for information with regard to the mathematical treatment of the problems. I do not think that the wave-form with the jet-wave rectifier is on the whole more square-shaped than that with the mercury-arc rectifier. At any rate we possess means for varying the width of the spark interval within wide limits, though so far we have always deemed it an advantage to make the interval as short as possible.

Mr. Aikman touches the question of oxidation of the mercury, and Mr. Crocker has very correctly stated the effect of such oxidation, which is a soiling of the pipe system, necessitating periodical cleaning. The oxidation in the jet-wave rectifier is due to the small amount of oxygen (about 0·5 per cent) generally contained in the commercial hydrogen used for filling the chamber. Owing to leakage at the packings of the connecting bolts the flow of hydrogen past the chamber, and therefore the oxidation, has so far been greater than it should be. Owing to the introduction of a special type of packing the leakage will be reduced to at least one-tenth of what it was, i.e. the consumption of hydrogen, the oxidation and the soiling will become quite negligible.

It has been stated in the course of the discussion that a 200-kW, 550-V rectifier plant has been installed in a substation for tramway traction at Bradford. I take this opportunity of thanking Mr. Roles for giving facilities for installing the rectifier in England for demonstration purposes. I also desire to thank Mr. Roles's collaborators and engineers, Mr. Dundas, Mr. Aikman, Mr. Bramwell and Mr. Crocker for their interest and kind assistance during the test. I very much appreciate the trouble which they have taken to subject the apparatus to a complete test. Finally I beg to express my gratitude to the Institution for giving me an opportunity of discussing my work with eminent British electrical engineers.

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* "The Jet-Wave," *Det kgl. danske Videnskabernes Selskabs math.-fys. Meddelelser*, 1929, vol. ix, No. 2 (English Paper).

THE NATURE AND EXTENT OF THE OSCILLATIONS PRODUCED IN A ROTARY CONVERTOR ON FLUCTUATING LOADS AND ON SHORT-CIRCUIT.[*]

By H. COTTON, M.B.E., D.Sc., Associate Member.

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SUMMARY.

The following investigation is concerned with the operation of a rotary convertor during conditions of abnormal loading, such as violent fluctuations occurring at definite intervals or during short-circuit conditions. In the former case the rotary convertor, being an oscillatory system having a natural period of its own, behaves just like any mechanical oscillatory system which is subjected to uniformly timed impulses. It is shown that when the natural and the forcing periods synchronize, resonance takes place and very large displacements may be set up, not only with the fundamental period of the disturbance but also by selective resonance with any harmonics which may be present. Methods of determining the natural period of the convertor and of calculating the amplitude of the oscillations set up under specified conditions are given, the methods being verified by experimental results.

The second part of the investigation deals with the motion of the rotor when the machine is subjected to a short-circuit of short duration. The mechanical analogy is in this case a ballistic pendulum, and expressions are developed which enable the displacement and slip velocity to be determined at the moment the short-circuit is cleared, and also the motion subsequent to clearing. These expressions also are verified by experiment, and considerable light is thrown on the requirements of the quick-acting circuit breakers which are commonly used on the d.c. side of rotary convertors.

The research has, of necessity, been conducted on a small experimental machine, but the theoretical and experimental investigations are found to be in reasonably close agreement and, in the case of the operation under short-circuit conditions particularly, it is possible that some other investigator having the necessary facilities may be induced to repeat the investigation on a machine of commercial size.

LIST OF SYMBOLS.

$\mathbf{T}_m$ = maximum value of synchronizing torque, in lb.-ft.;
$\mathbf{T}_l$ = load torque, in lb.-ft.;
$\mathbf{T}_i$ = induction-motor torque, in lb.-ft.;
$\mathbf{T}_s$ = total synchronizing torque = $F(\theta)$;
$\mathbf{T}_d$ = torque due to damping winding;
ρ = ratio of load torque to synchronizing torque;
p = $180/T$, where T = duration of short-circuit;
$\mathbf{I}$ = moment of inertia of armature;
T, T' = time periods;
g = acceleration due to gravity;
ω = slip, in mechanical radians per sec.;
$p\omega$ = slip, in electrical radians per sec.;

LIST OF SYMBOLS—*continued.*

E = applied p.d. per phase;
R = resistance, per phase, of the stator;
Z = impedance, per phase, of the stator;
θ = angular distance between stator and rotor fluxes, in electrical radians;
m = ratio of power of synchronous motor to maximum theoretical power.

(1) GENERAL CONSIDERATIONS OF THE EQUATION OF MOTION.

When a rotary convertor is working in the normal manner, that is, converting from alternating to direct current, it behaves on its a.c. side exactly like any other synchronous machine, the fundamental features of its operation not being affected by the internal reactions due to the d.c. load. Thus the machine constitutes an oscillatory system having a definite frequency of its own, and it is with the nature and extent of these oscillations that this research is concerned.

The problem of the oscillation of a synchronous motor with smooth-cored rotor has been considered in detail by Carr, the present author and others,[*] the behaviour of the machine while oscillating having been based on the equation

$$-\rho\mathbf{T}_m + \mathbf{T}_m \sin\theta + \frac{\rho\mathbf{T}_m}{p\omega}\cdot\frac{d\theta}{dt} + \frac{\mathbf{I}}{p}\cdot\frac{d^2\theta}{dt^2} = 0$$

This is the equation of motion of a mechanical model consisting of a heavy disc of moment of inertia $\mathbf{I}/p$ which can rotate about a horizontal axis (Fig. 1). If the disc is considered as having unit radius then the various components of the equation have the following derivation. The term $-\rho\mathbf{T}_m$ is the uniform torque due to a massless weight of $\rho\mathbf{T}_m$ hanging from a string passing round the periphery of the disc; $\mathbf{T}_m \sin\theta$ is the sinusoidal torque set up on displacement from the equilibrium position by a massless weight $\mathbf{T}_m$ which is secured to the periphery of the disc; the term $\rho\mathbf{T}_m/(p\omega) \,.\, (d\theta/dt)$ is a frictional torque which is proportional to the speed of the disc $d\theta/dt$, and therefore represents a torque such as is set up in an induction motor, or the damping windings of a rotary convertor when slip takes place. Finally, the term $\mathbf{I}/p \,.\, (d^2\theta/dt^2)$ represents the torque required to produce acceleration of the disc.

In the present investigation the rotary convertor is initially running at synchronous speed under zero external load, so that the initial conditions of the model of slip motion are that $\mathbf{T}_m$ is present but the weight $\rho\mathbf{T}_m$ suspended from the string is absent; the disc will thus be at rest with the weight $\mathbf{T}_m$ at the bottom position A. (Actually ρ will have a small value ρ_0 because of the friction and iron losses in the machine; the disc will, however, still be at rest, but with the weight $\rho_0\mathbf{T}_m$ displaced a small distance from A.) The next step is to imagine that a load is thrown on the d.c. side of the machine, the weight $\rho\mathbf{T}_m$ in the model therefore becoming suddenly established. There are three cases to consider.

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

[*] L. H. A. CARR: "The Pulling into Step of an Induction-type Synchronous Motor," *Journal I.E.E.*, 1923, vol. 61, p. 692; H. COTTON: "Pulling into Step of a Synchronous Induction Motor," *ibid.*, 1925, vol. 63, p. 211; H. COTTON: "The Synchronous Induction Motor," *World Power*, 1921, vol. 1, p. 329, and vol. 2, p. 45.

(1) *A load of fixed value* $\rho\mathbf{T}_m$ *is suddenly thrown on, and is subsequently kept constant.*—If we imagine that the weight $\rho\mathbf{T}_m$ is suddenly hung from the string wound round the disc, it is easy to see that motion in a clockwise direction will take place, and that owing to the inertia of the disc the weight $\mathbf{T}_m$ will be carried beyond the position B, of stable equilibrium. Then if the velocity is brought to zero before $\mathbf{T}_m$ reaches the position C (of unstable equilibrium), damped oscillations about the position B will take place, the disc finally settling down with $\mathbf{T}_m$ at B. This corresponds to the angular shift of the rotor of the machine which takes place when a load is put on, the angle α representing the angle through which the armature rotating field moves backwards in space relative to the fixed magnetic field of the magnet system.

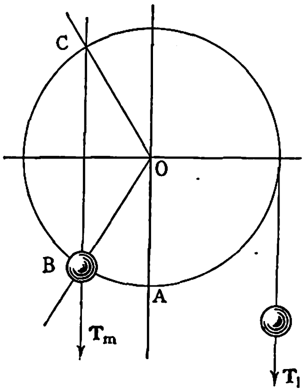

FIG. 1.—Mechanical model to illustrate the slip motion.

If $\rho\mathbf{T}_m$ is so large that the weight $\mathbf{T}_m$ is carried round beyond the position C of unstable equilibrium, then the disc will continue to make whole revolutions and will never come to rest. This corresponds to an overload being switched on to the machine beyond its pull-out capacity.

(2) *The load* $\rho\mathbf{T}_m$ *being a fluctuating quantity. In this case, provided the machine is not pulled out of step, oscillations will be maintained, the nature of the oscillations depending on the manner in which* $\rho\mathbf{T}_m$ *varies with time.*—This aspect of the problem represents a convertor subjected to a fluctuating load on its d.c. side. This form of load is very common since all machines subjected to industrial loads or traction loads, especially the latter, have to withstand very intense, and often very rapid, changes in the magnitude of the load. If the load is fluctuating in a very irregular manner the problem presents little of interest, because in such a case the forced oscillations to which the machine will be subjected will, in all probability, not reach any great amplitude and the machine will continue to run in a normal manner. If, however, the fluctuations in the load occur at sensibly equal intervals, the resultant oscillations will be more definite in character. In the particular case in which the load fluctuations synchronize with the natural period of oscillation of the machine, resonance will take place, and then the amplitude of the oscillation may become very large even if the machine is not overloaded from the point of view of the magnitude of the load fluctuations.

This phenomenon must be of very common occurrence, since even with a very irregular load an examination of the chart from a recording instrument will often show that for a few seconds the peak loads were more or less evenly distributed.

(3) *The load* $\rho\mathbf{T}_m$ *is again suddenly established, but only for a small instant of time, this corresponding to a severe overload or to a short-circuit lasting for a fraction of a second only, until the circuit-breaker trips.*—In this case, provided the duration of the overload is not sufficiently long to pull the machine out of step, a sudden oscillation which is very quickly damped down again will be set up, and the most important point in the investigation of this case is the change in kinetic energy which has taken place, to find out how much of the energy of the short-circuit is derived from the rotational energy of the machine, and how much is derived electrically from the alternating-current side. This is a very important problem in connection with rotary convertors which may be frequently short-circuited, as for example when working on traction duty, since it determines very largely the nature of the overload protection used on the alternating-current side, and, more particularly, the setting of the overload trips.

(2) CONSTANTS OF THE TEST MACHINE.

The whole of the experimental work was performed on a small 3-phase rotary convertor rated as follows:—

Output:—3·5 kW.
A.C. voltage:—100 at frequency 50.
D.C. voltage:—165 at no load.
Full-load current on the d.c. side:—21 amperes.
No. of poles:—4.
Speed:—1 500 r.p.m.

Armature Resistance.—This was measured on both d.c. and a.c. sides, the measurement including brush contact-resistance and the resistance of the leads to the machine terminals. It was made by the ammeter and voltmeter method immediately after a full-load run.

Resistance on d.c. side, 0·235 ohm.

Resistance on a.c. side, measured between each pair of terminals in turn, (1) 0·190 ohm, (2) 0·208 ohm, (3) 0·202 ohm; mean 0·200 ohm.

As the armature of a rotary convertor is essentially mesh-connected, the resistance per phase is $1\frac{1}{2}$ times the above value, namely 0·30 ohm.

Armature Reactance and Impedance.—The machine was belt-driven by a motor and run at its normal speed of 1 500 r.p.m., and the voltage on the d.c. side was measured for different values of the excitation. Where the speed deviated slightly from the normal value the necessary correction was applied instead of attempts being made to maintain the speed absolutely constant. The a.c. voltage was then calculated by multiplying by the transformation ratio of 0·612 for a 3-phase convertor, a check reading showing that this was actually the ratio for the machine. This method was adopted in order to obtain accurate readings of the voltage right down to low values of the excitation, so that the open-circuit characteristic could be drawn accurately over the whole range. The three terminals on the a.c. side were then short-circuited and excitations over a restricted range applied, the external short-circuit current being measured by a single ammeter constituting one of the short-circuit paths. The armature impedance and reactance were then worked out by the Behn-Eschenberg method, the values so obtained taking account of armature reaction, and therefore being applicable with little error to the case of a salient-pole machine.

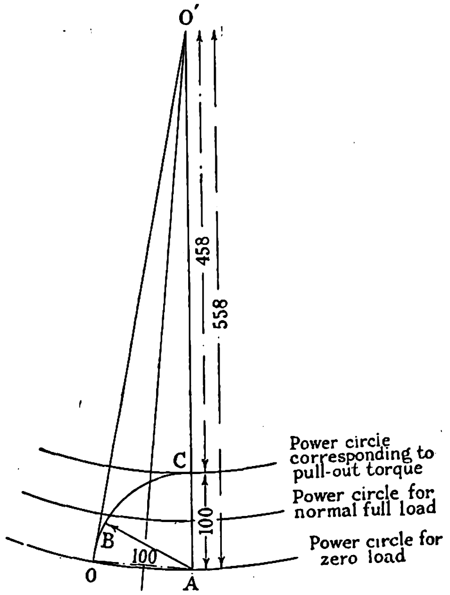
O′
458
558
C
B
100
100
O
A
Power circle corresponding to pull-out torque
Power circle for normal full load
Power circle for zero load

FIG. 2.—Blondel diagram of experimental machine.

During the experimental work the excitation was maintained constant at 1·51 amperes, the corresponding reactance of the armature per phase therefore being 0·78 ohm, and the impedance 0·836 ohm. This value of the excitation was chosen because it gave a power factor of unity on steady full load when working normally.

Iron and Friction Losses.—While still hot from a load run, the machine was run light as a d.c. motor, the applied voltage being adjusted to give the normal speed of 1 500 r.p.m. with the normal excitation of 1·51 amperes. The armature intake was measured on a wattmeter, and after correcting for armature copper-loss and brush contact-loss the iron and friction losses were found to be 550 watts.

Pull-out Torque.—The magnitude of $\mathbf{T}_m$ was determined from the Blondel diagram, as this was the most satisfactory method for the present investigation. The diagram is drawn to scale in Fig. 2. The base OA is equal to the a.c. voltage, E, per phase, namely 100, while each slant side is equal to

$$\frac{2Z}{R} \times E = \frac{2 \times 0{\cdot}836}{0{\cdot}3} \times 100$$
$$= 558 \text{ volts}$$

Now the total mechanical output of the motor, including iron and friction losses, is represented on the diagram by a series of concentric circles having their centre at O′. Again, the maximum power corresponding to any given excitation is defined by the point of intersection of the locus of the back-e.m.f. vector AB and the slant side O′A, namely the point C in the figure. But the length AB is equal to 100 and therefore

$$\text{O'C} = 558 - 100 = 458$$

It can be shown * that

$$\frac{\text{O'C}}{\text{O'A}} = \sqrt{(1 - m)}$$

where m is the ratio of the power represented by the circle passing through the point C to the maximum possible power (not to be confused with the power corresponding to the pull-out torque).

$$\because \sqrt{(1 - m)} = \frac{458}{558} = 0{\cdot}824$$
$$\therefore m = 0{\cdot}325$$

Again, the maximum possible power per phase is equal to $E^2/(4R)$, so that for the machine under test this is

$$\frac{100^2}{4 \times 0{\cdot}3} = 8\,350$$

∴ Power corresponding to pull-out torque

$$= m \times \frac{E^2}{4R} = 2\,710 \text{ watts per phase}$$

We have now to find the normal full-load power per phase. This is the sum of the output and the iron and friction losses.

Total power developed at normal full load by all three phases = 3 500 + 550 = 4 050 watts.

∴ Power developed per phase = 1 350 watts.

As the machine runs at a constant speed these powers are proportional to the corresponding torques. Hence when working on full load

$$\rho = \frac{1\,350}{2\,710}$$
$$= 0{\cdot}497$$

From $$\mathbf{T} = \frac{33\,000 \times \text{watts}}{2\pi N \times 746}$$

we have for the pull-out torque

$$\mathbf{T}_m = \frac{33\,000 \times 3 \times 2\,710}{2\pi \times 1\,500 \times 746}$$
$$= 38{\cdot}5 \text{ ft.-lb. units}$$

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* See H. COTTON: "The Graphical Theory of the Polyphase Synchronous Motor," *World Power*, 1926, vol. 5, p. 315, and vol. 6, p. 33.

Moment of Inertia.—The armature moment of inertia was obtained by removing the armature and timing the period of small oscillations made when it was suspended by means of a long bi-filar suspension. With the shaft fittings used during the experimental work the value was

$$\mathbf{I} = 10{\cdot}8 \text{ ft.-lb. units}$$

Knowing **I** it is possible to determine the time of free oscillation, the calculation being made in the next paragraph.

(3) FREE OSCILLATIONS.

In the experiments to be described, and which were made to determine the operation of the machine on fluctuating load, the number of large single oscillations per second was found to be of the order of 4·6 when the natural period synchronized with the forcing period. This gave a half-period of

$$\frac{T'}{2} = \frac{1}{4{\cdot}6} = 0{\cdot}218$$

$$\therefore\ T' = 0{\cdot}436 \text{ for large oscillations}$$

When breaking a current of 10 amperes in such a manner that the period of forced oscillations was made to coincide with the natural period of oscillation of the machine, the period was 0·218 sec., as above, the maximum displacement of the rotor being 82 electrical degrees. Regarding this load as equivalent to a sinusoidal load of amplitude 5 amperes superposed on a steady load of 5 amperes, the corresponding amplitude of swing as reckoned from the mean position is 41 electrical degrees. The actual period for small oscillations is, therefore, obtained from the pendulum correction for large angles. For a pendulum of length l we have

$$T = 2\pi\sqrt{\left(\frac{l}{g}\right)} \text{ for small oscillations}$$

and $$T' = 2\pi\sqrt{\left(\frac{l}{g}\right)} \times \frac{2}{\pi}\int_0^{\pi/2} \frac{d\phi}{\sqrt{(1 - \sin^2 \frac{1}{2}\alpha \,.\, \sin^2 \phi)}}$$

for large angles, α being the displacement from the mean position. In the above case $\alpha = 41°$.

$$\therefore\ \frac{2}{\pi}\int_0^{\pi/2} \frac{d\phi}{\sqrt{(1 - \sin^2 \frac{1}{2}\alpha \,.\, \sin^2 \phi)}} = 1{\cdot}032^*$$

$$\therefore\ T = \frac{T'}{1{\cdot}032}$$
$$= 0{\cdot}424 \text{ second}$$

Damping Constant.—In the general equation of motion all the constants have now been determined with the exception of the coefficient of $d\theta/dt$, this coefficient depending on the extent of the damping. In the present case the damping was produced only by eddy currents induced in the pole-faces, and as these are not amenable to convenient mathematical solution it was necessary to determine the damping in an indirect manner.

When there is no load on the machine, the equation of motion becomes

$$\mathbf{T}_{\mathbf{m}} \sin\theta + \text{const.} \times \frac{d\theta}{dt} + \frac{\mathbf{I}}{p}\frac{d^2\theta}{dt^2} = 0$$

or $$b\sin\theta + c\frac{d\theta}{dt} + d\frac{d^2\theta}{dt^2} = 0$$

where $b = 1$

c is unknown

$$d = \frac{\mathbf{I}}{gp\mathbf{T}_{\mathbf{m}}}$$
$$= 0{\cdot}0041$$

Hence $$\sin\theta + c\frac{d\theta}{dt} + 0{\cdot}0041\frac{d^2\theta}{dt^2} = 0$$

or $$\frac{d^2\theta}{dt^2} + 245c\frac{d\theta}{dt} + 245\sin\theta = 0$$

Now so long as θ is not greater than about half a radian, there is very little error in assuming that $\sin\theta = \theta$, the equation for small amplitudes then becoming

$$\frac{d^2\theta}{dt^2} + 245c\frac{d\theta}{dt} + 245\theta = 0$$

From the nature of the free oscillations it is known that $245 > \frac{1}{4} \times (245c)^2$, since the motion is not aperiodic. The solution is therefore

$$\theta = ae^{-122\cdot 5ct}(\cos nt + \epsilon)$$

where the period is

$$\frac{2\pi}{n} = \frac{2\pi}{\sqrt{(245)} \times \left\{1 - \frac{(245c)^2}{4 \times 245}\right\}^{\frac{1}{2}}}$$

Actually the quantity within the brackets will not differ greatly from unity, and we can write

$$\frac{2\pi}{n} \approx \frac{2\pi}{\sqrt{(245)}}$$

or $$n \approx \sqrt{(245)} \approx 15{\cdot}65$$

This gives for the period

$$T \approx \frac{2\pi}{15{\cdot}65} \approx 0{\cdot}4 \text{ second}$$

which is in reasonably close agreement with the experimentally observed period (when corrected to small oscillations) of 0·424 second.

So long as the motion is not aperiodic, the above differential equation is the equation to a damped oscillation, and the values of θ for which $d\theta/dt = 0$ will become progressively smaller. If we put

$$\frac{d^2\theta}{dt^2} + k\frac{d\theta}{dt} + \mu\theta = 0$$

where $k = 245c$ and $\mu = 245$, it follows that the ratio of one maximum swing in a given direction to the next maximum in the opposite direction is $e^{-\frac{1}{2}k\pi/n}$. Hence if the amplitudes of the successive swings could be observed this ratio could be determined, and the damping constant thus calculated. Actually it was impossible to observe the amplitudes of successive swings because the period was too small. Another method had therefore to be tried.

The function $d\theta/dt$ is also a simple harmonic function of continually diminishing amplitude, the form of this function, and the nature of its decay, being identical with those of θ. It thus follows that the ratio of successive maxima of the velocity curve is also equal to $e^{-\frac{1}{2}k\pi/n}$.* This suggested the following method of determining the changes in motion after throwing off the load. An insulated wire was stretched across one pole-face in a direction parallel to the shaft of the machine, so that when phase swinging took place one pole of the magnetic field set up by the armature currents oscillated across the wire. In this way, when the machine was executing damped oscillations, a damped alternating e.m.f., which was at any instant proportional to the velocity with which the flux moved across the wire, that is, to $d\theta/dt$, was induced in the wire. The induced e.m.f. obtained in this way was too small to operate the oscillograph, so it was amplified by means of a thermionic valve, the type of valve used being a Marconi L.S.5 working with an anode voltage of 400. No transformer was used as the slowness of the oscillations did not render this necessary. In order to operate the oscillograph satisfactorily it was found necessary to use two such valves in parallel.

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* From tables of elliptic integrals.

The record obtained is shown in Fig. 3, from which it will be seen that the fundamental voltage wave due to oscillations of the main flux has a second harmonic superposed on it. This harmonic is due to changes in magnitude of the flux accompanying the changes in position, and, therefore, the changes in the reluctance of the air-gap traversed by the flux. This effect, although large, has no direct bearing on the problem of the phase-swinging of an undamped or lightly damped rotary convertor, but it is obviously of importance in connection with the design of the damping grids for a commercial machine, since these grids will carry an appreciable double-frequency current in addition to the fundamental current.

To find the ratio of successive maxima in the induced e.m.f. curve, a portion of the film was placed between two lantern-slide covers and projected on to a large sheet of squared paper, on which the enlarged curve was then drawn. As the damping was small the curve was drawn for 15 oscillations, the ratio of the positive swings of the first and fifteenth being equal to 2·7. Hence,

$$\frac{\theta_2}{\theta_1} = \frac{\theta_3}{\theta_2} = \frac{\theta_4}{\theta_3} = \ldots = e^{-\frac{1}{2}k\pi/n}$$

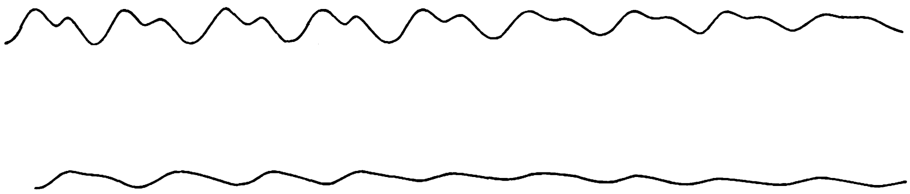
$$\frac{\theta_3}{\theta_1} = \frac{\theta_5}{\theta_3} = \frac{\theta_7}{\theta_5} = \ldots = e^{-k\pi/n}$$

For 15 complete oscillations there will be 14 terms in the above series, so that, multiplying all these terms and substituting the above ratio, we have

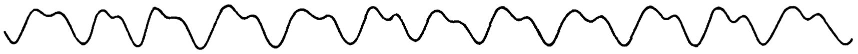
$$e^{-14\pi k/n} = \frac{1}{2\cdot 7} = 0\cdot 37$$

$$\therefore\ e^{-\frac{44\times 245c}{245\sqrt{(1-\frac{1}{4}c^2)}}} = 0\cdot 37$$

The solution of this is $c = 0\cdot 023$, showing that in the present case the damping is small.



Induced e.m.f. when executing free damped oscillations



Induced e.m.f. when executing forced oscillations at resonance frequency

FIG. 3.

Equation of Motion of Test Machine with Experimentally Determined Constants.—The complete equation of motion is, therefore,

$$\frac{d^2\theta}{dt^2} + 5\cdot 6\frac{d\theta}{dt} + 245\sin\theta = 0$$

when executing free oscillations.

(4) FORCED OSCILLATIONS OF THE ROTARY CONVERTOR.

A. *Theoretical Considerations.*—The above investigation shows how the damping factor for a rotary convertor can be determined experimentally, the method being applicable to a large commercial machine as well as to a small experimental machine. From the point of view of performance under actual working conditions it is also of importance to investigate the nature of the forced oscillations to which the machine will be subjected when severe fluctuations in the load take place, and these fluctuations occur for a short period at sensibly equal intervals of time. In such a case the load can be regarded as periodic, and unless the damping is very effective very large amplitudes can be set up in a very short time. If we assume a sinusoidally varying load of maximum value $\mathbf{T}_l = \rho\mathbf{T}_m$, then on putting $-\rho = a$ we have for the equation of motion

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* See Appendix 2.

$$d\frac{d^2\theta}{dt^2} = -b\sin\theta - c\frac{d\theta}{dt} + \rho\cos(pt+\epsilon)$$

Writing this in the general form, we have

$$\frac{d^2\theta}{dt^2} = -\mu\sin\theta - k\frac{d\theta}{dt} + f\cos(pt+\epsilon)$$

same as that of the forcing system, the fluctuating load in the present case, and the amplitude of which is equal to A. The damping coefficient k is relatively small, and therefore A is greatest when the denominator of A is least, that is, when

$$p^2 = \mu$$

We then have for the maximum amplitude

$$A = \frac{f}{kp} = \frac{f}{k\sqrt{\mu}}$$

TABLE 1.

Current varying sinusoidally between									
0–10 amps.		0–15 amps.		0–20 amps.		0–25 amps.		0–30 amps.	
Cycles per sec.	Total swing	Cycles per sec.	Total swing	Cycles per sec.	Total swing	Cycles per sec.	Total swing	Cycles per sec.	Total swing
0·5	3	0·45	5	0·5	6	0·59	10	0·75	12
0·66	5	0·65	6	0·75	8	0·75	12	0·94	13
1·2	8	0·92	9	0·92	10	0·93	14	1·15	17
1·41	13	1·15	11	1·25	14	1·19	16	1·5	30
1·63	14	1·53	19	1·67	25	1·27	20	1·68	44
1·77	21	1·83	30	1·87	37	1·43	24	1·86	60
2·02	29	2·0	42	2·02	54	1·6	36	1·96	90
2·11	40	2·15	60	2·05	70	1·75	43	2·05	122
2·22	60	2·22	79	2·11	90	1·85	60	2·06	136
2·25	70	2·23	92	2·10	121	1·97	75	2·12	140
2·3	79	2·25	96	2·14	110	2·0	91	2·2	156
2·35	72	2·3	100	2·19	124	2·05	116	2·25	160
2·38	61	2·35	98	2·24	130	2·12	131	2·26	154
2·42	51	2·35	90	2·26	127	2·15	136	2·32	150
2·45	40	2·36	85	2·33	124	2·17	126	2·33	131
2·5	32	2·4	70	2·35	110	2·18	133	2·35	120
2·58	21	2·41	61	2·44	90	2·2	140	2·35	104
2·75	13	2·43	53	2·54	70	2·25	132	2·41	98
3·2	5	2·52	38	2·62	54	2·27	124	2·44	83
3·4	3	2·65	25	2·63	44	2·32	117	2·5	70
3·65	2	2·88	14	2·78	36	2·34	105	2·78	45
—	—	3·25	6	2·92	23	2·35	95	3·0	30
—	—	3·5	4	3·2	14	2·4	90	3·28	21
—	—	3·75	4	3·54	8	2·5	74	—	—
—	—	—	—	3·8	7	2·52	64	—	—
—	—	—	—	—	—	2·67	47	—	—
—	—	—	—	—	—	2·82	35	—	—
—	—	—	—	—	—	3·1	20	—	—
—	—	—	—	—	—	3·32	14	—	—
—	—	—	—	—	—	3·5	12	—	—

Using the simplification $\sin\theta = \theta$, which, although not accurate for large oscillations, will give an idea of the order of the magnitudes involved, the solution for the maximum amplitude is

$$A = \left[\frac{f^2}{(\mu - p^2) + k^2p^2}\right]^{\frac{1}{2}}$$

and for θ is

$$\theta = A\cos(pt - \epsilon - \epsilon_1)$$

where $\tan\epsilon_1 = kp/(\mu - p^2)$.

This is a forced oscillation the period of which is the

Substituting the numerical values of the constants we thus have

$$\begin{aligned} A &= \frac{114}{5{\cdot}6 \times \sqrt{245}} \\ &= 1{\cdot}32 \text{ radians} \\ &= 76 \text{ degrees, or a total swing of 152 degrees.} \end{aligned}$$

For different values of p either greater than or less than $\sqrt{\mu}$ the amplitude falls away rapidly after the well-known manner of the resonance curve. The numerical calculation indicates that if the period of the fluctuations in the load coincides with the natural period of oscillation of the rotary convertor, then very violent oscillations may be set up, which, if they do not actually pull the machine out of step, will yet cause very severe fluctuations in line current, and in the power factor. This effect will be greater the smaller the degree of damping in the machine.

B. *Test Results with Sinusoidal Currents.*—In order to investigate this effect the machine was subjected to a d.c. load which varied in a very nearly sinusoidal manner. To accomplish this, a liquid resistance was made up with one electrode fixed and the other capable of rotation about a horizontal axis. This electrode was fixed eccentrically, its shape being such that the area of electrode immersed in the liquid was a sinusoidal function of the angular position of the electrode. In one position the electrode only just touched the electrolyte, so that, although the circuit was not actually broken, the current fell to a very small value. An oscillograph test showed that the current was very nearly sinusoidal. With the rotating electrode in the position giving maximum current, this maximum current was adjusted to a certain value by altering the strength of the electrolyte, since it was essential to keep the level constant in order that the minimum current should be close to zero. The electrode was then rotated by means of a small motor, and the amplitude of phase swing was determined as a function of the speed of the electrode. The amplitude of swing was determined by the stroboscopic method as follows. A disc was mounted on the convertor shaft, and two black patches were painted on at the opposite ends of a diameter. A small induction motor was mounted with its shaft in line with the convertor shaft, and on this was mounted a disc having two narrow slits cut in, also at opposite ends of a diameter. The induction motor was run up to speed in the usual way and then synchronized by switching direct current into the rotor circuit, and it then ran throughout at synchronous speed. Light from an arc lamp was directed through the slits on to the disc on the convertor shaft, the observed motion of the pattern then being a reproduction of the phase-swinging of the convertor. In order to measure the amplitude of phase-swing, a scale was fixed behind the disc, its graduations being in electrical degrees. Owing to the fairly rapid motion of the pattern it was rather difficult to read off the position just at the extremity of a swing, and, therefore, in order to facilitate this measurement, two small sliders were so arranged that they could be placed in any position of the scale. These were so adjusted that the black patch just touched them at each extremity of swing, this being much more accurate than the reading of the amplitude without their aid. Since the rotary electrode threw out a little

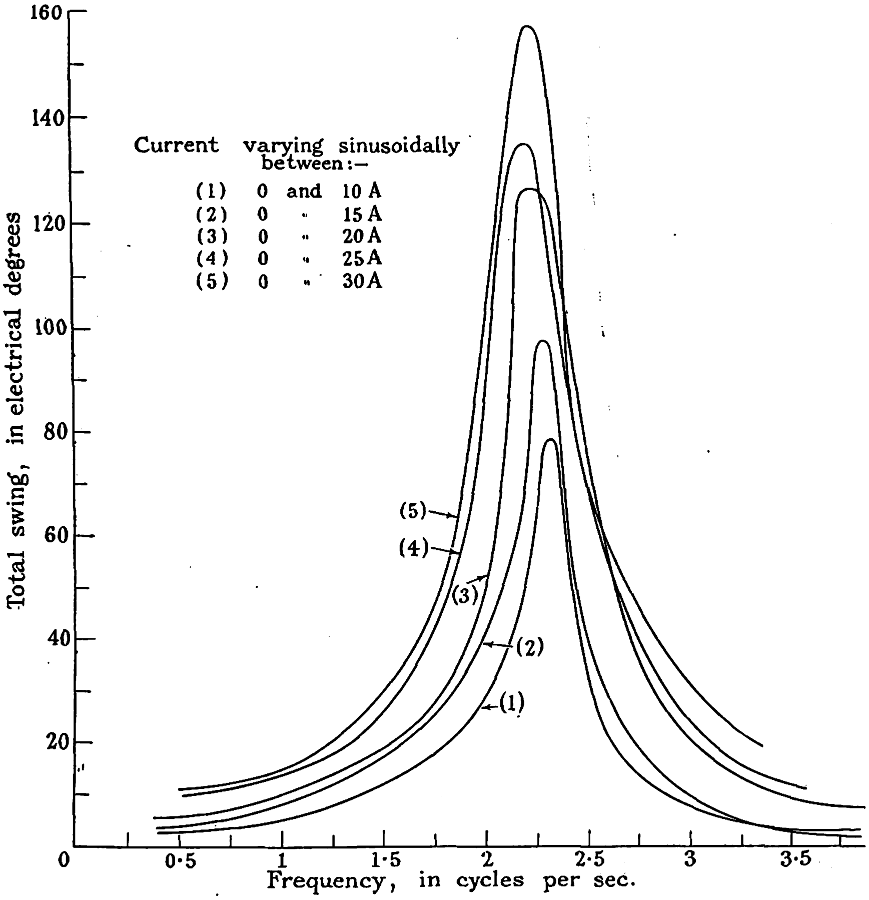

FIG. 4.—Forced oscillations with sinusoidal load current.

water it was necessary to make up the level from time to time, although this was minimized as far as possible by fixing over the disc a cowl which directed any water back into the tank. The maximum value of the current was also occasionally checked. Experiments were made with maximum currents of 10, 15, 20, 25 and 30 amperes, the results being given in Table 1 and plotted in Fig. 4.

It will be seen that they are of the same form as the curve obtained from purely dynamical considerations, showing that the performance of the machine can be predetermined with reasonable accuracy by these methods. The tabulated swings are all of twice the amplitude as measured from the mean position. The remarkable feature of the curves is the sharpness of the resonance peak, although this is to be expected since the damping is very small. It shows that such a machine will attain a large amplitude of swing in a very short time, if the frequency of the load fluctuations is correctly timed. This was shown to be the case, since if the speed of the rotating electrode was adjusted to give resonance, and the load then suddenly thrown on by closing the main switch on the d.c. side, the maximum amplitude appeared to be attained practically instantaneously.

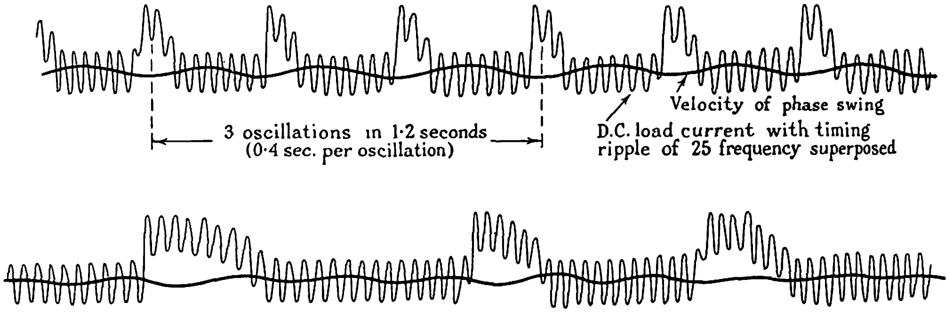

FIG. 5.—Oscillograms of fluctuating load current (with 25-cycle timing ripple superposed) and corresponding slip velocity. The upper oscillogram gives the conditions of resonance.

As previously pointed out, it was not possible to obtain the velocity of phase-swing under actual experimental conditions by the rotating disc method, and in the case of operation under fluctuating load the additional load imposed by the eddy current in the disc was such as to pull the machine out of step. In order to obtain a record of the nature of the motion, however, a few such speed determinations were made, with a fluctuating load both of resonance and of non-resonance frequency, and its maximum adjusted to a low value so that the machine was able to keep in step. The curves are reproduced in Fig. 5, from which it will be seen that the motion appears to be approximately sinusoidal at resonance. It was not thought necessary to calibrate this curve, since it was not obtained under the conditions used in the theoretical and experimental investigations. There does not appear to be any second harmonic present in the motion, and the resonance curves also do not exhibit any trace of the presence of such a harmonic, from which it can be concluded that in the case of the machine under investigation the double-frequency component of the torque due to the salient poles is negligible in its effect, thereby justifying its omission from the equation of motion.

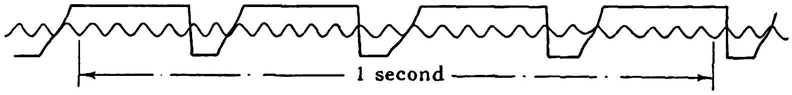

FIG. 6.—Oscillogram of fluctuating load current given by motor-driven rotary switch.

C. *Test Results with Intermittent Currents.*—Since it is very improbable that any rotary convertor will, under actual operating conditions, be subjected to a sinusoidally varying load, a second experimental load was arranged to reproduce the sudden changes which are more likely to occur in practice. When violent loads are imposed on a machine they are, as a rule, maintained for a small fraction of a second, so that a load consisting of a series of sudden peaks and sudden falls, with peak value of the current maintained for a short interval of time, would be more likely to reproduce actual conditions. Such conditions are obtained by alternately making and breaking a load of constant resistance. For this purpose the water load was again used, but this time the electrodes were kept in a fixed position, except that from time to time a little adjustment was necessary to keep the steady value of the current constant. The switching off and on was done by means of a rotary type of switch which was directly coupled to a d.c. motor. In order to obtain a sufficiently good contact between the fixed and rotating parts it was necessary to adjust the tension springs of the fixed contacts fairly tight, with the result that, while contact was made, a considerable load was imposed on the motor, this being increased by the fact that it was necessary to make use of a whole row of six contacts to save the switch from premature destruction by burning out. The result of this was that the periods of load were longer than the periods of no-load, but as the operation under such a load is not amenable to convenient mathematical analysis this was considered of no importance. An oscillogram of the current curve so obtained is given in Fig. 6, and owing to the fact that the periods of load and of no-load are not equal there are even as well as odd harmonics present in the analysis into sinusoidal components. Denoting the fundamental component by unity, the first five components are as follows:—Fundamental 1·0, 2nd harmonic 0·679, 3rd harmonic 0·304, 4th harmonic 1·21, 5th harmonic 0·0539.

The maximum value of the current was adjusted to a series of values, as before, and the amplitude of phase-swing determined as a function of the frequency of the load fluctuations, the results being given in Table 2 and plotted in the curves of Fig. 7.

TABLE 2.

Current fluctuating, as in Fig. 14, between

0-10 amps.		0–15 amps.		0–20 amps.		0–25 amps.		0–30 amps.	
Cycles per sec.	Total swing	Cycles per sec.	Total swing	Cycles per sec.	Total swing	Cycles per sec.	Total swing	Cycles per sec.	Total swing
0	38	0	58	0	90	0	108	0	Slipped a pole on breaking the circuit
0·63	66	0·95	46	0·87	77	0·87	99		
1·03	24	1·06	22	1·13	45	0·98	60	0·71	126
1·15	34	1·13	32	1·21	64	1·08	49	0·79	155
1·29	10	1·25	20	1·3	40	1·18	60	0·87	140
1·53	4	1·36	10	1·36	24	1·23	34	1·06	122
1·69	6	1·38	10	1·52	17	1·27	20	1·10	55
1·87	10	1·58	4	1·59	24	1·36	30	1·24	48
2·13	16	1·88	8	1·82	30	1·9	32	1·40	18
2·3	82	2·1	30	1·89	41	1·95	100	1·56	23
2·48	24	2·25	92	2·04	45	2·13	126	1·74	20
2·83	8	2·43	108	2·10	80	2·25	132	1·88	34
3·81	2	2·54	22	2·15	133	2·31	126	1·91	46
—	—	3·0	8	2·36	114	2·33	105	2·08	129
—	—	3·35	4	2·54	64	2·35	95	2·13	146
—	—	—	—	2·65	43	2·54	60	2·2	158
—	—	—	—	2·75	29	2·78	33	2·25	150
—	—	—	—	3·05	17	3·25	13	2·33	118
—	—	—	—	3·35	11	3·43	11	2·39	80
—	—	—	—	3·81	7	—	—	2·5	62
—	—	—	—	—	—	—	—	3·27	21

The results of this series of experiments show that resonance can take place with each harmonic, and that, particularly in the case of the third harmonic, the amplitude obtained may be very nearly as large as that given by the fundamental. It is thus obvious that if a load is fluctuating at such a rate that a prominent harmonic is in synchronism with the natural period of the convertor, then a large amplitude of swing may again be produced. The shape of the curves shows that the resonance peaks with the harmonics are very sharply defined, this also being due to the small amount of damping. The equation of motion with such a load is of the form

$$\frac{d^2\theta}{dt^2} = -\mu\theta + k\frac{d\theta}{dt} + f_1 \cos(pt + \epsilon_1) + f_2 \cos(2pt + \epsilon_2) + f_3 \cos(3pt + \epsilon_3) + \ldots$$

and, as is well known, if k is small the amplitude at resonance with any one of the components is due to that component only, the others being of negligible effect. Denoting these amplitudes by A_1, A_2, A_3, etc., the relation

$$A_1 : A_2 : A_3 : \ldots = f_1 : f_2 : f_3 : \ldots$$

should hold. It was found impossible to identify the peaks due to harmonics higher than the third, because they come so close together that the slighest variation in the time of revolution of the switch caused the motion to change completely and to become very complex. From the analysis of the wave-form we have

$$f_1 : f_2 : f_3 = 1\cdot0 : 0\cdot679 : 0\cdot304$$

while from the experimental results we have

$$A_1 : A_2 : A_3 = 1\cdot0 : 0\cdot772 : 0\cdot891$$

when the maximum current was 30 amperes

$$A_1 : A_2 : A_3 = 1\cdot0 : 0\cdot455 : 0\cdot75$$

when the maximum current was 25 amperes

$$A_1 : A_2 : A_3 = 1\cdot0 : 0\cdot481 : 0\cdot58$$

when the maximum current was 20 amperes

$$A_1 : A_2 : A_3 = 1\cdot0 : 0\cdot296 : 0\cdot426$$

when the maximum current was 15 amperes

and $A_1 : A_2 : A_3 = 1\cdot0 : 0\cdot415 : 0\cdot805$

when the maximum current was 10 amperes.

Since the changes in load were sudden, and not gradual as with the sinusoidally varying load, points corresponding to a frequency of fluctuation of zero were obtained by taking the swing when the load was suddenly switched on, these being the initial points on the curves.*

Under actual working conditions, it is more probable that the magnitude of the fluctuations will be less than 100 per cent of the maximum current. Another series of experiments was therefore made with two loads in parallel, one of them kept permanently in circuit, and the other switched in and out by the rotary switch as before. The maximum current in the second resistance was made equal to the current permanently flowing in the first, so that the percentage fluctuation of the load was now 50 per cent, or some other value, instead of 100 per cent. The maximum current taken by the whole load was given a series of values as before, this time 31, 30, 24 and 24 amperes, the minimum values being 10, 15, 12 and 8 amperes, respectively. The four curves, along with the experimental points, are plotted in Fig. 8, and it will be seen that the results are sensibly the same as before, except that with very large amplitudes the machine pulled out of step. At first sight it might appear that the machine should carry such a load more easily than a load in which the fluctuations were 100 per cent of the maximum, but the reason is probably due to the fact that the mean load is now three-quarters of the maximum, instead of one-half, the angular position of the rotor at this mean load, therefore, being considerably nearer to the position of instability.

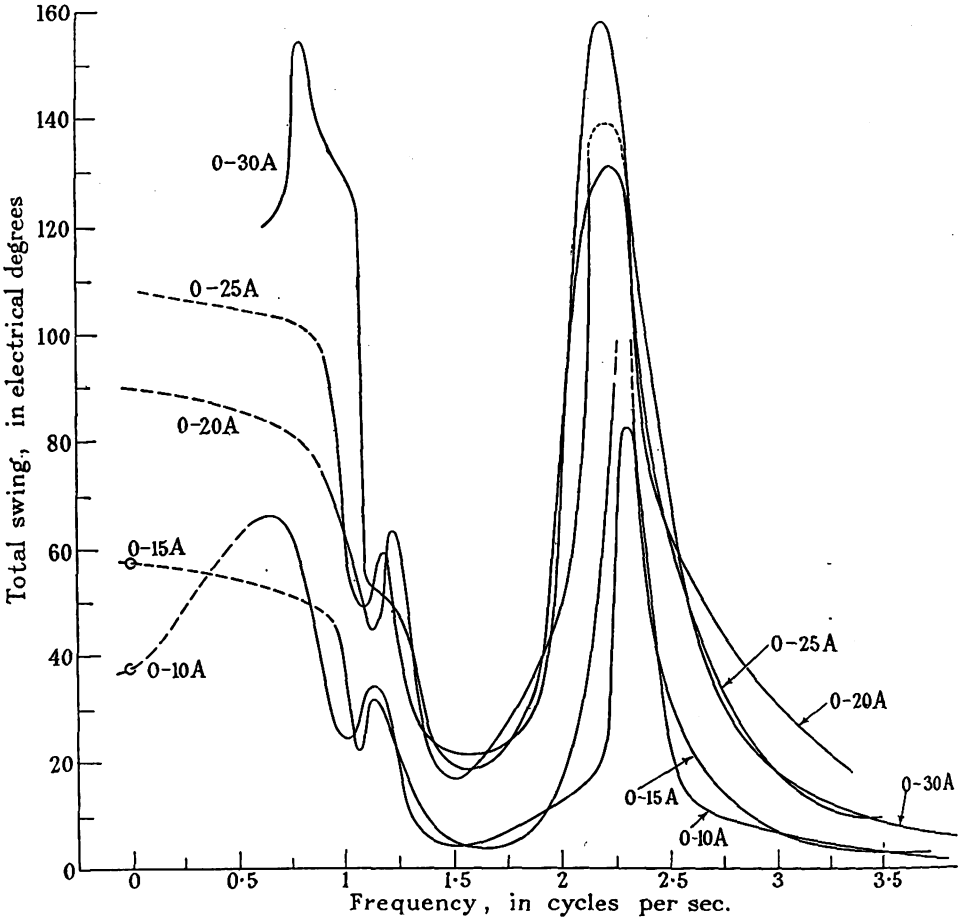

FIG. 7.—Forced oscillations with non-sinusoidal current.

While these experiments were in progress it was suggested to the author that the operation of a rotary convertor under such conditions as explained above would be, of necessity, somewhat inconsistent, and that quite different results would be obtained if identical tests were carried out at different times. To test this the rotary switch was arranged to switch on and off a load of 15 amperes and observations were made by several observers at a very large number of speeds of the switch. The experimental points obtained are plotted in Fig. 9, from which it will be seen that for speeds not less than that corresponding to the third harmonic the points are grouped about a curve identical with the corresponding curve of Fig. 7. At speeds less than third-harmonic speed it was certainly impossible to obtain any definite information.

A final series of tests with fluctuating load was made with different excitations of the machine. It was found that the excitation made very little difference to the operation unless it was reduced to such an extent that the power factor on steady load was as low as about 0·7, when the machine very readily fell out of step. It has, therefore, not been considered necessary to give actual experimental data for these tests as they do not give any additional information.

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* Actually the wave-form changed with speed of the switch because of the slowing-down effect when the switch closed, this effect naturally being much greater as the speed decreased. Agreement between the experimental peaks and the analysed wave could therefore hardly be expected.

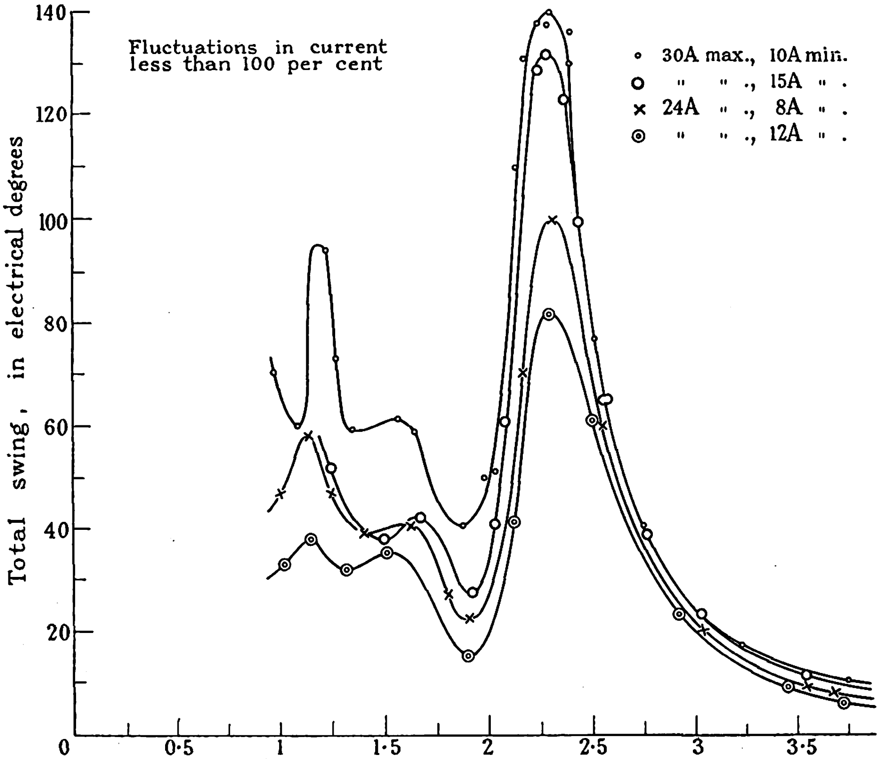

FIG. 8.—Forced oscillations with load fluctuations of less than 100 per cent.

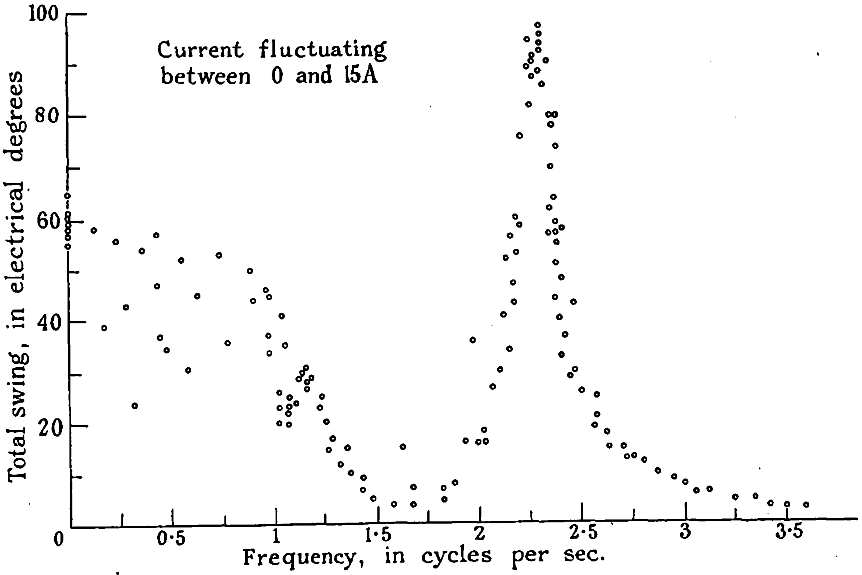

FIG. 9.—Results obtained by several independent observers.

(5) BEHAVIOUR UNDER SHORT-CIRCUITS.

A. *Theoretical Considerations* (*undamped*).—In this section of the investigation, the changes in motion and in phase position of the rotor are determined for violent overloads of short duration, such as may frequently take place in the case of a rotary convertor operating on a traction load. This case also can be studied by means of the mechanical model previously referred to.

Suppose that the machine is initially on no-load, the weight $\mathbf{T}_m$ attached at B then being in the bottom position $\theta = 0$ and the weight $\rho\mathbf{T}_m$ equal to zero; that is, $\theta = 0$ if we neglect the iron and friction losses taking place at no load. This is justifiable in the present case because the opposing torque due to these losses will be exceedingly small when compared with that due to an overload approaching the short-circuit value. To represent the short-circuit, imagine that the weight $\rho\mathbf{T}_m$ is suddenly attached to the string: also imagine that this weight remains operative for only a very short interval of time, which, in practice, is determined either by the duration of the overload, if this is exceedingly brief, or by the time taken for the circuit breaker on the d.c. side to open. In practice the opening of the d.c. breaker, and not the oil circuit-breaker on the a.c. side, is assured by the use of very quick-acting breakers which have been recently developed for use with rotary convertors.

It is very easy to see in a general way what changes will take place during such a short-circuit. The ratio ρ may, of course, be greater than unity, so that for a sustained short-circuit there is no position of equilibrium of the model, either stable or unstable, which means that the model will continue to rotate through whole revolutions at gradually increasing speed, this corresponding to the case of a convertor falling out of step.

If the short-circuit is only of very short duration, then two things can happen. First, the point B (Fig. 1) will have been carried to some angular position less than 180° by the time the short-circuit has cleared, and, furthermore, the disc will not have attained a sufficiently high velocity for the inertia to carry this point B as high as the position $\theta = 180°$. Strictly speaking, this critical position will be the position of unstable equilibrium defined by the value of ρ corresponding to the iron and friction losses, but, as stated above, this will be very little short of 180° in practice.

Secondly, the point B will have reached or passed the position $\theta = 180°$ by the time the short-circuit has cleared, or the velocity attained during this time will be such that the inertia of the disc will carry the point beyond the position $\theta = 180°$.

In the first case the rotary convertor will not fall out of step, whereas in the second case it will, even though the duration of the short-circuit is less than the time taken for the disc to swing from the position $\theta = 0°$ to the position $\theta = 180°$. It therefore follows that for a given circuit breaker having a given minimum time of clearing the circuit, there is a maximum short-circuit current which a given convertor can withstand without falling out of step, and an examination of the operation of a machine under such conditions is, therefore, of extreme practical, as well as theoretical, value.

Consider, then, the mechanical model of the motion of the machine. Since the operation is being worked out as a problem in mechanics the following symbols will be used:—

$\mathbf{I}$ = moment of inertia of the disc in ft.-lb. units, i.e. not including g,
W = weight attached to B and producing the synchronizing torque $T_m \sin\theta$,
F = weight attached to the end of the string, and producing the load torque $\rho\mathbf{T}_m$,
a = radius of disc, in feet.

Then for the equation of motion we have

$$\mathbf{I}\frac{d^2\theta}{dt^2} = (F - W\sin\theta)ag$$

where θ is any angular displacement. This gives

$$\begin{aligned}\mathbf{I}\left(\frac{d\theta}{dt}\right)^2 &= 2Fag\theta - 2Wag(1-\cos\theta)\\ &= 2Fag\left[\theta - \frac{W}{F}\left\{1-\left(1-\frac{\theta^2}{2!}+\frac{\theta^4}{4!}-\frac{\theta^6}{6!}\cdots\right)\right\}\right]\\ &= 2Fag\theta\left\{1-\frac{W}{2F}\left(\theta-\frac{\theta^3}{12}+\frac{\theta^5}{360}-\frac{\theta^7}{201\,060}\cdots\right)\right\}\end{aligned}$$

$$\therefore \frac{d\theta}{dt} = \left[\frac{2Fag\theta}{\mathbf{I}}\left\{1-\frac{W}{2F}\left(\theta-\frac{\theta^3}{12}+\frac{\theta^5}{360}-\frac{\theta^7}{201\,060}\cdots\right)\right\}\right]^{\frac{1}{2}}$$

This enables the angular velocity $d\theta/dt$ to be determined in terms of θ.

In order to find the relationship between t and θ there are two methods available.

(1) *Graphical Method.*

We have

$$\int\frac{dt}{d\theta}\cdot d\theta = \int dt$$
$$= t + C$$

Hence, if the reciprocal of the velocity, namely $dt/d\theta$, is plotted against θ, the areas under the curve between the limits $\theta = 0$ and θ equals a series of values, will give the times corresponding to these values of θ. The constant of integration, C, will be zero, since when $\theta = 0$, $t = 0$.

(2) *By Calculation.*

From the equation for $d\theta/dt$

$$\frac{d\theta}{dt} = \sqrt{\left[\frac{2ag}{\mathbf{I}}\right]}\sqrt{[F\theta - W(1-\cos\theta)]}$$

we have

$$t = \sqrt{\left[\frac{\mathbf{I}}{2ag}\right]} \times \int_0^\theta \frac{d\theta}{\sqrt{[F\theta - W(1-\cos\theta)]}}$$

If, now, the short-circuit current is exceedingly large, as might happen if the short-circuit occurred right up to the machine, we could neglect W in comparison with F, and obtain for an approximate solution

$$\begin{aligned}t &= \sqrt{\left[\frac{\mathbf{I}}{2agF}\right]} \times \int_0^\theta \theta^{-\frac{1}{2}}\,.\,d\theta\\ &= \sqrt{\left[\frac{\mathbf{I}}{2agF}\right]} \times 2\sqrt{\theta}\end{aligned}$$

$$\therefore\ \theta = \tfrac{1}{2}\frac{Fag}{\mathbf{I}}\,.\,t^2$$

This shows that the angular displacement attained by the end of the short-circuit varies as the square of the time, thus showing the necessity for a very quick-acting breaker if the machine is not to be pulled out of step.

If the short-circuit is not so intense that the above approximation is justifiable, then we have

$$t=\sqrt{\left[\frac{\mathbf{I}}{2agF}\right]}\int_0^{\theta}\frac{d\theta}{\theta^{\frac{1}{2}}}\left\{1+\frac{W}{4F}\left(\theta-\frac{\theta^3}{12}+\frac{\theta^5}{360}\cdots\right)\right\}$$

$$=\sqrt{\left[\frac{\mathbf{I}}{2agF}\right.}\left[\left\{2\theta^{\frac{1}{2}}+\frac{W}{4F}\left(\frac{2}{3}\theta^{3/2}-\frac{2}{7}\cdot\frac{\theta^{7/2}}{12}+\frac{2}{11}\cdot\frac{\theta^{11/2}}{360}\cdots\right)\right\}\right.$$

From this expression we can plot a family of curves of θ against t, each curve corresponding to a given value of F, and from these we can read off directly what will be the angular displacement at the moment of clearing the short-circuit. The value of t calculated for this value of θ will also enable the change in kinetic energy of the rotor to be made, and this energy will have been fed into the fault, the supply, therefore, having been relieved of a corresponding amount.

If the convertor is already on load at the moment the short-circuit takes place, then, owing to the fact that the initial angular position is no longer $\theta = 0$, but is now $\theta = \theta'$, where θ' is the steady displacement corresponding to the load, the conditions for just remaining in step will be modified, although not to any great extent, since θ' will, for normal loading, only be of the order of 3° or 4°.

In this case we have

$$\mathbf{I}\left(\frac{d\theta}{dt}\right)^2 = 2Fag\theta + 2Wag\cos\theta + C$$

To determine the new value of C, we have $d\theta/dt = 0$ when $\theta = \theta'$, which gives

$$C = 2ag\left[F\theta' + W\left(1 - \frac{(\theta')^2}{2!} + \frac{(\theta')^4}{4!}\cdots\right)\right]$$

Neglecting terms in θ' of orders higher than the second we have

$$C = 2ag\left[W + F\theta' - \tfrac{1}{2}W(\theta')^2\right]$$

Hence, generally,

$$\mathbf{I}\left(\frac{d\theta}{dt}\right)^2 = 2Fag\theta + 2Wag(1-\cos\theta) - 2ag\left[F\theta' - \tfrac{1}{2}W(\theta')^2\right]$$

$$= 2Fag\theta\left[1 - \frac{W}{2F}\left(\theta - \frac{\theta^3}{12} + \frac{\theta^5}{360}\cdots\right)\right] - 2ag\left[F\theta' - \tfrac{1}{2}W(\theta')^2\right]$$

The curve of $d\theta/dt$ against θ can thus be determined in the manner previously described. The effect of the initial displacement will be very small for intense short-circuit conditions, and can be neglected, but it may not be negligible if the overload is only two or three times the normal full load.

To convert the equations to a form comparable with those used in the previous parts of the investigation substitute

$\frac{\mathbf{I}}{p}$ for $\mathbf{I}$; $\quad \mathbf{T}_m$ for Wa

$\mathbf{T}_l$ for Fa; $\quad \rho$ for F/W

Before applying the above method to the particular machine under investigation it is of value to study the problem from another point of view. If Ω is the synchronous angular velocity of the machine, then the armature will possess an amount of stored energy U given by

$$U = \tfrac{1}{2}\mathbf{I}\Omega^2$$

If any change in the conditions of load takes place, there will be a momentary change in the angular velocity of, say, $\delta\Omega$, which will bring about a change in kinetic energy equal to

$$\delta U = \Omega\mathbf{I} \times \delta\Omega \div g \text{ ft.-lb.}$$

Suppose that this change has taken place in an interval of time of δt seconds, then the slowing down will be equivalent to an average power output of

$$\frac{\Omega\mathbf{I} \times \delta\Omega}{550 \times \delta t \times g} \text{ h.p.}$$

or

$$\frac{\Omega\mathbf{I} \times \delta\Omega}{732 \times \delta t \times g} \text{ kW}$$

For the experimental machine we have

$\mathbf{I} = 10{\cdot}8$ ft.-lb. units.

$\Omega = 157$ radians per sec., corresponding to a speed of 1 500 r.p.m.

Suppose we take a change in angular velocity of 4 per cent, that is $\delta\Omega = 6{\cdot}3$, and an interval of $0{\cdot}015$ sec., this being the order of time taken by a quick-acting circuit breaker to clear a short-circuit. Then for the average power given up due to the slowing down of the rotor we have

$$\frac{157 \times 10{\cdot}8 \times 6{\cdot}3}{732 \times 0{\cdot}015 \times 32{\cdot}2} = 29{\cdot}7 \text{ kW}$$

This is 8·5 times the normal output of the machine, and corresponds, in fact, to the amount of power which would flow into a short-circuit. We are, therefore, led to the conclusion that when a rotary convertor is subjected to a momentary short-circuit, practically the whole of the energy flowing into the short-circuit may be derived from the slowing down of the rotor, and that only a very small proportion will be drawn from the a.c. supply.* This is a very important consideration from the practical point of view, since it ensures that the onus of clearing the fault can be safely left to the quick-acting breaker on the d.c. side, and that the construction of the breaker on the a.c. side, and the setting of its trip coils and relays, need not be different from those adopted where the possibilities of frequent severe short-circuits do not arise. This, of course, necessitates that the d.c. breaker shall clear the fault before there is any falling out of step, otherwise there will be flashing-over at the commutator, and a transference of the short-circuit conditions to the a.c. side as well. On the other hand, if the d.c. breaker clears the fault before the position $\theta = 180°$ is reached, but the velocity attained is such that the machine falls out of step, the a.c. breaker will operate, but not under severe conditions.

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* See also *Brown Boveri Review*, 1924 vol. 11, p. 9.

B. *Effect of Damping.*—Now consider the effect of a damping winding during the change in speed. The torque due to this winding is directly proportional to the slip and can be written

$$\mathbf{T}_d = K \times \frac{d\theta}{dt}$$

where K is a constant.

Suppose that if, when the machine is run as an induction motor with this winding acting as the squirrel-cage winding, the slip at normal full-load torque is 4 per cent, this being the order of magnitude of the slip in a commercial machine when run in this manner, then if we apply this to the experimental machine for which the normal full-load torque is

$$\begin{aligned}\mathbf{T}_l &= \rho\mathbf{T}_m \\ &= 0{\cdot}464 \times 41{\cdot}2 \\ &= 19{\cdot}1 \text{ lb.-ft.}\end{aligned}$$

the torque for any percentage slip σ is

$$\begin{aligned}\mathbf{T}_l &= \frac{19{\cdot}1 \times \sigma}{4} \\ &= 4{\cdot}8\sigma\end{aligned}$$

Hence with the previously assumed slip of 4 per cent

$$\mathbf{T}_d = 19{\cdot}1 \text{ lb.-ft.}$$

The speed attained when the torque has reached this value is 96 per cent of Ω, namely 1 440 r.p.m. Hence power of the damping winding at this instant

$$\begin{aligned}&= \frac{2\pi \times 1\,440 \times 19{\cdot}1}{33\,000} \text{ h.p.} \\ &= 5{\cdot}25 \text{ h.p., or } 3{\cdot}91 \text{ kW}\end{aligned}$$

The mean power will then be approximately one-half of this, say 2 kW. This is so very small compared with the power given up by the decelerating armature that we can conclude that while the short-circuit is taking place the effect of the damping winding on the operation of the machine is quite negligible. On the other hand its effect on holding the machine in step after the fault has been cleared is very important, and it is obvious that the greater the degree of damping the greater can be the velocity at any given angular position which can be brought to zero before the position of instability is reached. This point is considered in the next section.

The power corresponding to the synchronizing torque is even smaller than that due to the damping torque. We have

$$\begin{aligned}\mathbf{T}_s &= \mathbf{T}_m \sin\theta \\ &= \mathbf{T}_m\theta \text{ for small values of } \theta \\ &= 41{\cdot}2 \times \theta \text{ ft.-lb. units.}\end{aligned}$$

For the previously assumed values of $\delta\Omega = 6{\cdot}3$ radians per sec., and $\delta t = 0{\cdot}015$ sec., the displacement at the end of the interval will be approximately

$$\begin{aligned}\tfrac{1}{2}\delta t \times \delta\Omega &= \tfrac{1}{2} \times 0{\cdot}015 \times 6{\cdot}3 \\ &= 0{\cdot}047 \text{ mechanical radian} \\ &= 0{\cdot}094 \text{ electrical radian}\end{aligned}$$

in the case of a 4-pole machine.

$$\begin{aligned}\therefore \mathbf{T}_s &= 41{\cdot}2 \times 0{\cdot}094 \\ &= 3{\cdot}87 \text{ lb.-ft.}\end{aligned}$$

Power due to this torque

$$\begin{aligned}&= \frac{2\pi \times 1\,440 \times 3{\cdot}87}{33\,000} \\ &= 1{\cdot}065 \text{ h.p., or } 0{\cdot}8 \text{ kW}\end{aligned}$$

The synchronizing torque will, of course, continue to increase, after the instant the short-circuit is cleared, up to the displacement $\theta = 90°$ provided the inertia of the armature carries the displacement so far, but the asynchronous torque will begin to decrease from the same instant, since the slip velocity will decrease.

The above calculations are approximately correct, since in an actual machine θ does not reach large values, and they are valuable because they indicate in a simple manner the relative magnitudes of the quantities involved.

C. *Motion after Removal of Short-Circuits.*—The next step is to determine whether the velocity is such that the machine will fall out of step, in spite of the fault having been cleared before an angular displacement of $\theta = 180°$ is attained. Suppose the fault is cleared at the instant the displacement is equal to θ'', then the angular velocity attained at this instant must be such that the velocity must fall to zero at some further angular position situated between $\theta = \theta''$ and $\theta = 180°$. Now after the fault is cleared, the motion of the convertor when the damping is light is similar to that of a pendulum swinging through a large arc, and the critical case will be defined by the motion of the pendulum which just makes whole revolutions, i.e. the angular velocity of which is zero at the position $\theta = 180°$. Again, for a pendulum swinging under such conditions the linear peripheral velocity at any position is equal to the velocity which would be attained by the bob if it were allowed to fall freely under gravity through a height equal to the vertical distance between the position $\theta = 180°$ and the position in question. Thus for a simple pendulum of length l if the bob is at any angular position θ this height is

$$h = l(1 + \cos\theta)$$

Hence the peripheral velocity is

$$\begin{aligned}v &= \sqrt{[2gh]} \\ &= \sqrt{[2gl(1 + \cos\theta)]}\end{aligned}$$

The angular velocity is therefore

$$\frac{d\theta}{dt} = \frac{v}{l} = \sqrt{\left[\frac{2g(1 + \cos\theta)}{l}\right]}$$

In the case of the rotary convertor, the equation of free oscillations is

$$\frac{\mathbf{I}}{p} \cdot \frac{d^2\theta}{dt^2} = -\mathbf{T}_m \sin\theta$$

and comparing this with the equation of motion of a simple pendulum of length l we see that the length of the simple equivalent pendulum is given by

$$l = \frac{\mathbf{I}g}{\mathbf{T}_m p}$$

(Note that $\mathbf{I}$ is now in ft.-lb. units.)

Hence the critical angular velocity at any position θ is given by

$$\left(\frac{d\theta}{dt}\right)_{max.} = \sqrt{\left[\frac{2(1 + \cos\theta) \times \mathbf{T_m}p}{\mathbf{I}}\right]}$$

If the velocity attained at the moment of the clearing of the fault is less than the above, then the machine will remain in step, while if it is greater it will fall out of step. For the machine under investigation this critical velocity reduces to

$$\left(\frac{d\theta}{dt}\right)_{max.} = 3{\cdot}91\sqrt{[1 + \cos\theta]}$$

It is plotted against θ in Fig. 10.

The case of a heavily damped machine is more difficult and it cannot be solved in the above manner. With finite damping the equation of free oscillation is

$$\mathbf{T_m}\sin\theta + \frac{\rho\mathbf{T_m}}{p\omega}\cdot\frac{d\theta}{dt} + \frac{\mathbf{I}}{p}\cdot\frac{d^2\theta}{dt^2} = 0$$

which can be written in the form

$$\sin\theta + c\cdot\frac{d\theta}{dt} + d\cdot\frac{d^2\theta}{dt^2} = 0$$

By putting $y = d\theta/dt$ this can be transformed in the usual way into the following differential equation of the first order:—

$$\sin\theta + cy + d\,.\,y\frac{dy}{d\theta} = 0$$

or

$$\frac{dy}{d\theta} = -\frac{\sin\theta}{d\,.\,y} - \frac{c}{d}$$

The method of solution by taking increments of θ has already been given in detail by Carr and the present author, and it is, therefore, unnecessary to give it again.

D. *Experimental Results* (*undamped*).—In order to verify the above theory the rotary convertor was subjected to a series of short-duration short-circuits of graded severity, the extent of the phase-swing being determined by the stroboscopic method, and the energy fed into the short-circuit being calculated from oscillograph records of the current and voltage on the d.c. side. In the case of a large commercial machine it is usual to carry out such short-circuit tests by means of a quick-acting circuit breaker, but in the present case this was quite out of the question and fuses were used instead. In fact it is probable that fuses were preferable to a circuit breaker, since it is very doubtful whether a breaker would give consistent results in a series of tests. On the other hand, fuses were found to be exceptionally consistent, the amount of the phase-swing on closing the circuit through a given low resistance and a fuse of given size being practically the same each time the test was made, the fuse being placed inside a large box so as to exclude draughts.

It was found that for these experiments the use of a stroboscopic disc driven by a synchronous motor was inadmissible because the reaction of the rotary convertor on the alternator caused a momentary swinging in this motor, which gave a false reading. This was overcome by using a Crompton-Robertson electrically driven tuning-fork and projecting the light from a lantern through the slots on to a disc mounted on the shaft of the convertor. A scale was placed behind this disc so that the position of the pattern could be easily read off. The difficulty presented by this method was that of holding the alternator speed absolutely constant; in fact it was impossible to do this, but if all the machines had been running on steady load for several hours before carrying out the tests, conditions had then become so constant that it was possible to hold the speed steady while making a test. Only those observations were recorded for which the pattern on the disc remained stationary after the blowing of the fuse; if the pattern rotated slowly, as sometimes happened, especially with the large fuses, the observation was rejected.

The current and voltage records were taken on cinematograph film by means of a Duddell two-element oscillograph, and, since the speed of the film had to be known in order that the energy in the short-circuit could be calculated, it was necessary to arrange for a timing ripple in addition. This was done by controlling the current vibrator with a two-pole throw-over switch by means of which this vibrator could be connected to a low-voltage supply of known frequency both just before and just after the test. Since it is possible that others may wish to carry out similar tests a diagram of connections is given in Fig. 11. This should be self-explanatory.

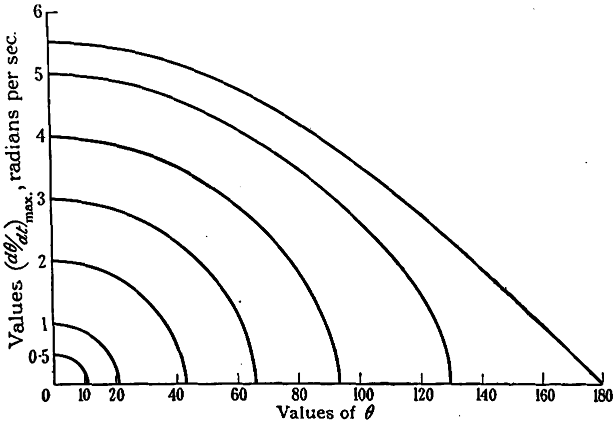

FIG. 10.—Curves of maximum angular velocity for the test machine to remain in step.

The voltage records verified a phenomenon which is of very great importance in connection with the breaking of the circuit of an overloaded rotary convertor, i.e. that if the cut-off is too rapid the self-induction of the circuit will set up an e.m.f. which may cause the e.m.f. across the brushes to become much larger than the normal machine voltage, and a rise in pressure with its attendant risk of breakdown may therefore be set up by the very appliance which is installed to do away with this risk.*

The rise of current will follow approximately the exponential law

$$i = \text{const.} \times (1 - e^{-at})$$

* See also R. TOWNEND: "1 500-Volt, 50-Cycle Traction Rotary-Convertor Equipments," *Metropolitan-Vickers Gazette*, 1927, vol. 10, p. 184.

and the decay of current, if over-voltages are to be prevented, should obey the complementary law

$$i = \text{const.} \times e^{-at}$$

If the decay of current is greater than that given by the above law, e.g. by the blowing of a fuse with explosive violence, or the operation of a quick-acting circuit breaker with too rapid a break, then rises of pressure of possibly serious proportions may be set up.

In the experimental observations on the small rotary convertor there were a good many cases in which the above phenomenon masked the true drop in voltage due to the ordinary working characteristics of the machine, and therefore when calculating the output of the machine during any particular test the voltage corresponding to a steady current equal to the mean current was taken.

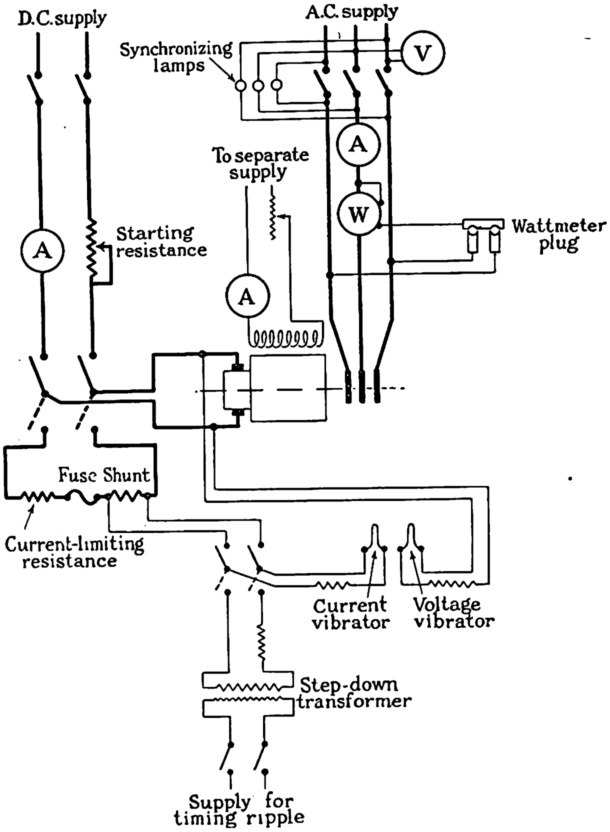

FIG. 11.—Connections for short-circuit tests.

The current and voltage curves were projected by means of a lantern on to a screen so as to give a magnified image, and were then re-drawn on squared paper so that the change in the output over the short-circuit period could be calculated and the mean output then determined. Suppose that this mean output is W_s watts, then, since the power of the machine corresponding to its pull-out torque is 2 710 watts per phase, or

$$3 \times 2\ 710 = 8\ 130 \text{ watts altogether,}$$

the corresponding value of ρ is

$$\rho = \frac{T_l}{T_m} = \frac{W_s}{8\ 130}$$

TABLE 3.

Fuse	Total rotor displacement on short-circuit (4 observations)	Duration of short-circuit	Maximum value of short-circuit current	Mean value as determined from oscillogram	Mean value of d.c. voltage during short-circuit	Mean output	Mean armature I^2R loss	Mean power during short-circuit	ρ	Displacement attained at moment of clearing, electrical degrees	Velocity attained at moment of clearing, electrical radians per sec.	Total rotor displacement (calculated)
	deg.	sec.	amps.	amps.	volts	watts	watts	watts				
1	8, 7, 7, 8	0·00313	49·5	31·3	156	4 890	230	5 120	0·63	0·04	0·445	9
2	16, 19, 17, 18	0·00413	49·5	35·8	155	5 560	300	5 860	0·72	0·08	0·67	15
3	12, 14, 14, 14	0·00415	42	29·9	155	4 650	210	4 860	0·598	0·07	0·56	12
4	17, 15, 17, 16	0·00443	52·5	47·5	152	7 210	530	7 740	0·951	0·12	0·955	20
5	20, 19, 20, 20	0·00720	46·5	32·5	155	5 040	250	5 290	0·65	0·22	1·055	22
6	28, 27, 28, 29	0·00910	48·6	30·6	156	4 800	220	5 020	0·618	0·33	1·27	26
7	21, 22, 21, 22	0·00720	52·5	34·2	155	5 300	280	5 580	0·686	0·25	1·21	24
8	35, 31, 31, 32	0·00945	48	30·1	156	4 700	210	4 910	0·605	0·35	1·3	27
9	55, 59, 62, 61	0·0187	58·5	41·2	152	6 250	400	6 650	0·817	1·86	3·45	77
10	31, 30, 28, 30	0·0078	58·5	36·5	155	5 660	310	5 970	0·735	0·29	1·3	27
11	95, 96, 97, 100	0·0305	53·1	36·0	155	5 590	305	5 895	0·725	5·03	5·75	Should pull out
12	120, 120, 114, 115	0·0168	87	59·0	148	8 750	820	9 570	1·18	2·15	4·45	110

In the application of the previous analysis it was assumed that the actual short-circuit was equivalent to this average ρ applied for the whole time of the short-circuit, as determined from the oscillograms. Altogether, tests were made with 12 different sizes of fuse, the results obtained being given in Table 3.

E. *Types of Deceleration Laws* (*undamped*).—The next step was to determine whether the mean or some other value of the current should be adopted, and to investigate the errors involved in the various possible assumptions. An examination of the current oscillograms shows that where the time of short-circuit is very short the current curve is roughly in the form of a triangle, whereas when the time is relatively long the curve is rectangular. With the latter form it is sufficiently accurate to determine the area under the curve and to take the average height as being the magnitude of the absolutely steady current which produces the same effect in the same time. With the triangular shape this may not be permissible, and it may be necessary to adopt some more accurate method. This is especially important in view of the fact that the short-circuits of commercial machines are almost invariably of this form.

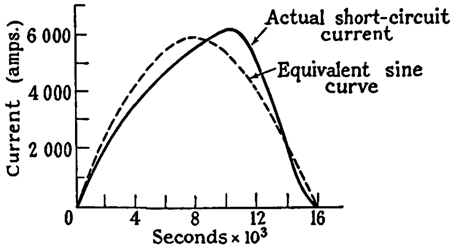

FIG. 12.—Short-circuit current of large machine.

In a paper entitled "The Generating Effect in Rotary Convertors on Short-Circuit"* the actual curve is replaced by the equivalent sine curve, and for the example given there the sine curve fits the actual curve reasonably closely. Adopting this approximation, we can write

$$\mathbf{T}_1 = m \times \mathbf{T}_1' \sin pt$$

where $\mathbf{T}_1'$ = max. value of load torque corresponding to the max. current in the equivalent sine curve,

$p = 180/T$, where T = duration of short-circuit,

m = ratio of terminal voltage during short-circuit to the no-load voltage. This correction is necessary since there is a very appreciable voltage-drop, especially if the convertor is used with a transformer, as is generally the case.

In the mechanical model of the slip motion we can, therefore, assume that the suspended weight is allowed to act for a time T seconds, and that its magnitude varies according to the above sinusoidal law. Again, since T is very short for those cases which admit of this method of treatment we can neglect the effects of both synchronizing and damping torques, and assume that the disc is acted on only by the torque $\mathbf{T}_1$. In order to investigate the degree of the error made by replacing an actual current curve by some simple equivalent form amenable to mathematical analysis, consider the curve of Fig. 12 which is taken from the article in the *Brown Boveri Review* quoted above.

Neglecting all torques but that due to the load, the equation of motion becomes

$$\frac{\mathbf{I}}{p} \cdot \frac{d^2\theta}{dt^2} = \phi(t)$$

or $$\frac{d^2\theta}{dt^2} = F(t)$$

since in a comparison of this kind it is not necessary to insert the constants of the machine, and values of $d\theta/dt$ and θ in arbitrary units are sufficient.

(1) Use the equivalent sine curve.

Then $$F(t) = 5\,950 \sin\left(\frac{\pi}{0 \cdot 016} \times t\right)$$

$$\therefore \frac{d^2\theta}{dt^2} = +\,5\,950 \sin (196t)$$

At the end of short-circuit, $t = 0 \cdot 016$.

$$\therefore \frac{d\theta}{dt} = 30 \cdot 4(1 - \cos \pi) = 60 \cdot 8 \text{ arbitrary units}$$

$$\theta = -\,0 \cdot 155 \sin \pi + 0 \cdot 486 = 0 \cdot 486 \text{ arbitrary units}$$

(2) Use the equivalent constant current.

Its value will be the mean height of the short-circuit current curve, namely 3 800.

$$\therefore \frac{d^2\theta}{dt^2} = 3\,800$$

Hence at the end of short-circuit, when $t = 0 \cdot 016$

$$\frac{d\theta}{dt} = 3\,800 \times 0 \cdot 016 = 60 \cdot 9$$

$$\theta = 1\,900 \times 0 \cdot 000256 = 0 \cdot 486$$

(3) Use the equivalent linear current curve.

Its peak value will be $2 \times 3\,800 = 7\,600$ amperes, so that

$$\frac{d^2\theta}{dt^2} = 7\,600 \times \frac{t}{0 \cdot 016} = 475\,000t$$

Hence at the end of short-circuit, when $t = 0 \cdot 016$

$$\frac{d\theta}{dt} = 288\,000 \times (0 \cdot 016)^2 = 74 \text{ arbitrary units}$$

$$\theta = 0 \cdot 394 \text{ arbitrary units}$$

(4) Use the actual current curve or a more accurate equation.

It is possible to proceed by a step-by-step method or to find two curves which fit the curve closely. The former method is laborious, and therefore the latter method is here adopted, especially as it is possible to make a very close approximation to the actual curve. The first part of the curve is obviously that of the rise of current in an inductive circuit, so that the equation is

$$i = \mathbf{I}(1 - e^{-at})$$

---

* *Brown Boveri Review*, 1924, vol. 11, p. 9.

From the curve we have

$$i = 4\,350 \quad \text{when} \quad t = 0\cdot005$$

and $$i = 6\,170 \quad \text{when} \quad t = 0\cdot01$$

$$\therefore \frac{6\,170}{4\,350} = \frac{1 - e^{-0\cdot01a}}{1 - e^{-0\cdot005a}}$$

$$1\cdot42 = 1 + e^{-0\cdot005a}$$

$$\therefore a = 174 \quad \text{and} \quad \mathbf{I} = 7\,500$$

As a check, if the above constants are correct, the current should be 0·6321 × 7 500, namely 4 741 amperes in 1/174 or 0·00575 sec. This point is actually on the curve, showing that the first part of the curve is fitted exactly by the equation for i. This portion holds from $t = 0$ to $t = 0\cdot0105$, the current then having risen to 6 250 amperes. It is sufficient to take the second part as being a straight line, falling from $i = 6\,250$ at $t = 0\cdot0105$, to $i = 0$ at $t = 0\cdot016$, since this will be more accurate than another exponential curve, owing to the inflection in the actual curve.

The calculation of $d\theta/dt$ and θ at the end of short-circuit is made in two parts as follows, the first of which is strictly accurate, while the second is approximate with a probable error of negligible order.

$$\frac{d^2\theta}{dt^2} = 7\,500(1 - e^{174t})$$

$$\frac{d\theta}{dt} = 7\,500t + \frac{7\,500}{174}e^{-174t} + A$$

and $$\theta = 3\,750t^2 - \frac{7\,500}{174^2}e^{-174t} + At + B$$

when $t = 0$, $d\theta/dt = 0$, and $\theta = 0$.

$$\therefore A = -43\cdot0, \quad \text{and} \quad B = 0\cdot248$$

∴ $d\theta/dt = 42\cdot75$ arbitrary units, $\theta = 0\cdot17$ arbitrary units, at the end of the first step.

Take $t = 0$ at the commencement of the decay of the current. Then

$$\frac{d^2\theta}{dt^2} = 6\,250 - \frac{6\,250}{0\cdot0055} \times t$$

$$\frac{d\theta}{dt} = 6\,250t - 568\,750t^2 + A$$

$$\theta = 3\,125t^2 - 189\,600t^3 + At + B$$

when $t = 0$, $d\theta/dt = 42\cdot75$, and $\theta = 0\cdot17$.

$$\therefore A = 42\cdot75 \quad \text{and} \quad B = 0\cdot17$$

Hence when the current has finally died down to zero, $t = 0\cdot0055$.

$$\therefore \frac{d\theta}{dt} = 59\cdot8 \text{ arbitrary units}$$

$$\theta = 0\cdot493 \text{ arbitrary units}$$

A check by the step-by-step method gave almost identical results. These values are given in Table 4.

TABLE 4.

$F(t)$	$d\theta/dt$	θ	Percentage error in $d\theta/dt$	Percentage error in θ
1. Sinusoidal	60·8	0·486	1·7 % high	1·4 % low
2. Constant	60·9	0·486	1·85 % high	1·4 % low
3. Linear	74·0	0·394	23·75 % high	20 % low
4. Combination of exponential and linear	59·8	0·493	—	—

It will be seen that for the particular short-circuit current curve investigated there is very little to choose between the various functions, except No. 3, which has a considerable error. Nos. 1 and 2 give slightly high values for $d\theta/dt$ and slightly low values for θ, with the result that if they are used in the determination of the motion subsequent to the clearing of the short-circuit, the errors in this calculated motion will be even less than those tabulated. This is because after clearing, $d\theta/dt$ diminishes with increase in θ. It thus follows that the error will be very small if either the first or the second function is used. The table shows very clearly that the effect on the machine depends not only on the energy in the short-circuit, which was the same in all four cases, but also on the shape of the current curve, and that this should be determined very carefully, particularly if the time taken to decay to zero is a very short fraction of the whole period of short-circuit, as is sometimes the case, since then the curve more closely approximates to the linear function of t than to either No. 1 or No. 2.

In working out the displacement from the oscillograms it will be seen from Table 3 that the average value of the current has been taken, and this value has been assumed to be operative throughout the whole of the short-circuit period. This average value was determined by means of a planimeter from the enlarged curves which are reproduced in Fig. 13. Also a correction for the change in voltage on the d.c. side was, as explained previously, made when calculating the values of ρ. The total displacement which, according to the above theory, should have taken place during each test is worked out in two steps, the second step corresponding to the continued movement following the clearing of the short-circuit, requiring the use of the curves given in Fig. 10. It will also be seen that the values of ρ are, with one exception, all less than unity although all corresponded to an overload. This was necessary because of the small size of the machine under test, coupled with the ease with which it could fall out of step owing to its very small damping.

On comparing the calculated with the observed deflections it will be seen that both are of the same order, which is, perhaps, as much as could be expected from such an investigation. For the small deflections the calculated values are on the small side, while for large deflections the reverse is the case. This is to be expected since, although damping has no appreciable effect so long as the deflection is small, it does have some effect on the magnitude of a large displacement following a severe short-circuit, even though the damping is small as in the present case. Thus in tests 11 and 12 the calculated velocities indicate that the machine should fall out of step because the velocities obtained are greater than the critical velocity for the absolutely undamped machine, namely 5·52 electrical radians per second. Actually, owing to the existence of finite damping the machine showed no indication of falling out of step no matter how many times the fuse corresponding to test 11 was blown, but during test 12 it did fall out of step on several occasions, showing that the velocity attained at the moment of clearing the short-circuit was just about the same as the critical value for that particular angular position of the armature. In Table 3 the figures underlined in col. 2 are the displacements actually observed when the oscillograms were taken: the other figures are displacements observed on blowing the same size of fuse wire, no oscillograms being taken. It will be seen that the method gave quite consistent results.

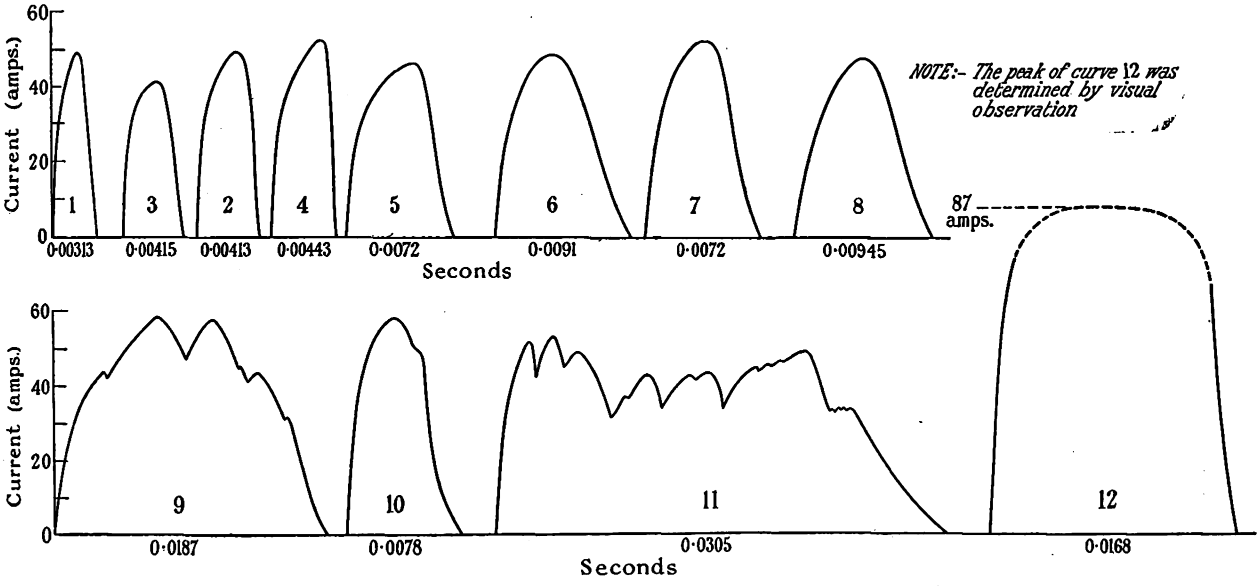

FIG. 13.—Short-circuit currents with small experimental machine.

(6) MOTION OF A DAMPED ROTARY CONVERTOR.

Further Considerations.—The equation of damped motion is

$$\frac{d^2\theta}{dt^2} + k\frac{d\theta}{dt} + \mu\theta = 0$$

and for critical damping we have the well-known relationship

$$k^2 = 4\mu$$

or

$$k = 2\sqrt{\mu}$$

Since $\mu = 245$, the value of k for critical damping is

$$k = 2\sqrt{245} = 31\cdot 3$$

It is doubtful whether the damping in an actual machine can ever be equal to the critical value, and a more representative value of k will be considerably less than the above. The value of 20 has, therefore, been taken so that the equation of motion with the machine under load becomes

$$a + b\sin\theta + c\frac{d\theta}{dt} + d\frac{d^2\theta}{dt^2} = 0$$

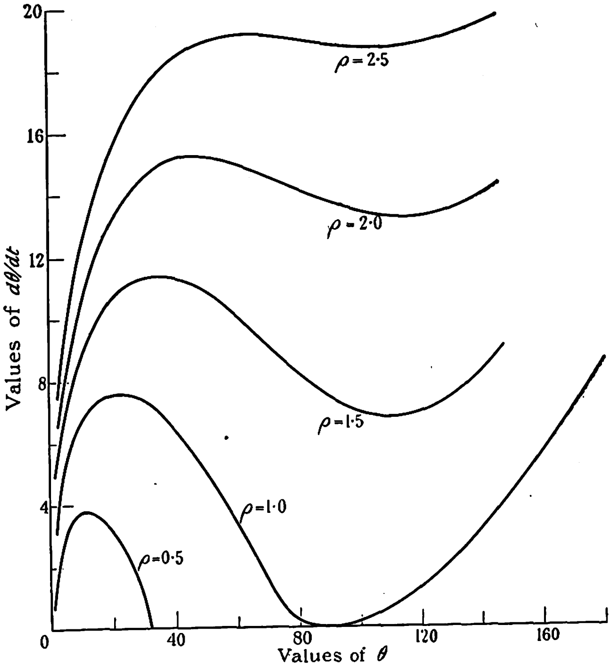

FIG. 14.—Motion of a heavily damped rotary convertor during short-circuit.

where $a = -\rho$
$b = 1{\cdot}0$
$c = k \times d = 20 \times 0{\cdot}0041 = 0{\cdot}082$
$c/d = 20$

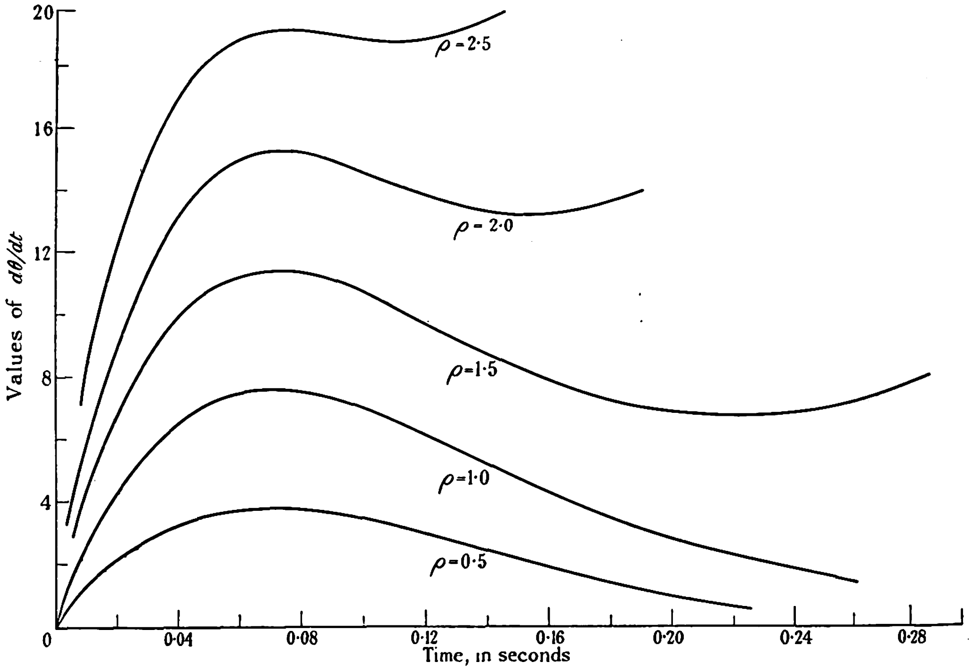

FIG. 15.—Motion of a heavily damped rotary convertor during short-circuit.

The equation with damping can only be solved by the step-by-step method, and the results of the investigation are given in the curves of Figs. 14 and 15. On comparing these curves with those for the same machine without damping (Figs. 16 and 17), it will be seen that for large displacements the damping does limit the displacement as would naturally be expected, but for small displacements produced by a disturbance acting only during a small fraction of a second the damping is practically inoperative since the initial portions of corresponding characteristics are the same both with and without damping. This is a more complete and satisfactory proof of the principle expounded in an elementary manner on page 1002, and it follows that as far as the motion during short-circuit is concerned, that is, not including the continued motion after clearing, it is quite justifiable to neglect the damping, no matter how strong this may be.

The author is glad to make acknowledgments to his colleague Mr. E. W. Golding and to Mr. F. W. Campbell

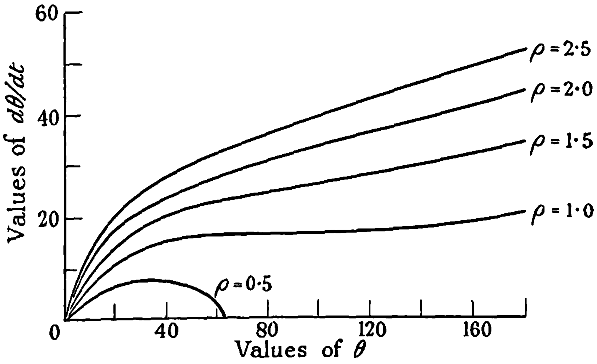

FIG. 16.—Variation of $d\theta/dt$ with θ for an undamped machine.

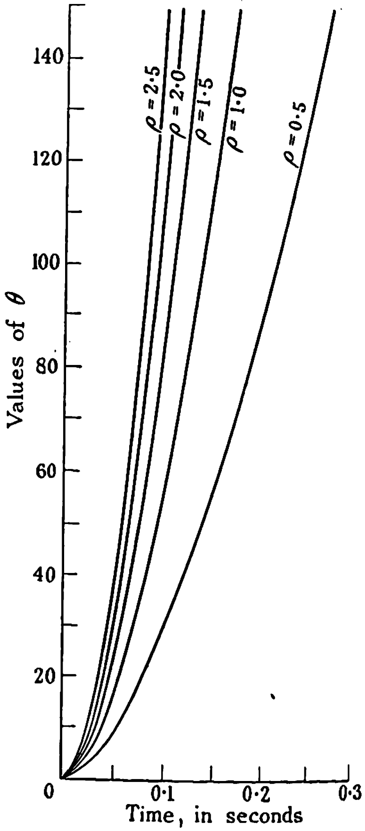

FIG. 17.—Variation of θ with t for an undamped machine.

for assistance in making some of the observations, to Mr. S. A. Swann for assistance with computations, and to the Royal Society for a grant of money with which to purchase certain apparatus.

APPENDIX 1.

A SPECIAL SOLUTION OF THE EQUATION OF MOTION.

If large slip velocities are produced, the criterion for a synchronous machine to be just able to keep in step is that the slip velocity shall be brought to zero at the angular position

$$\theta = \pi - \alpha, \text{ where } \alpha = \arcsin (\mathrm{T_l/T_m})$$

Now the author has found, when making step-by-step solutions of this problem, that the curve of $d\theta/dt$ against θ is very nearly an ellipse. In the limiting case, if ω_0 is the maximum possible slip velocity in mechanical radians per second at the position for the machine just to keep in step, then we can write as a first approximation, putting $\phi = (\pi - \alpha)$,

$$\frac{\theta^2}{\phi^2} + \frac{(d\theta/dt)^2}{\omega_0^2} = 1$$

$$\therefore \left(\frac{d\theta}{dt}\right)^2 = \omega_0^2\left(1 - \frac{\theta^2}{\phi^2}\right)$$

or

$$\frac{d\theta}{dt} = \frac{\omega_0}{\phi}\sqrt{(\phi^2 - \theta^2)}$$

$$\therefore \frac{dt}{d\theta} = \frac{\phi}{\omega_0} \times \frac{1}{\sqrt{(\phi^2 - \theta^2)}}$$

$$\therefore t = \frac{\phi}{\omega_0}\int_0^{\phi}\frac{d\theta}{\sqrt{(\phi^2 - \theta^2)}}$$

$$= \frac{\phi}{\omega_0} \times \frac{\pi}{2}$$

the constant of integration being zero, since when $\theta = 0, t = 0$.

Now this expression for t is the area under the curve of $dt/d\theta$ against θ. It was found that the departure from the pure elliptical form of the curve of $dt/d\theta$ against θ was such that the ratio of the area under the actual curve to the area under the ellipse with the same semi-axes was about 1 to 1·1. Hence a somewhat more correct value for t will be given by taking the ratio of the area under the curve of $dt/d\theta$ to the area under the curve of reciprocals of the ordinates of the ellipse, to be 1·1 to 1. In other words the corrected value for t is

$$t = \frac{\phi}{\omega_0} \times \frac{\pi}{2} \times 1{\cdot}1$$

Now this value of t will be the quarter-period when swinging with an amplitude of 0 to ϕ, plus the quarter-period when swinging from α to ϕ

$$\therefore t = \pi\sqrt{\left(\frac{\mathrm{I}}{\mathrm{T_m}p}\right)} \times k$$

where k is the correction factor for this amplitude.

Equating these two expressions for t, we have

$$\frac{\phi}{\omega_0} \times \frac{1{\cdot}1\pi}{2} = \pi\sqrt{\left(\frac{\mathrm{I}}{\mathrm{T_m}p}\right)} \times k$$

$$\therefore \omega_0 = \frac{1{\cdot}1\phi}{2k \times \sqrt{[\mathrm{I}/(\mathrm{T_m}p)]}}$$

Probably the best illustration of the order of accuracy given by this method is to calculate ω_0 for the data given by Carr * for a synchronous induction motor, namely

$\mathrm{T_m} = 2\,000$ lb.-ft.
$\mathrm{T_l} = 1\,000$ lb.-ft.
$\mathrm{I} = 200$ foot, pound, second, units
$p = 5$

$$\therefore \alpha = \arcsin\frac{1\,000}{2\,000} = 30^\circ$$

and

$$\phi = 150^\circ$$
$$= \frac{150 \times \pi}{180} \text{ radians}$$

k is obviously the mean of the correcting factors for the swing of 0 to α, the position of stable equilibrium, and the factor for the swing from α to ϕ.† The first swing is one of 30°, for which the correcting factor is 1·0174. The second is from 30° to 150°, i.e. 120°, for which the factor is 1·3729. The value of k is therefore

$$k = \frac{1{\cdot}0174 + 1{\cdot}3729}{2}$$
$$= 1{\cdot}195$$

Hence, finally,

$$\omega_0 = \frac{1{\cdot}1 \times 150\pi/180}{2 \times 1{\cdot}195 \times \sqrt{[200/(2\,000 \times 5)]}}$$
$$= 8{\cdot}5$$

as against 8·58 when calculated by the step-by-step method. The agreement is sufficiently close to show that, unless extreme accuracy is required, the above solution of this special problem is sufficient for most purposes, especially as the calculation can be made in a few moments as against an hour or more by the step-by-step method. Also it should be noted that if the motion is such that the curve of $dt/d\theta$ against θ becomes very steep, it is necessary to take very small intervals of θ when using the step-by-step method, otherwise very appreciable errors may be made, and this renders the method extremely laborious.

APPENDIX 2.

The equation for θ can be written

$$\theta = ae^{-kt}\cos nt$$

$$\therefore \theta = \text{Real part of } (ae^{-kt+jnt})$$

$$\therefore \frac{d\theta}{dt} = \text{Real part of } \left\{(-k + jn)ae^{-(k+jn)t}\right\}$$

$$= \text{Real part of } \left\{(-k + jn)ae^{-kt}e^{jnt}\right\}$$

$$= ae^{-kt}\left[\text{Real part of } (-k + jn)(\cos nt + j\sin nt)\right]$$

$$= ae^{-kt}(-k\cos nt + n\sin nt)$$

$$= \frac{a}{\sqrt{(k^2 + n^2)}} \cdot e^{-kt}\cos(nt - \epsilon)$$

where $\tan\epsilon = k/n$.

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* *Loc. cit.*

† This is not rigorously correct, as the motion is not exactly sinusoidal, but the error introduced will be very small.

APPENDIX 3.

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THE PRODUCTION OF UNIFORM ILLUMINATION OVER LARGE AREAS.*

By H. R. S. McWhirter, B.Sc.(Eng.), Associate Member.

(*Paper first received* 18*th November*, 1929, *and in final form* 15*th January*, 1930.)

Summary.

It is shown that when planning a lighting system for a large "working plane," using the standardized industrial reflector (B.S.S. No. 232—1926), it is better to place the lamps over the centres of certain contiguous rhombuses than over the centres of contiguous squares of equal area. A new definition is proposed for the term "spacing ratio." A convenient method of drawing isolux diagrams is described and such diagrams are given for the above-mentioned standardized reflector at a spacing ratio of 1·5. It is shown how uniformity of illumination varies with spacing ratio with the above reflector. A plea is made that manufacturers of other reflectors should publish similar information relating to their goods. Finally, some brief practical rules for designers of electrical lighting systems are given, from whose point of view the paper has been written.

Introduction.

There is a widespread belief among engineers, fostered by statements in certain reference books and pamphlets, that to provide the most uniform illumination over a large working plane with a given number of lighting units (i.e. lamps and reflectors) it is best to divide the plane into squares and suspend a unit over the centre of each square. This belief is shown in the paper to be erroneous, and a more correct theory is developed.

When the positions of lighting units are fixed, the present method of fixing their height is to rely on a statement of the reflector manufacturers, that the "spacing ratio" must not exceed a certain maximum. This ratio is taken to be

$$\frac{\text{(Distance apart of lamps)}}{\text{(Height above working plane)}}$$

and for various industrial reflectors it varies between 1 and 2.

The inadequacy of this definition of spacing ratio and of this method of fixing the height of the lamps is shown in the paper, and more satisfactory methods are given.

The subject is dealt with under the following headings:—

(1) General discussion.
(2) Practical rules for the design of electric lighting systems.

(1) General Discussion.

The case considered will be that of a large horizontal plane divided into a number of equal areas of the same shape, which completely cover the plane but do not overlap, the plane being illuminated by direct lighting units suspended one over the geometrical centre of each area, the lighting units being similar to each other in all respects.

If the plane is sufficiently large the distribution of illumination over each area will, in the cases to be discussed, be sensibly the same, except for those areas around the borders of the plane. Neglecting the latter areas for the time being, and assuming that no light is reflected on to the plane from the ceiling, the average illumination over each area will be equal to the lumens emitted in the lower hemisphere by one lighting unit, divided by the value of the area in square feet. The result so obtained will be in foot-candles.

The ratio of the minimum illumination occurring in each such area, to the average, will be referred to in the paper as α. The ratio of the maximum illumination to the average will be referred to as β. Clearly α must be less than unity and β greater than unity.

The values of α and β will depend on the value of each area in square feet, the mounting height of the units in feet, the shape of their polar distribution curve and the geometrical shape of the areas. If, however, the term "spacing ratio" is defined as

$$\frac{\sqrt{\text{(Area under each unit)}}}{\text{Mounting height of unit}}$$

then the values of α and β will depend on only three variables, viz. spacing ratio, the shape of the polar distribution curve of the units, and the geometrical shape of the areas. Hereinafter the term "spacing ratio" will be assumed to be defined as above.

This proposed definition coincides with the generally accepted one (see Introduction) when the units are suspended over squares. The latter definition, however, suffers from the disadvantage that when the lamps are not over squares it is often ambiguous, as the distance between lamps in one direction is greater than the distance between them in another direction.

For a given reflector and spacing ratio, therefore, α and β depend only on the geometrical shape of the area. It is necessary to ascertain what shape of area will make α as high as possible.

The total illumination on an area under one unit is due partly to the unit above it and partly to all the other units. As the spacing ratio is increased, however, the illumination due to the lighting unit above the area becomes an increasingly great proportion of the whole. Assuming that the polar distribution curve of a unit is the same in every plane through the vertical axis of the unit, it is to be expected that, at least for high values of spacing ratio, a would be highest when the area was the nearest possible approximation to a circle.

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A plane, however, cannot be divided into circles which completely cover it without overlapping; the nearest approximation to a circle that can be used is the hexagon. It is therefore to be expected that this shape of area would make a as high as possible.

Fig. 1 shows in small circles the positions of units hung over the centres of hexagons. Three contiguous hexagons are shown in dotted lines on the left of the figure, while on the right are shown four contiguous rhombuses. When they divide the plane into hexagons the lighting units also incidentally divide it into rhombuses of which the acute angle is 60°.

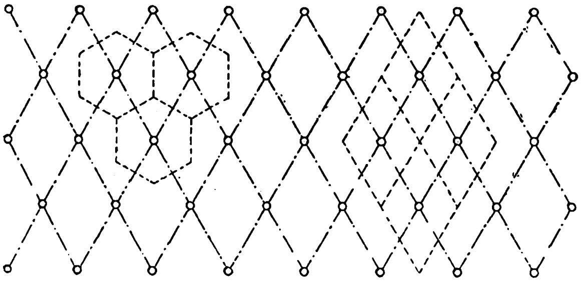


FIG. 1.

The square, however, is only a particular case of the rhombus in which the angle is 90°; and if the value of a is a maximum when the angle of the rhombus is 60° it must be less when the angle is 90°, and there must be another value for the angle, less than 60°, for which the value of a would be equal to that corresponding to 90°. This angle of less than 60° will be referred to as the "critical angle" and the ratio (Major diagonal)/(Minor diagonal) for the rhombus corresponding to it will be referred to as the "critical ratio." The critical ratio is thus equal to the cotangent of half the critical angle. It is desirable to introduce this ratio because in designing lighting systems it is easier to deal with than the angle.

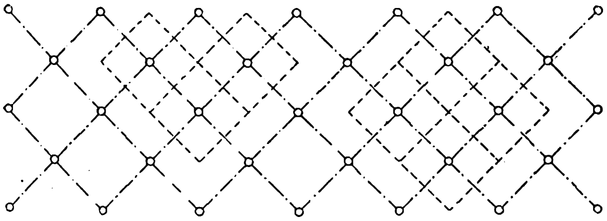


FIG. 2.

If the plane is divided into rhombuses the ratio of whose diagonals is less than the critical ratio but greater than unity, the value of a will be greater than if it is divided into squares of equal area.

Fig. 2 shows a plane divided into squares, and Fig. 3 shows a plane divided into 45° rhombuses, the areas in each case being the same as that of the 60° rhombuses in Fig. 1.

It is interesting to note how the dotted areas in the left of the three figures coalesce into each other as the angle of the rhombus changes. These areas on the left differ from the rhombuses in that they are cyclic, and form the closest approximation to a circle that the respective arrangement of points permits. It is necessary, however, to refer mostly to the rhombuses, in preference to referring to the areas on the left, because in designing lighting systems it is simpler to deal with rhombuses.

The above conclusions can be made of practical use by referring to the lighting distribution curve of what is probably the most widely used reflector in industrial lighting, namely that standardized in B.S.S. No. 232—1926 entitled "Industrial Reflector Fittings for Electrical Lighting (No. 1)." Particulars of this fitting may be obtained from the Specification and from Technical Paper No. 3 of the Department of Scientific and Industrial Research entitled "Light Distribution from Industrial Reflector Fitting No. 1." This latter paper is obtainable at H.M. Stationery Office.

For those unfamiliar with this reflector it may be stated that it is an all-metal bowl fitting, enamelled white inside, and so arranged that the rim of the bowl cuts off all direct light from the filament at an angle of 20° below the horizontal. According to the specification the efficiency of this reflector must not be less than 60 per cent.

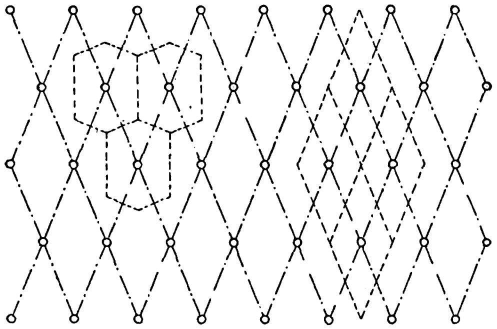


FIG. 3.

In the technical paper referred to, the contour of the reflector and its average polar distribution curve are given. These are reproduced, by kind permission of the Controller of H.M. Stationery Office, as Figs. 4 and 5.

By using a modification of Rousseau's method on Fig. 5 it was found that the mean spherical candle-power of a unit with this polar distribution curve would be 1/4·5 times the radius vector vertically downwards. The reflector efficiency being 60 per cent, it is clear that when a lamp is placed in one of these reflectors the candle-power of the combination vertically downwards is 2·7 times the mean spherical candle-power of the lamp alone. It is stated in the above-mentioned technical paper that the ratio of tip-end candle-power to mean spherical candle-power of ring-filament gas-filled lamps is about 1·25. Therefore when such a lamp is placed in its appropriate reflector of the above type the candle-power in the direction of the tip-end of the lamp is increased in the ratio of 2·16.

The mean spherical candle-power of any standard gas-filled lamp may be obtained from B.S.S. No. 161—

1928, and as the candle-power vertically under such a amp when placed in the appropriate standard reflector may be found by multiplying this by 2·7, the candle-power in any other direction from the combined lamp and reflector may be found by making use of the curve of polar distribution, Fig. 5.

If any number of such lighting units are suspended over a plane the illumination at any point may be found by adding together the illumination at that point due to each lamp taken separately.

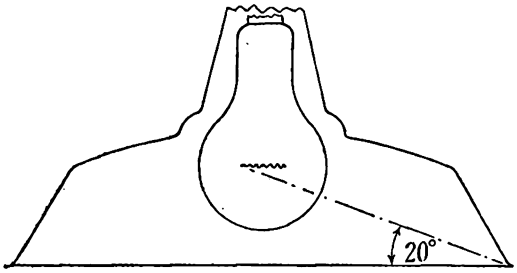


Fig. 4.

If a large number of such calculations are to be made, it is useful to proceed as follows: Lay out on a plan the positions of the units to a suitable scale, and mark on it the point at which the value of illumination is required. Draw, to the same scale on tracing paper, the isolux diagram for one unit, which will consist of a system of concentric circles. Place the centre of the diagram over the point on the plan at which the illumination value is required. For each lighting unit on the plan which falls within the diagram, there will correspond an illumination value which can be read off from the diagram. Add these values together, and the sum will give the total illumination value at the point in question.

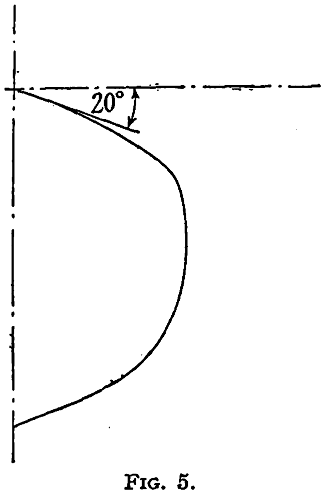


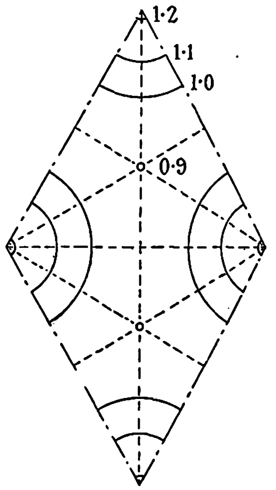
Fig. 5.

By using such a method the author found the value of α for these reflectors when used at a spacing ratio of 1·5 (which is the value quoted in the Standard Specification). When the lamps were placed in squares the value was 0·85. When the lamps were placed in rhombuses the value rose to a maximum of 0·9 when the acute angle of the rhombus diminished to 60°, and then decreased until when the angle of the rhombus was 45° the value of α was again 0·85. This, therefore, is the critical angle for the standard reflector when used at a spacing ratio of 1·5. The corresponding critical ratio is 2·414.

The rhombuses in Fig. 3 have an acute angle of 45°. Therefore the lay-outs of lighting units in Figs. 2 and 3 will give the same average illumination, and the same minimum illumination, if the standard reflector at a spacing ratio of 1·5 is used. If the angle of the rhombus is made intermediate between 45° and 90°, the illumination will be better, i.e. the value of α will be higher.

In making these calculations it was assumed that minimum illumination occurred at the corners of the dotted areas on the left of Figs. 1, 2 and 3.

There is no difficulty in showing that in this reflector the "critical ratio" varies with the spacing ratio. As the light is cut off at 20° below the horizontal, the minimum illumination is zero when the lamps are placed in squares at a spacing ratio of 3·89. Consideration shows that the critical angle for this spacing ratio is the apex angle of that isosceles triangle which, while not being a right-angled triangle, has the same radius of circumscribed circle as an isosceles right-angled triangle of equal area. The corresponding critical ratio is the real root of the equation $x^3 - 3x^2 - x - 1 = 0$, which is approximately 3·383. The critical angle is 32° 56′. That the critical ratio also varies with the shape of the polar distribution curve may be seen from the fact that if the light were cut off at an angle other than 20° below the horizontal, the value of spacing ratio at which the critical ratio is 3·383 would correspondingly vary.

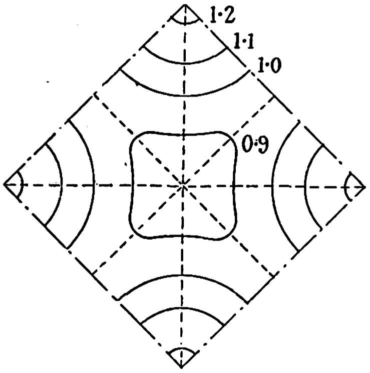


Maximum = 1·213
Minimum = 0·9

Fig. 6.

It would be of interest to have a curve giving the critical ratio for any spacing ratio for this reflector, but owing to the labour involved the author has omitted this. Until such a curve is drawn, however, it is considered that no great error would be made by taking the critical ratio as 2·414 for any value of spacing ratio likely to occur in practice.

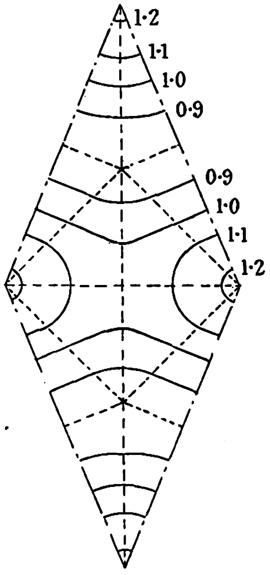
The isolux diagrams corresponding to Figs. 1, 2 and 3 are given in Figs. 6, 7, and 8 respectively. These latter figures represent rhombuses with a lamp (not shown) at each corner taken from the centre of a large number of lamps arranged as in Figs. 1, 2 and 3, respectively, and at a spacing ratio of 1·5. The difference in illumination between adjacent isolux lines is one-tenth of the value of average illumination. The line of average illumination is shown.



Maximum - 1·237
Minimum - 0·85

Fig. 7.

In the case of Fig. 7, the isolux diagram was drawn by plotting a contour illumination curve for half the diagonal, for half the side of the square, and for the line joining the centre of the side to the centre of the square. The points on these curves at which the illumination was equal to 0·9, 1·0, 1·1 and 1·2 times the average were then ascertained and marked on the squares. Suitable curves were then drawn between the points. Similar methods were adopted for Figs. 6 and 8.



Maximum - 1·23
Minimum - 0·85

Fig. 8.

These curves clearly show that there is a large area between lamps at which the illumination varies very little from the minimum value. This emphasizes the importance of knowing the minimum value of illumination as distinct from the average value.

The increase in illumination obtained by dividing the plane into rhombuses instead of squares is not so big as to justify going to great lengths to effect it; but in practice cases are not rare in which the obstructions in a ceiling would favour the use of rhombuses; in such cases it is of value to know that something is gained by not adhering to the use of squares.

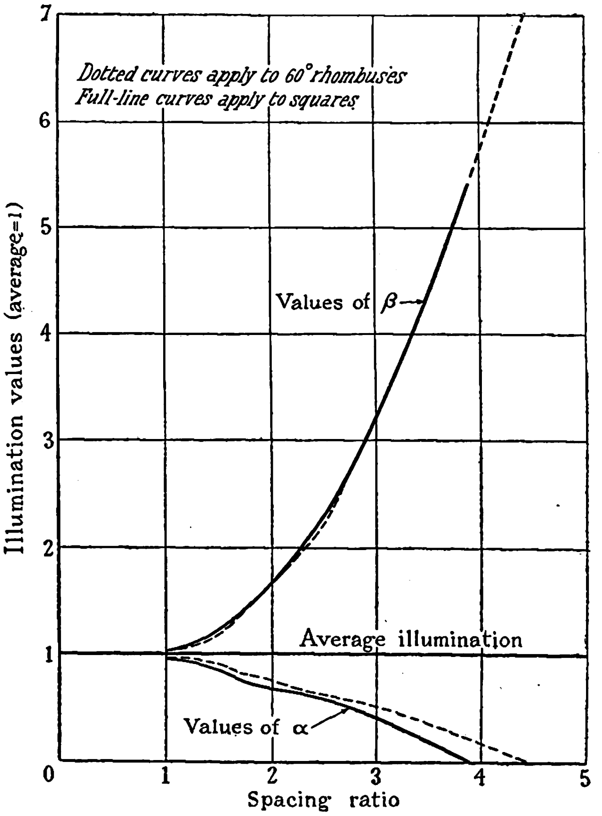


Fig. 9.

It is now necessary to consider how α and β vary with the spacing ratio. Lack of information on this point is one of the most constant sources of annoyance to the designer of lighting systems. A mere statement that a certain value of spacing ratio must not be exceeded is not sufficient in a case where, if it is exceeded by, say, 20 per cent, the number of lamps used can be halved. This would lead to an important economy if it could be safely done, and such cases frequently occur in practice, due to the fixed height of ceilings and disposition of beams, etc., in the ceiling. Hitherto, however, there has not, as far as the author is aware, been any means by which it was possible to ascertain how the values of α and β would be affected by exceeding the prescribed value of spacing ratio.

The curves in Fig. 9 are intended to supply this omission, as far as the standardized industrial reflector is concerned. Values of α and β are plotted as ordinates against values of spacing ratio as abscissæ. The abscissa at unity represents average illumination; the full-line curves apply to the case where the lamps are arranged in squares and the dotted curves apply to the case where they are arranged in 60° rhombuses. The curves below the abscissa at unity represent values of α, and those above it values of β.

It will be seen that for the values of β the dotted curve coincides with the full-line curve for most of its length; but for the values of α the dotted curve is always above the full-line curve.

These curves show that the smaller the spacing ratio the more uniform is the illumination, and they should be of great use to designers in estimating the *minimum* illumination of a proposed system, which, as pointed out above, is quite as important as the average illumination. The curves would be more complete if another curve were added, showing how the critical ratio varied with the spacing ratio. For the ordinates of this additional curve the same scale might be used as is already shown on the vertical axis of Fig. 9. Such a set of curves could be drawn for any direct reflector and would have a very well-defined meaning. They would be of more use than the polar distribution curve, and might be termed the "characteristic curves" of the reflector. It would be very useful if manufacturers would publish such curves relating to their reflectors.

The curves apply to the case in which the plane is divided into squares or rhombuses, but not to the case where it is divided into rectangles, which is frequently found convenient in practice. In such a case, of course, the term "spacing ratio" as defined above has a definite meaning, and the value of α would be less than that given by Fig. 9 for a square at the same spacing ratio. How much less is a matter that could in any particular case be calculated by using the distribution curve in Fig. 5 and the other information given above. This, however, would be somewhat laborious, and an experienced designer could make a guess that would be near enough for practical purposes.

It is necessary now to review the assumptions that have been made and consider how their validity affects the results.

It was assumed, in the first place, that the plane was very large and the portion along the edges, to which the results do not apply, was neglected. This portion, however, increases in area as the spacing ratio is diminished. It would be very laborious to take complete account of this effect, which might be called the "fringe effect." An idea of its magnitude may be gained by considering a very large area covered by lamps arranged in horizontal and vertical rows in squares. Numbering the vertical rows of lamps (starting from the end row) as 1, 2, 3, etc., the value of α between rows 1 and 2 would be equal to that given by Fig. 9, unless the spacing ratio were less than 1·74, in which case α would be less. Similarly the value of α between rows 2 and 3 would be equal to that given by Fig. 9, unless the spacing ratio were less than 1·08. This is about as low a spacing ratio as is likely to occur in practice, so that it will be seen that the effect is not very marked, especially if the end rows of lamps are placed close against the walls, and the latter are of a light colour and reflect the light well.

The whole of the numerical results obtained assumes that all the light on the plane comes direct from the units, none being reflected from the ceiling. This condition obtains with the standard reflector, provided the ceiling is of a dark colour. If it is white, light reflected from the plane may strike the ceiling and be reflected back on to the plane, causing a uniform increase in its illumination at all points. In workshops, however, this may usually be neglected, as such ceilings, if white at first, do not usually remain white after a short period.

The assumption that the polar curve of light distribution is the same in all planes containing the vertical axis of the unit is shown in Technical Paper No. 3 (mentioned above) to be approximately correct. Slight differences are introduced by the fact that the "ring filament" of a lamp has a gap in it, and slight errors in manufacture sometimes result in the axis of the lamp not being quite collinear with the axis of the reflector. Obviously no account can be taken of these factors, and they would not materially affect the result.

The assumption that every unit of the same wattage is identical as regards light output is not exactly true, owing to the tolerance allowed on the output of lamps of the same wattage, and to the fact that variation in efficiency may be shown between individual reflectors. The Standard Specification specifies only a lower limit (60 per cent) for the efficiency of reflectors; therefore if this value were to be used in calculations the results obtained would be slightly on the low side. This, however, should only be by a few per cent. The discrepancies due to these variations of the lamps, however, would be less as the spacing ratio decreased.

Another assumption that has been made is that the light from a unit is completely cut off at 20° below the horizontal. While the light from the filament is so cut off there would still be a very small amount of light emitted above this angle, owing to reflection from the inner surface of the bowl of the fitting. This would also have the effect of making the value of minimum illumination, calculated from the curves of Fig. 9, a trifle on the low side.

The remaining important assumption that has been made is that the unit is a point source of light, and that the inverse-square law holds for light emitted from it. This, of course, is not exactly true for points near the reflector. In an Appendix to the Standard Specification a point-to-point method of measuring the efficiency is described in which it is stated that the distance between the photometer head and the light centre of the lamp shall not be less than 8 times the diameter of the reflector. It is to be presumed, therefore, that at distances greater than this the inverse-square law is sensibly true. The diameter of the reflector varies from 10 in. for 40-watt lamps to 20 in. for 1 500-watt lamps. The general effect of this departure from the inverse-square law would be to make the values of β, obtained from Fig. 9, somewhat high, and the values of α somewhat low. In general, however, the effect would be extremely small, especially in those cases where no part of the plane was nearer to a reflector than 8 times the diameter of the reflector.

It is not contended that this paper deals with the subject exhaustively. It would be useful to have the curve of critical ratio plotted against spacing ratio added to Fig. 9, and it would be interesting to have curves similar to Fig. 9, but such as apply to a lighting unit in which the polar distribution curve is a circle (as is the case with diffusing globes).

There is also the possibility that some general theorems may be deduced regarding the value of the critical ratio, which will apply whatever the shape of the polar distribution curves.

However, it is thought that the results obtained are sufficient to be of use in the design of lighting systems, and they are embodied as briefly as possible under the following heading.

(2) Practical Rules for the Design of Electric Lighting Systems.

The following rules apply where a large number of direct lighting units are used to illuminate an area of great length and breadth. It is assumed that the standard industrial reflector (B.S.S. No. 232—1926) is used.

(*a*) Assuming that no light is reflected from the ceiling, the average illumination in foot-candles will be equal to 60 per cent of the number of lumens emitted by one lamp, divided by the area under it in square feet. This area is referred to as " A."

(*b*) If h is the mounting height of the lamp it is convenient to define the spacing ratio as $\sqrt{A}/h$, units being of course consistent. The ratio (Minimum illumination)/(Average illumination) is referred to as α, and (Maximum illumination)/(Average illumination) is referred to as β. α and β depend on the spacing ratio and the shape of the area " A." For a given spacing ratio α is a maximum when A is a rhombus, as in Fig. 1, having the ratio $p/q = 1 \cdot 732$, where $p =$ longer diagonal and $q =$ shorter diagonal of rhombus. The values of α and β corresponding to any spacing ratio under these conditions are given by the dotted curves in Fig. 9. When A is a square, as in Fig. 2, the values of α and β corresponding to any spacing ratio may be found from the full-line curves in Fig. 9. When A is a rhombus having a value for p/q less than $1 \cdot 732$ and greater than unity, the values of α and β for any spacing ratio will lie between the dotted and full-line curves in Fig. 9. The same will be the case when A is a rhombus having a ratio of p/q greater than $1 \cdot 732$ but less than a certain " critical " value, and the latter depends on the spacing ratio. When the spacing ratio is $1 \cdot 5$, the critical ratio is $2 \cdot 414$. For practical purposes no great error will be introduced by assuming that this value obtains for all spacing ratios.

When A is a rectangle the value of α will be less than that given in the full-line curve shown in Fig. 9. How much less is a matter that must be left to the judgment of the designer.

(*c*) The following example will make clear the application of the rules:—

A lighting system consists of 150-watt, 200-volt gas-filled lamps in the standardized industrial reflector arranged in rhombuses similar to those shown in Fig. 3, but the longer diagonal of the rhombus is 22 ft. and the shorter diagonal is 10 ft. The lamps are 9 ft. above the ground. Find the average and minimum illumination on a plane 3 ft. above the ground.

In solving this, the value of A is 110 sq. ft., the spacing ratio is 1·75, the lumens emitted by each unit are 1 014, and the average illumination is 9·22 foot-candles. As the value of p/q is 2·2 the value of α will be between the full-line curve and dotted curve in Fig. 9, where the spacing ratio is 1·75, i.e. between 0·81 and 0·73. Assume the value to be 0·75. This makes the minimum illumination 6·9 foot-candles.

For reasons indicated under the previous heading these results are probably a trifle on the low side and to give an arbitrary correction for this they might be increased by 5 per cent, giving 9·7 and 7·25 foot-candles respectively. These results would be correct when the reflectors were new and clean. To allow for their depreciation it is customary to divide by a " depreciation " factor which for fairly clean situations is usually taken as 1·3. This would reduce the results to 7·5 and 5·6 foot-candles, respectively.

HYSTERESIS MEASUREMENTS ON STRAIGHT BARS AND STRIPS.*

By C. E. WEBB, B.Sc., Associate Member, and L. H. FORD, B.Sc.

[From the National Physical Laboratory.]

(*Paper received* 11*th December*, 1929.)

SYNOPSIS.

The method of testing straight samples of high-permeability material, by using search-coils for the measurement of H and eliminating flux leakage from the length under test by means of compensating magnetizing windings, has been previously described in relation to permeability measurements. Its application to hysteresis measurements is found to involve more complicated switching operations, but a comparison of results obtained on bars and strips with those for rings of similar material shows good agreement when compensation is employed at each point on the loop. In the absence of compensation, large differences occur between the loops determined for straight and ring specimens.

In tests on magnet-steel bars compensation produces a negligible effect on the results and is unnecessary.

A drum controller to perform the switching operations required in carrying out a hysteresis loop under compensated conditions is described.

(1) INTRODUCTION.

In a recent paper † the authors described a method of making accurate permeability measurements on straight bars and strips of high-permeability material, such as is now commercially available for electrical machine construction. The method involved the use of search-coils for the measurement of the magnetizing force, H, and the elimination of flux leakage along the length of specimen spanned by the search-coils by the use of compensating magnetizing windings. It was shown that only by the application of such "compensation" could satisfactory results be obtained in the region of high permeability, and that in the absence of compensation the search-coil method was liable to very large errors (up to 35 per cent) in the value of H for a given value of B below about $H = 15$.

In determining hysteresis loops on straight samples of materials having high maximum permeability, and consequently low coercive force, similar errors are likely to occur. Tests were therefore made to see whether satisfactory results could be obtained by a method of compensation for flux leakage similar to that successfully employed in permeability measurements.

(2) DESCRIPTION OF TESTS AND RESULTS OBTAINED.

(a) *Apparatus Used.*

For a full description of the yoke tester and search-coils employed and of the methods of calibrating the instruments and measuring H and B, reference should be made to the previous paper. It may be briefly stated here, however, that both B and H are determined ballistically after equality of flux has been established between the middle and the mean of the two ends of the length of specimen under test. This equality is obtained by adjusting the current in two compensating coils, one at each end of the specimen, independently of the main magnetizing current, until on reversing both currents simultaneously there is no deflection on the ballistic galvanometer when connected to two opposing B search-coils of equal numbers of turns, one distributed over approximately 4 cm at the centre of the test-length, and the other in two halves each spread over approximately 1 cm at a mean distance of 3·5 cm from the centre.

The only change from the apparatus used in the previous investigation was in the magnetizing winding. As a result of tests to find the best arrangement of main and compensating coils, a bobbin was made up to carry a main winding of approximately 400 turns of No. 14 S.W.G. enamelled wire on the central 15 cm and a compensating winding in two sections, each of approximately 40 turns of 121/·0048-in. flexible cord on 1-cm lengths at the two ends. These windings were used throughout the hysteresis-loop tests.

(b) *Method of Testing at Low Values of* $H_{max.}$

The standard hysteresis test on high-permeability material is to determine the loop for $B_{max.} = 10\,000$. This corresponds to a maximum H equal to only two or three times the coercive force and allows all throws to be made to or from the tip-point. The first tests were therefore made at this value of $B_{max.}$, and loops having values of $H_{max.}$ equal to many times the coercive force, for which additional switching operations are required, were considered subsequently.

In permeability measurements by the method of reversals, the corresponding values of B and H are deduced from the galvanometer deflections when the material is taken from the positive to the negative tip of the hysteresis loop for the desired value of H, i.e. from P_1 to P_2 in Fig. 1. Since the magnetization has only to be reversed and not altered in magnitude, only one adjustment of the compensating current is required in determining each point on the permeability curve. To determine points on the hysteresis loop under compensated conditions, however, it is necessary to obtain zero leakage along the test-length at each point as well as at the tip-points, and more complicated adjustments of the magnetizing currents are required.

Starting from the positive tip-point, P_1 (Fig. 1), of the

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* The Papers Committee invite written communications, with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† "Precision Permeability Measurements on Straight Bars and Strips in the Region of High Permeability," *Journal I.E.E.*, 1929, vol. 67, p. 1302.

loop for $B_{max.} = 10\,000$ with the compensating current adjusted, as in a permeability test, to give compensation for a complete reversal, it is found that, when the main current is switched off, a considerable fraction of the original compensating current must continue to flow if compensation is to be maintained. The exact value of the compensating current required is found by trial, and the galvanometer deflections are then read when the main current is switched off and the compensating current simultaneously reduced to this value. In this way a point A on the loop is determined. Points intermediate between P_1 and A, such as X_1, may be determined similarly by decreasing both currents from their values at P_1, the appropriate value of the compensating current being first found by trial for each point. For more negative values of H than that at A the main magnetizing current must be reversed as well as reduced in magnitude, the compensating current remaining in its original direction but becoming progressively smaller as the negative value of the main current increases, until at some point B no compensating current is required. Thus for points between A and B, such as X_2, the main and compensating magnetizations are in opposition. For points between B and P_2 both currents are in the negative direction, and a point such as X_3 may be determined by adjusting for compensation and then throwing to the tip-point, P_2, by increasing both currents simultaneously to their tip-point values.

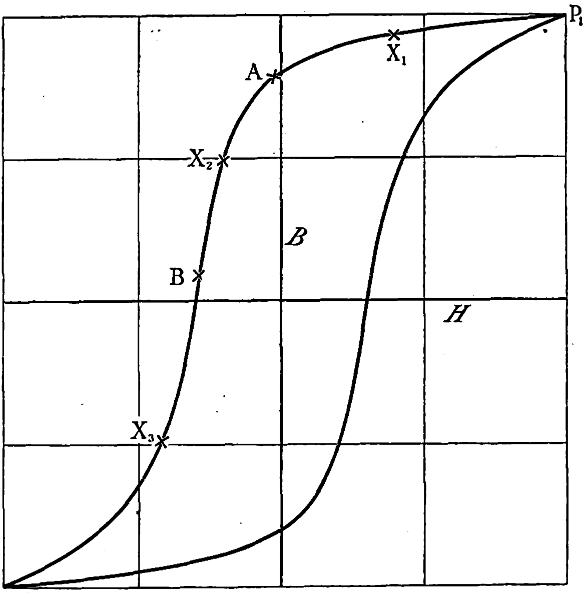

FIG. 1.—Typical hysteresis loop.

TABLE 1.

Point on loop to be reached	Resistances to be set	Switching operations to throw from P_1
X_1	R_3, R_4	Open S_3
A	$R_3 = \infty$, R_4	Open S_3
X_2	R_4, R_5	Open S_4, then open S_3 and reverse S_1
B	R_5	Open S_4, then open S_2 and reverse S_1
X_3	R_5, R_6	Open S_4 and S_5, then reverse S_1 and S_2

It will be seen that various combinations of simultaneous adjustments to the main and compensating currents have to be carried out, e.g. both currents altered in magnitude but not in direction, one current altered in magnitude but not in direction and the other both in magnitude and direction, etc. In the preliminary tests a number of mercury switches were used to perform the necessary operations, and a suitable circuit is shown in Fig. 2. Thus with switches S_1 and S_2 in position (1) and the remaining switches closed, the specimen may be brought to the positive tip-point, P_1, of the required loop by adjusting R_1 and R_2, while the resistance adjustments and switching operations for throwing from P_1 to each of the typical points on the loop, shown in Fig. 1, are given in Table 1.

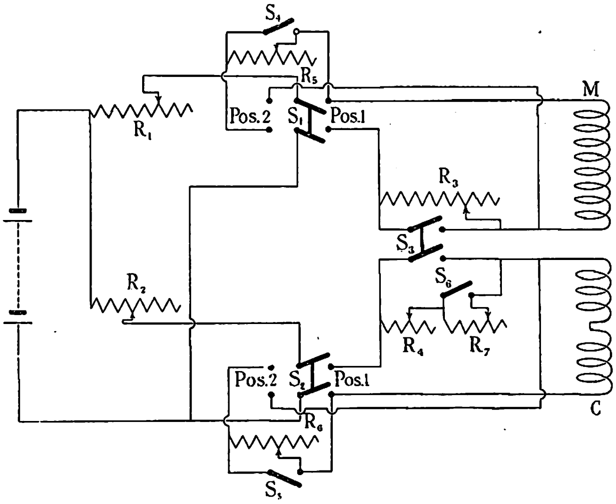

FIG. 2.—Circuit for performing switching operations required in a compensated hysteresis test.

Switch S_6 and resistance R_7 are not required when throwing only to or from the tip-point, but will be found to be needed when obtaining loops at high values of $H_{max.}$.

(c) Results Obtained at $B_{max.} = 10\,000$.

The hysteresis loop for $B_{max.} = 10\,000$ was determined, by the method described, on the sample of sheet material numbered 3B, which had been prepared for the previous investigation and had been found to have a maximum permeability of about 5 000. The loop is shown in Fig. 3 together with the loop obtained on the same sample without compensation. Without compensation the value of $H_{max.}$ is increased about 40 per cent (as would be expected from the results of permeability measurements recorded in the previous paper), while the remanence is decreased 12 per cent and the coercive force increased 10 per cent.

The individual points plotted in Fig. 3 show values obtained on the rings, numbered 3A, cut from the same sheets as strips 3B and very carefully annealed with them. These rings and strips possessed almost identical permeability, as shown in Table 4 of the previous paper, and the very close agreement between the points and the compensated curve in Fig. 3 affords a strong proof of the accuracy of the search-coil method of testing high-permeability strips for static hysteresis when compensation is applied.

A similar comparison of the hysteresis loops for $B_{max.} = 10\,000$ was made between the Armco iron bar 2D and ring 2A, which, as shown in Table 5 of the previous paper, also gave very close agreement for permeability. Some difficulty was experienced in these tests owing to the deflections depending to some extent on the rapidity of switching; this was a consequence of the high permeability of the material and the large cross-section of the specimens. Within the limits of error set by this tendency to variability, however, agreement was again obtained between the loops for the ring and for the bar (with compensation).

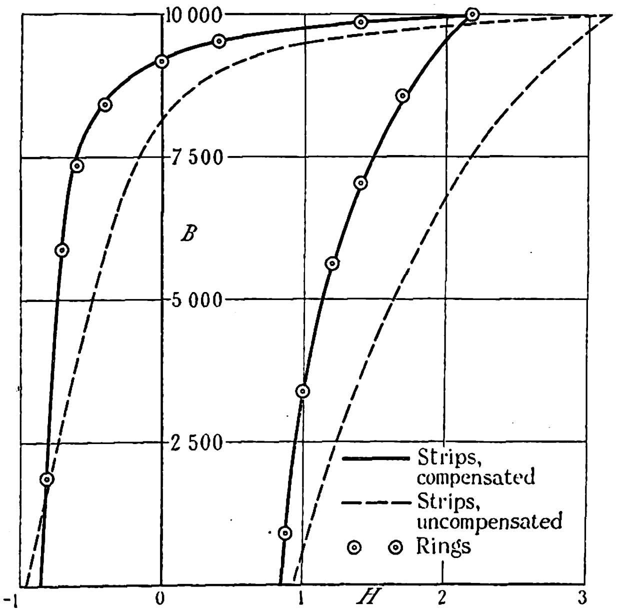

FIG. 3.—Hysteresis loops for $B_{max.} = 10\,000$ on sheet material strips and rings.

(d) Tests at High Values of $H_{max.}$

For hysteresis loops having a value of $H_{max.}$ equal to many times the coercive force the method of finding H and B by throwing from the tip-point of the loop is not sufficiently accurate, since the results depend ultimately on the determination of a small difference between two large galvanometer deflections. Points on the loop corresponding to low values of H were, therefore, found by throwing from the switch-off point of the main magnetizing current, A (Fig. 1). Much more sensitive calibrations of the galvanometer could then be used and the values of H and B relative to those at A could be found with high accuracy.

To determine with precision the value of H at A, an inductometer was connected with its primary in series with the main magnetizing winding and its secondary in opposition to the H search-coil. It was adjusted to give no deflection on the galvanometer when both currents were reversed, and the deflection on switching from the tip-point to the point A was then read, a sensitive calibration again being used. From this the value of H at A could be deduced with much increased accuracy.

The principal limitation to the accuracy obtainable lies in the uncertainty of the balance between the inductometer and the H search-coil, owing to the tendency for a double kick to occur. On this account there is some advantage in balancing the deflection due to the search-coil only partially instead of completely, and allowing for the amount of unbalance in computing the value of H at switch-off.

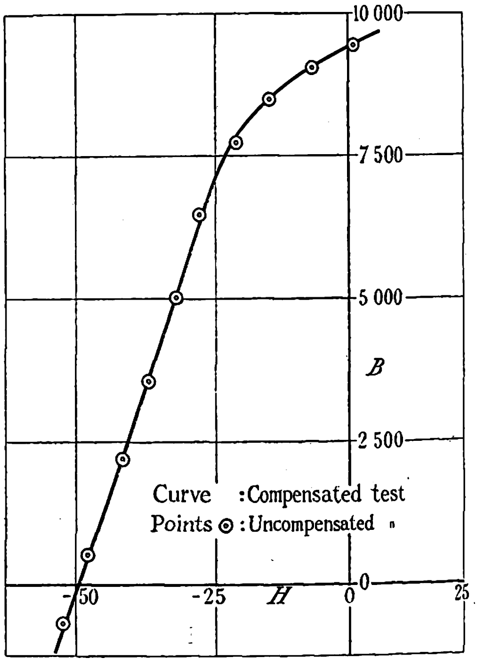

FIG. 4.—Portion of hysteresis loop for magnet-steel bar with and without compensation.

After A had been determined the inductometer was disconnected, its secondary being replaced by an equal resistance so as not to alter the galvanometer calibration, and further points on the loop, such as X_2 and B, were found by throwing from A as described above. The switching operations with the circuit of Fig. 2 were as before (see Table 1), except that after reaching A by opening switch S_3 further points such as X_2 were found by adjusting R_5 and R_7 to give compensation, and opening switch S_6 simultaneously with the reversal of S_1.

Comparative tests on rings and strips (with compensation) at high values of $H_{max.}$, similar to those at $B_{max.} = 10\,000$, showed good agreement, although there was greater uncertainty in the H readings at low values on the strips owing to the difficulty in balancing with the inductometer.

(e) Tests on Magnet-steel Bars.

The results plotted in Fig. 3 show clearly that considerable error results in hysteresis measurements on soft.

high-permeability material if compensation is not applied to eliminate leakage along the test-length. To find whether the effect of leakage is appreciable in tests on straight bars of hardened magnet steel by the yoke and search-coil method, a tungsten-steel bar, approximately $3 \times 1\cdot25$ cm^2 section, was subjected to a magnetization of $H_{max.} = 400$, and the portion of the hysteresis loop between the remanence and coercive force points was determined with and without compensation. The results are given in Fig. 4 and it will be seen that the points obtained without compensation lie almost exactly on the curve obtained with compensation. As this specimen had a coercive force of only about 50 it is a relatively soft magnet steel and thus represents the most favourable case for showing errors due to flux leakage. It may, therefore, be concluded that in all hysteresis tests on hardened magnet-steel specimens the effect of leakage is negligible.

(3) CONSTRUCTION OF DRUM CONTROLLER.

The switching operations in obtaining a complete hysteresis loop are complicated, and interlocking of the switches for main and compensating currents is needed to make operations in the two circuits satisfactorily simultaneous. To effect this and to allow the correct combinations of adjustments to be obtained automatically, a drum controller was designed and constructed. It is shown diagrammatically in Fig. 5.

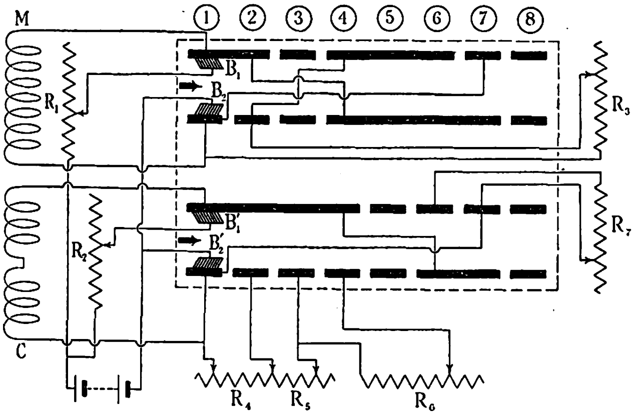

FIG. 5.—Circuit of drum controller for obtaining compensated hysteresis loops.

The central spindle of the controller carries two pairs of carbon brushes B_1, B_2 and B_1', B_2' connected to the source of supply through independent adjustable resistances, R_1 and R_2, and feeding the main magnetizing winding, M, and the compensating winding, C, respectively, through four banks of gunmetal contacts. The brushes, which are mounted on plungers sliding in cylindrical guide-arms, bear on the contacts with a considerable pressure applied by strong spiral springs, and are set in four perpendicular directions to balance the thrust on the spindle. Current is led to these brushes through four gunmetal slip-rings (not shown in the diagram) on the lower half of the spindle, the brushes for which are carried on keramot pillars mounted on the brass base of the controller. The gunmetal contacts are mounted inside four keramot rings supported on brass pillars. The whole controller is enclosed in a brass cylinder, approximately 12 in. high × 10 in. diameter, to exclude dust.

There are eight positions of the controller, numbered 1 to 8 in Fig. 5 (in which, it should be noted, the relative angular displacement of the brushes has been ignored and, for simplicity, they are shown as if they were in one vertical plane). The spindle is fitted with a cranked handle and by means of an adjustable stop, which can be made to operate on any of the eight positions, it is possible to throw rapidly from any one position to any other.

The operations performed in the various positions are given in Table 2, which also shows the points on the hysteresis loop to which each position corresponds (see Fig. 1).

TABLE 2.

Position on controller	Operation performed on		Point on loop
	(i) Main magnetizing current	(ii) Compensating current	
1	Set by R_1	Set by R_2	P_1
2	Reduced by inserting R_3	Reduced by inserting R_4	X_1
3	Reduced to zero	Further reduced by inserting R_5	A
4	Reversed and reduced by inserting R_3	Further reduced by inserting R_6	X_2
5	Reversed and reduced by inserting R_3	Reduced to zero	B
6	Reversed and reduced by inserting R_3	Reversed and reduced by inserting R_7	X_3
7	Reversed	Reversed	P_2
8	Zero	Zero	—

It will be seen that 8 is an off-position for both circuits and that the remaining positions, 1 to 7, correspond to the typical points on the loop of Fig. 1. Thus one complete revolution of the spindle carries the sample round a complete hysteresis loop, and by suitable adjustments of the associated variable resistances any desired point on the half of the loop from P_1 to P_2 can be attained.

By using positions 1 and 7 of the controller a simple reversal of current is obtainable, and the calibration of the galvanometer and demagnetization of the specimen may therefore be carried out on the controller, if desired. It is more convenient, however, to insert a mercury reversing switch in the main circuit for use in these operations.

A repetition of some of the previous measurements, using the controller, showed that it provides a quick and satisfactorily accurate means of obtaining hysteresis loops where compensation is necessary. By turning the spindle always in a clockwise direction a cyclic condition is automatically maintained, while by using the adjustable stop rapid throws can be made without difficulty either from the tip-point or from the switch-off point, A, to any desired point on the loop. Care must be taken, however, particularly when throwing from A, not to turn the spindle too rapidly through the positions corresponding to the tip-points when completing the loop after a throw in preparation for the next throw. Otherwise sufficient time may not be allowed for the flux to reach its proper maximum value. In practice, with a normal sample, no difficulty is experienced in this connection, provided the spindle is not turned very quickly.

(4) Conclusions.

(i) As would be expected from the results of permeability tests previously recorded, the yoke and search-coil method without compensation is found to be subject to large errors in hysteresis measurements on strips or bars of high-permeability material.

(ii) Accurate results are obtained by this method on such samples, however, when compensation is applied to eliminate flux leakage along the test-length at each point on the hysteresis loop. This is shown by the close agreement with tests on rings of similar material.

(iii) In determining hysteresis loops for values of $H_{max.}$ equal to many times the coercive force, increased accuracy may be obtained by balancing the H search-coil wholly or partially against an inductometer for a complete reversal, and deducing the value of H at switch-off from the deflection on switching off the main current. Points on the loop at low values of H are then found by throwing from the switch-off point instead of from the tip-point.

(iv) Magnet-steel bars may be tested without compensation with no appreciable error.

(v) The necessary switching operations for obtaining a hysteresis loop may be carried out satisfactorily with the drum controller described.

In conclusion, the authors desire to express their thanks to Dr. D. W. Dye, F.R.S., for helpful suggestions in the course of the work, and to Mr. A. Gridley for valuable assistance in the construction of the drum controller.

AN INVESTIGATION OF THE FREQUENCY VARIATIONS IN INDUCTION WATT-HOUR METERS.

By A. E. MOORE, M.Sc.Tech., Member, and W. T. SLATER, M.Sc.Tech., Student.

(*Paper first received 26th November,* 1929, *and in final form* 3*rd February,* 1930; *read before the* METER AND INSTRUMENT SECTION 7*th March,* 1930.)

SUMMARY.

The paper contains an account of experiments carried out by the authors to analyse some of the various factors concerned in the behaviour of induction watt-hour meters, with particular reference to the changes in accuracy produced by different frequencies.

The subject is dealt with under the following headings:—

Experimental determination of the changes in accuracy of induction watt-hour meters with changes in frequency.
The causes of the changes, namely braking effect of the voltage flux, and reactance of the disc.
Separation of the two effects, and determination of their relative magnitudes.
Determination of the time-constants of the discs.
Explanation of the torques produced in induction meters.
Determination of some of the other phase errors in the meters.
Conclusions.

LIST OF SYMBOLS.

V = voltage applied to the voltage coil.
I = current in the current coil.
ϕ = angle of phase difference between V and I.
Φ_V = active voltage flux.
Φ_I = active current flux.
e_V and e_I = e.m.f.'s induced in the disc by Φ_V and Φ_I respectively.
i_V and i_I = eddy currents produced by e_V and e_I in the disc, respectively.
θ_V = phase angle by which i_V lags behind e_V.
θ_I = phase angle by which i_I lags e_I.
δ = phase angle between V and Φ_V.
$\alpha = 90° - \delta$.
β = phase angle between I and Φ_I.
$\gamma = 90° - \phi_S$, where ϕ_S is the phase angle between V and I when the meter registers zero power factor.

EXPERIMENTAL DETERMINATION OF THE CHANGES IN ACCURACY OF INDUCTION WATT-HOUR METERS WITH CHANGES IN FREQUENCY.

In 1911 one of the authors gave an account of some tests on induction watt-hour meters with alternating currents of different wave-shapes,* and several possible causes of the variation in accuracy were set out as follows:—

(1) Alteration in the nature of the rotating or shifting magnetic fields.
(2) Effects on the fluxes in the cores by changes in the eddy currents and the hysteresis of the iron.
(3) Effects on the quadrature adjustments.
(4) Effects of frequency: it will be noted that as more of the harmonic wave is added the resultant wave approaches more nearly to the triple-frequency wave of the harmonic.

In the discussion on the paper referred to, Mr. J. T. Irwin stated that the indications of the meters were the sums of the indications for each separate frequency taken separately; that is, if $W_1 + W_3 + W_5$, etc., is the total load on the meter, the suffixes denoting the frequency with reference to the fundamental, and if K_1, K_3, K_5, etc., denote the constants for the meter at the corresponding frequency, power factor and load, the registration of the meter will be equal to $K_1W_1 + K_3W_3 + K_5W_5$, etc.

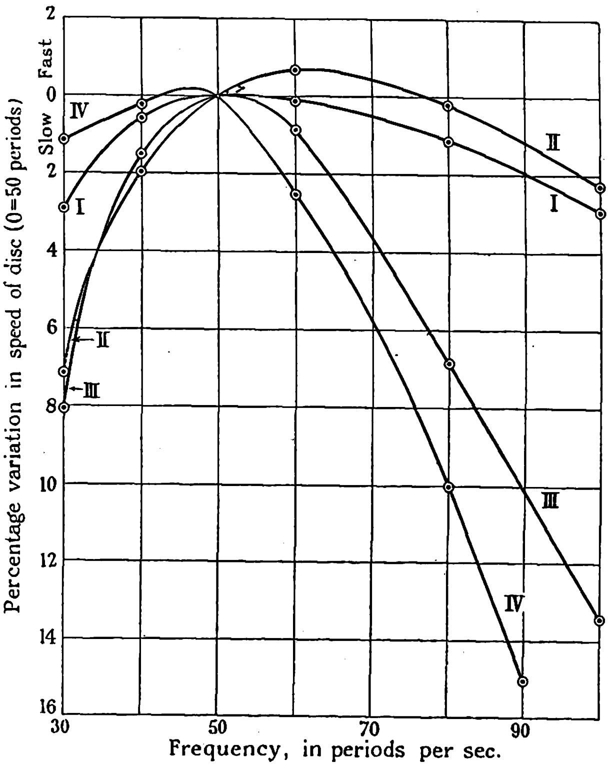

FIG. 1.—Curves showing the percentage variation in the speed of the disc with variation in frequency, for 4 induction watt-hour meters. The load is constant and the power factor unity.

Irwin analysed the curves of wave-shapes given and showed that the actual registrations of the meters agreed fairly well with the results calculated from this formula.

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* H. A. RATCLIFF and A. E. MOORE: "Electricity Meters, with Notes on Meter Testing," *Journal I.E.E.*, 1911, vol. 47, p. 3.

In the authors' reply to the discussion on the earlier paper two curves were given showing the variation in accuracy with changes in frequency of two of the meters previously tested. These two meters were those which gave the least and the greatest variations respectively with changes in wave-shape, and the two curves I and IV, Fig. 1, are here reproduced, together with curves for two other meters. All the meters ran slower on the distorted waves than on the sinusoidal waves, and as they all appear to run slower as the frequency is increased there were good reasons for believing that their inaccuracy on distorted waves was mainly a question of their accuracy at different frequencies.

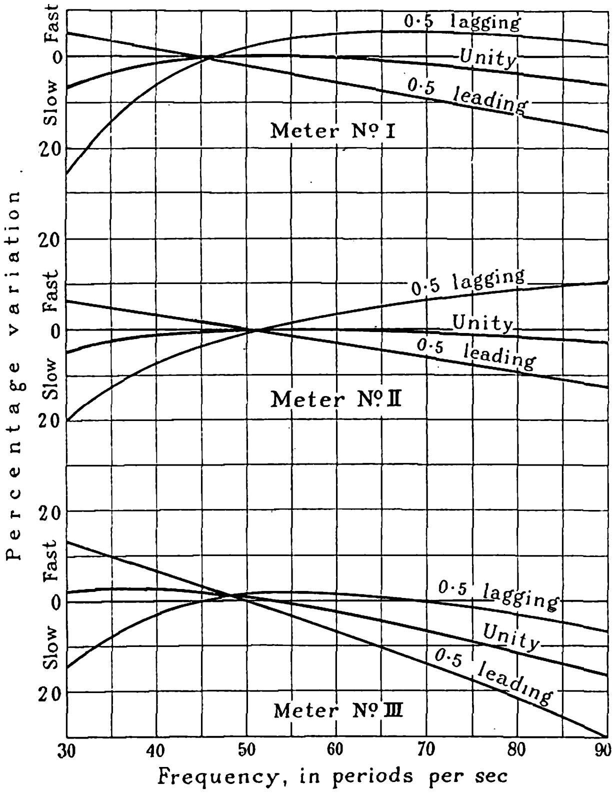


FIG. 2.—Curves showing the percentage variation in accuracy of 3 induction watt-hour meters with change in frequency, from the accuracy at unity power factor at a frequency of 50. The meters were adjusted to register approximately correctly on low power factors at a frequency of 50.

Causes of the Changes.—The changes in accuracy with changes in frequency are least when the power factor of the load is unity, the reason being that the power-factor adjustment in the meter depends on the frequency of the supply. Fig. 2 illustrates this point. Curves of accuracy are shown for three meters for which the adjustment for power factor was made at a frequency of approximately 50 periods per sec. The meters were tested at 80 per cent of full-load volt-amperes at unity power factor and at a power factor of 0·5 with both leading and lagging currents, and at frequencies varying from 30 to 90. The meters are, as may be expected, very inaccurate at 0·5 power factor at other than normal frequency, but they also show varying degrees of inaccuracy with changes in frequency even at unity power factor, and it was in search of the explanation of these unity power-factor errors that the investigation described below was undertaken.

The meter represented by curve I, Fig. 1, is a Metropolitan-Vickers type "N" meter. These meters employ a thin disc and it was thought that possibly their good characteristics were due in some measure to this. An induction meter may, for the moment, be considered as a small induction motor with short-circuited rotor, and the conditions obtaining—even when the disc is rotating at full-load speed—are somewhat similar to the starting condition in the induction motor. If the time-constant of the rotor is high the starting torque is small and the torque may be increased by increasing the resistance of the rotor. Applying this reasoning to the meter, it might be expected that the same conditions would obtain. A thin disc would have a lower time-constant than a thick one of the same material, and if discs of different thicknesses of the same material, or of the same thickness of different materials, were tried in the meter, it might be expected that the thinner discs and the discs of higher specific resistance would be less affected by changes in the frequency of the rotor currents than would the thicker or more highly conducting discs.

For the purpose of carrying out tests the Metropolitan-Vickers Co. supplied three interchangeable discs for a type "N" meter, (I) a standard disc of corrugated aluminium 0·022 in. thick, (II) a copper disc, 0·034 in. thick, and (III) an aluminium disc, 0·063 in. thick.

The meter was rated at 5 amperes, 100 volts, 50 cycles, and was tested at 100 volts, 4 amperes, unity power factor, at frequencies varying from 30 to 100, with each of the discs in turn. The results obtained for the discs I, II and III are represented in Fig. 3 by curves I, II and III respectively.

The curves are similar to those in Fig. 1, and they were considered sufficiently good to justify further investigation on the same lines. Four more discs were obtained as follows: (IV) a thinner plain aluminium disc, 0·018 in. thick, (V) a plain Eureka disc, 0·034 in. thick, (VI) a corrugated copper disc 0·022 in. thick, and (VII) a corrugated Eureka disc 0·022 in. thick.

The meter was tested again with discs Nos. IV and V in the same manner as already described and the results are shown by curves IV and V in Fig. 3. The curves appear to indicate that the thickness and conductivity of the disc play an important part in the behaviour of the meters under certain conditions. With the thick discs of high conductivity the speed and, therefore, the driving torque, rapidly diminish when the frequency is increased above a certain value, but this diminution in speed is less marked with the thinner discs and is changed to an increase of speed in the cases of the very thin aluminium and the thick Eureka discs. It is not suggested that Eureka alloy would be suitable for the discs of these meters—on the contrary the driving torque when it is used is so very small that probably they would be useless—but it was desirable to make experiments with high-resistance discs in order to strengthen or disprove the assumptions made.

After obtaining the curves in Fig. 3 it was necessary to explain why the speed at 30 was lower than at 50 periods per sec.; and also why, in the cases of the thinner aluminium and the Eureka discs, the speed of the meter increased throughout the range of frequencies 30 to 100.

At first the diminution in speed below 50 periods per sec. was thought to be due to the ohmic resistance of the pressure coils, and in some meters it may be so to a certain extent. The effect of the ohmic resistance would be to limit the magnetizing current as the frequency is diminished and hence, therefore, to limit the voltage flux. If such were the case the permeability of the iron would also affect the result. From measurements of the resistance and impedance of the voltage coils, however, it was concluded that the effect—in this meter at any rate—must be relatively small and unimportant.

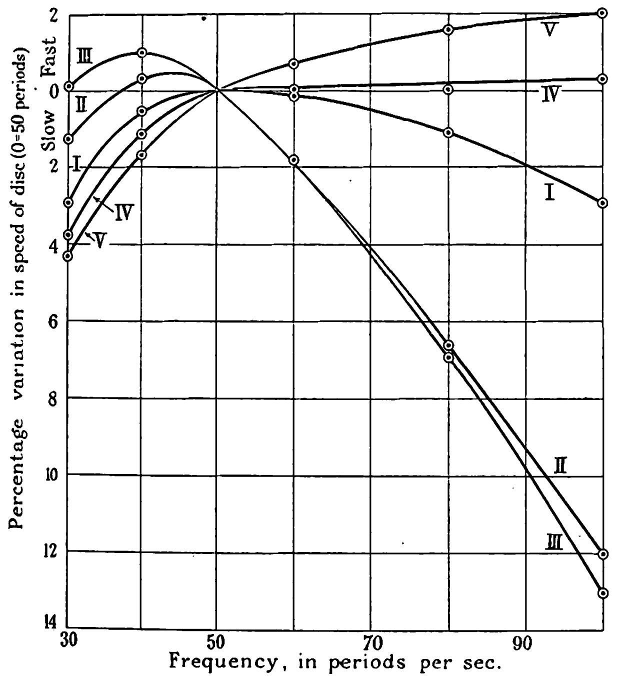


FIG. 3.—Curves showing the percentage variation in the speed of the disc with variation in frequency, for 5 different discs in one meter. Load constant at unity power factor.

The next cause which suggested itself was the change in the brake torque due to changes in the strength of the voltage flux with changes in the frequency. If we consider the driving torque to be due to the eddy currents induced by, say, the voltage pole acting on the flux of the current pole, then the driving fluxes also act as brake fluxes, and the voltage-coil flux acts in this manner to a very considerable extent. The eddy currents are proportional to the frequency and the flux, but the voltage flux is inversely proportional to the frequency. Hence the eddy currents due to the voltage flux are independent of frequency. The current flux is substantially independent of frequency, and therefore the driving torque produced by the current flux and voltage flux eddy-currents is also independent of frequency. The brake torque produced by the voltage flux is, however, proportional to the square of the voltage flux.

When the frequency is doubled the voltage flux is halved; so that if the voltage flux is at all comparable in magnitude with the flux of the permanent brake magnet there is a considerable diminution in total brake torque as the frequency is increased and, of course, a considerable increase in the brake torque as the frequency is diminished. It may be noted how rapidly the curves in Figs. 1 and 3 bend down as the frequency is diminished below 50.

In order to verify this assumption, tests were made on two different makes of polyphase meter (two single-phase elements combined) in the following manner. Only one of the elements in each meter was loaded with current and voltage at the normal frequency of 50 (100 volts, 4 amperes, 400 watts). The voltage coils only of the second element were excited from an entirely separate a.c. supply, with normal voltage but with successively different frequencies. The two curves shown in Fig. 4 were obtained in this manner, and they obviously indicate that the speed of the meter approaches a maximum as the frequency of the supply to the free voltage-coil circuit is increased. The maximum speeds were obtained by disconnecting the supply from the free voltage-coil circuits, and they are given in Fig. 4. It will be noted that they are little in excess of the speeds obtained at a frequency of 100.

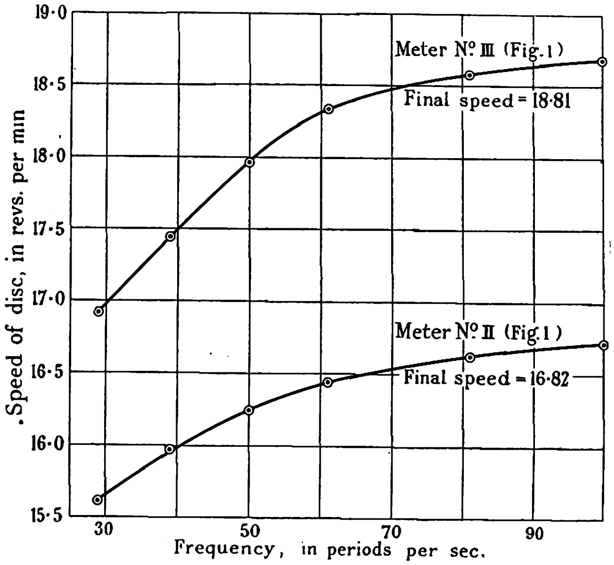


FIG. 4.—Curves showing how the braking action of the voltage flux slows the meter down with decrease of frequency, due to increase in voltage flux.

From the foregoing results it may be inferred that the changes in the reactance of the disc, and the changes in the magnitude of the voltage flux, due to changes in frequency, act in opposite senses, the one slowing the meter down and the other speeding it up with increase in frequency.

Separation of the Two Effects, and Determination of their Relative Magnitudes.—The next set of tests was made for the purpose of separating the two effects in order to ascertain, if possible, their relative magnitudes. The polyphase meters were used again, but in this case the isolated voltage-coil was energized from the same supply and therefore at the same frequency as the working element of the meter. Observations were made over a range of frequency from 30 to 100, and the revolutions of the disc were timed (*a*) with the isolated voltage-coil energized, and (*b*) with it not energized. If the voltage coils of the two meter elements are alike—and presumably they are very nearly so—then, if the difference in the times be subtracted from time (*b*) the result is the time which would be taken if the voltage fluxes acted only as driving fluxes and not as brake fluxes also (assuming always that there is no very great interference between the two elements of the meters). The results of these tests on two meters are shown in Fig. 5. Curves II and III represent the variation in speed with both voltage fluxes acting as brake fluxes, curves II_a and III_a with only one voltage flux acting as brake flux, and curves II_b and III_b are deduced, as stated above, to represent the variation in speed if neither voltage flux acted as a brake flux. Curves II_b and III_b therefore represent changes in speed with changes of frequency due to the reactance of the disc. The effect of the reactance of the disc is thus shown to slow the meter down with increase of frequency of the supply.

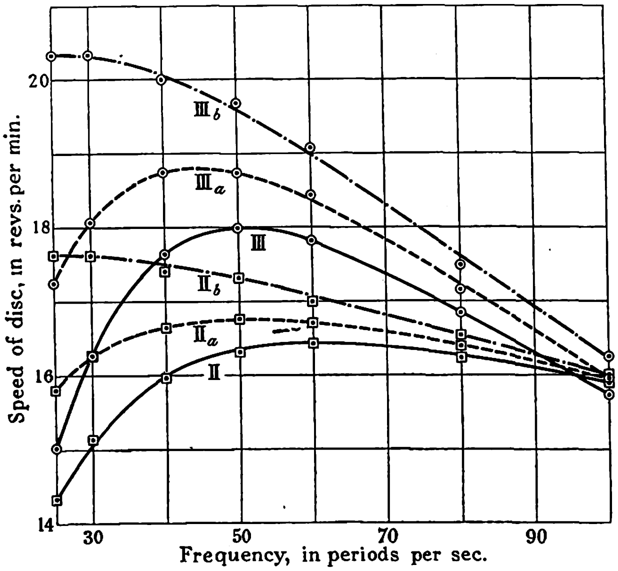


FIG. 5.—Curves showing how the reactance of the disc slows the meter down with increase in frequency.

Curves II_b and III_b should be the curves connecting the driving torque of the meters with the frequency. To test this, the driving torques of the meters were measured with the discs stationary in order to eliminate the effects of the driving fluxes acting as brake fluxes. A curve for one disc is shown in Fig. 6, and it is very similar in shape to curves II_b and III_b in Fig. 5. The torque/frequency curves for stationary discs all obey the rule that the more conductive the disc the steeper is the curve.

The next procedure was the deduction of theoretical curves for a meter having particular data. Values for the time-constant of the disc and also for the ratio of voltage flux to brake-magnet flux were assumed, and, after several values had been tried, calculations were made for two meters as follows:—

(1) Voltage flux at 50 periods per sec. to have a value equivalent to 20 per cent of that of the permanent brake magnet.
Time-constant of the disc to be 0·0005.
(2) Voltage flux as in (1).
Time-constant of the disc to be 0·001.

The figures from which the curves in Fig. 7 are plotted were obtained in the following manner.

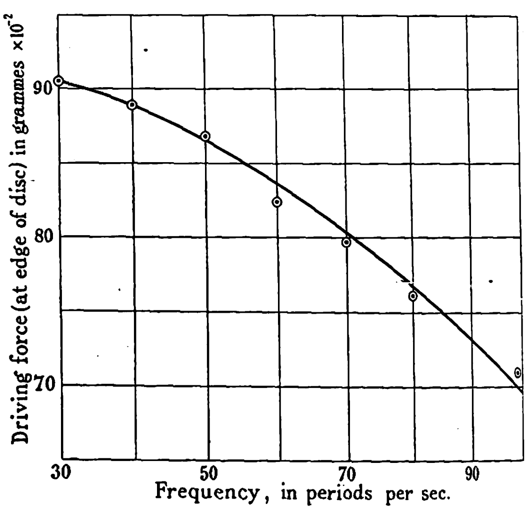


FIG. 6.—Curve showing the variation in driving torque at different frequencies. Disc stationary.

Braking Effect (*Curve A in Fig.* 7).

The brake torque at 50 periods per sec. is proportional to (Brake-magnet flux)^2

+ (Voltage flux at 50 periods per sec.)^2

This is proportional to $1^2 + \left(\frac{20}{100}\right)^2$

The voltage flux is inversely proportional to the frequency, so that the brake torque at *f* periods is proportional to

$$1^2 + \left(\frac{20}{100} \times \frac{50}{f}\right)^2$$

The percentage deviation of the brake torque at different frequencies from the brake torque at 50 periods was then calculated and plotted as curve A in Fig. 7.

Disc Effect (*Curves* C *and* E *in Fig.* 7).

Next the values for the effect of the reactance of the disc on the speed were calculated thus:—

If *L* and *R* are the inductance and resistance respectively of the eddy-current path in the disc, the angle of lag of the eddy current will be θ, where $\tan\theta = \omega L/R$. It is shown on page 1028 that the torque is proportional to $\cos^2\theta$. Then

For case (1), at *f* periods $\tan\theta = 2\pi \times f \times 0{\cdot}0005$, and
For case (2), at *f* periods $\tan\theta = 2\pi \times f \times 0{\cdot}001$

The percentage deviation of the driving torque at different frequencies from that at 50 periods per sec. is shown by the dotted curves C and E in Fig. 7.

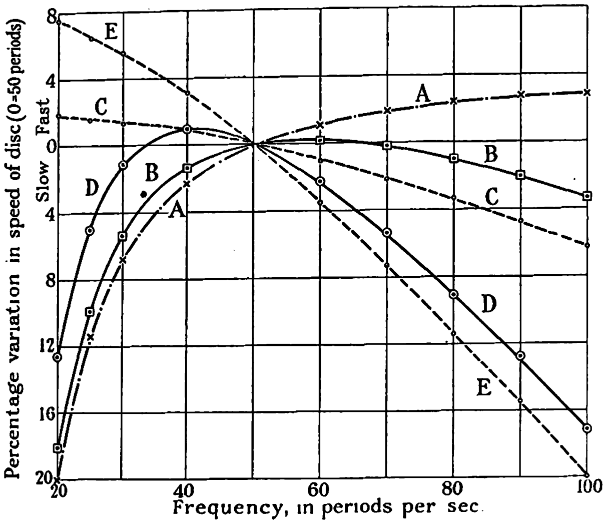


FIG. 7.—Curves plotted from assumed values of brake-magnet flux, voltage flux and disc reactance, showing how the speed should vary with frequency. (Compare curves B and D with those given in Figs. 1 and 3.)

The remaining curves B and D represent the percentage deviation due to the combined effects of the voltage flux and disc reactance for the two cases chosen. These curves appear to justify the assumptions previously made, for

Curve A is of the same general shape as the curves in Fig 4.

Curves C and E are of the same general shape as curves II_b and III_b in Fig. 5.

Curves B and D are of the same general shape as the curves in Fig. 3.

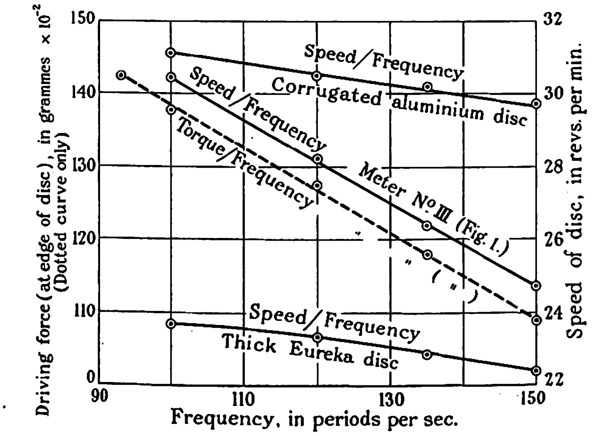


FIG. 8A.—Curve showing the diminution of speed of the thick Eureka disc with frequencies above 100. Also Speed/frequency and Torque/frequency curves for meter No. III (Fig. 1).

From these theoretical curves it was inferred that although the curves for the thin aluminium disc and the Eureka disc in Fig. 3 continue to rise as the frequency increases to 100, they would probably fall at higher frequencies. That this was actually the case is shown by the curves in Fig. 8A. Tests were carried out at frequencies varying from 100 to 150 on (1) the standard corrugated disc, (2) the thick Eureka disc, and (3) meter No. III, Fig. 1. Fig. 8B shows the curves for 100 to 150 periods per sec.—dotted lines—plotted as continuation curves to the corresponding curves I and V in Fig. 3. It must be pointed out, however, that two different machines were used for the supply, and, while the wave-shape of the machine used for all the tests up to 100 periods per sec. was approximately sinusoidal,

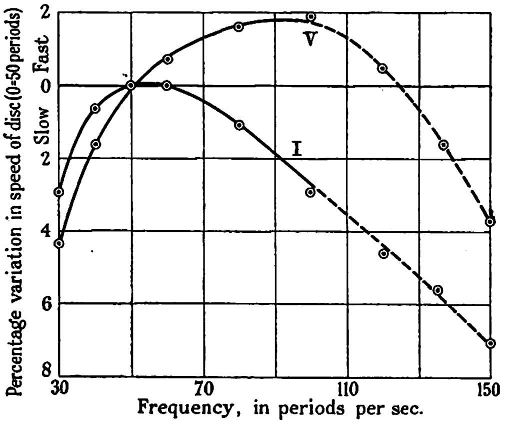


FIG. 8B.—Speed/frequency curves for
I. Standard aluminium disc.
V. Thick Eureka disc.

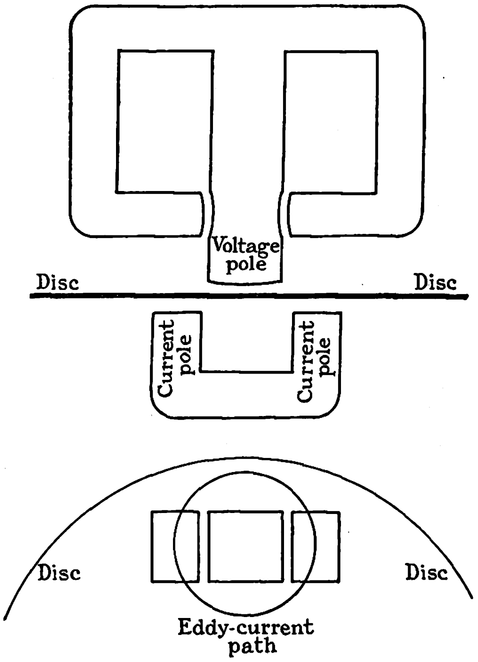
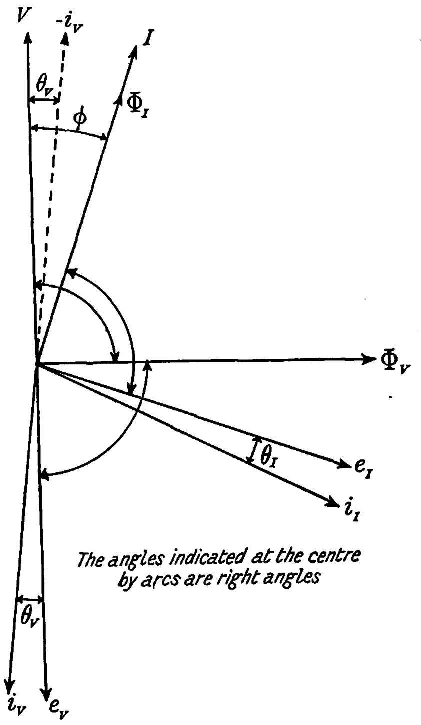


FIG. 9.

that for frequencies above 100 was very far from being sinusoidal. Also, the adjustments of the type "N" meter had been disturbed between the two sets of tests. In drawing the curves as continuation curves, therefore, it has been assumed that the speeds of the discs would be the same at 100 periods per sec. in both sets of tests. The dotted torque curve in Fig. 8A is an almost exact continuation of the torque curve in Fig. 6, the difference in the torque scale being that both elements of the meter were used in the tests for Fig. 8A, whilst only one element was used for the curve in Fig. 6.

The driving torque has been assumed to be proportional to $\cos^2 \theta$, where θ is the angle of lag of the eddy current due to the reactance of the disc. This is arrived at as follows. Fig. 9 is a diagrammatic representation of the meter element, and Fig. 10 shows the vector diagram assumed. In considering the theory so far, only the torque between the current flux and the eddy current produced by the voltage flux has been considered; the second part of the torque is dealt with later and will be shown to follow the same laws. The voltage flux Φ_V is assumed to be in quadrature with the voltage V at all frequencies, and also to be strictly inversely proportional to the frequency in magnitude. The current flux Φ_I is assumed always to be in phase with the current and to be strictly proportional to the current, whatever the frequency. In modern meters operating at unity power factor these assumptions are justifiable, at least as a first approximation.



The angles indicated at the centre by arcs are right angles

FIG. 10.

The torque is produced by the eddy current i_V acting on the current flux Φ_I and is proportional to

$$\Phi_I i_V \cos(\phi - \theta_V)$$

Now $$i_V = \frac{e_V}{R} \cos \theta_V$$

where R is the resistance of the eddy-current paths, and e_V is the voltage induced in the disc by the flux Φ_V. Substituting these values the torque is proportional to

$$\Phi_I \frac{e_V}{R} \cos \theta_V \cos(\phi - \theta_V)$$

But $$e_V \propto \Phi_V \times f$$
$$\propto \frac{V}{f} \times f$$
$$\propto V$$

where f is the frequency, and $\Phi_I \propto I$.

The torque is therefore proportional to

$$IV \cos \theta_V \cos(\phi - \theta_V)$$

At unity power factor $\phi = 0$ and the torque is then proportional to

$$VI \cos^2 \theta_V$$

DETERMINATION OF THE TIME-CONSTANTS OF THE DISCS, AND THE RATIO OF THE VOLTAGE FLUX TO THE BRAKE-MAGNET FLUX.

The formula Torque $\propto VI \cos^2 \theta$ was used to calculate the time-constants of several discs from the standstill torque/frequency curves already obtained.*

We have $$\cos^2 \theta = \frac{1}{1 + T^2\omega^2}$$

where T is the time-constant of the disc, and $\omega = 2\pi f$.

Let the standstill torques for two frequencies f_1 and f_2 be $\mathbf{T}_1$ and $\mathbf{T}_2$ respectively. Then

$$\frac{\mathbf{T}_1}{\mathbf{T}_2} = \frac{1 + (2\pi f_2 T)^2}{1 + (2\pi f_1 T)^2}$$

$$\therefore \quad \mathbf{T}_1 - \mathbf{T}_2 = (2\pi T)^2 (\mathbf{T}_2 f_2^2 - \mathbf{T}_1 f_1^2)$$

from which T can be calculated directly. The following time-constants were calculated in this way.

Disc	Time-constant
Thick copper	0·0008
Thin copper	0·0005$_5$
Standard aluminium	0·0004$_5$
Very thin aluminium ..	0·0002

The last value is very approximate, since the small torque rendered the measurement of the small variations rather uncertain.

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* It may be of interest to explain that the experimental work already described was carried out by one of the authors in 1914–15, but the work was then discontinued. The values for the time-constants previously used for Fig. 7 were found by trial only; the values by calculation were not determined until the work was resumed some six or seven years later. It is interesting to note that the values determined for the time-constants of the thick copper and the standard aluminium discs agree very closely with the values assumed for them in respect of Fig. 7. The value assumed on page 1026 for the ratio of the voltage flux to the brake-magnet flux also appears to be very nearly the same as that found by determination at the later date, page 1029.

Experiments were also carried out to determine the value of the ratio Φ_V/Φ_B for the meter on which most of the tests were carried out, Φ_B being the brake-magnet flux.

A 2-element meter was driven by a constant load on the top element. In the first case (A) the bottom element was not in circuit, and the brake torque was therefore due to two brake magnets and one voltage pole. In the second case (B), the voltage pole of the bottom element was energized and the brake torque was then due to two brake magnets and two voltage poles. The figures for case (B) are the average of two readings obtained when the connections to the bottom voltage pole were reversed, the two readings being taken to eliminate any error due to magnetic interaction between the elements.

For case (A) the disc made 15 revolutions in 95·8 seconds, and for case (B) the average time for 15 revolutions was 97·45 seconds.

Let x denote the ratio Φ_V/Φ_B.

The brake torque in case (A) is proportional to

$$2\Phi_B^2 + \Phi_V^2$$
$$= \Phi_B^2(2 + x^2)$$

The brake torque in case (B) is proportional to

$$2\Phi_B^2 + 2\Phi_V^2$$
$$= \Phi_B^2(2 + 2x^2)$$

Since the speed is inversely proportional to the brake torque we have

$$\frac{2 + x^2}{2 + 2x^2} = \frac{95\cdot 8}{97\cdot 45}$$

from which $x = 0\cdot 187$.

The tests just described were carried out at a frequency of 50. A second similar set of tests was now made at a frequency of 30 and gave the result

$$x = 0\cdot 318.$$

If the theory be correct the ratio

$$\frac{x \text{ at 30 periods per sec.}}{x \text{ at 50 periods per sec.}} = \frac{0\cdot 318}{0\cdot 187} = 1\cdot 7$$

should be the same as the ratio $50/30 = 1\cdot 67$, since the voltage flux is inversely proportional to the frequency. The result is in good agreement. Another point of interest is that the ratio Φ_V/Φ_B is very nearly the same as that arbitrarily chosen in the earlier experiments, viz. 0·2 at 50 periods per sec.

EXPLANATION OF THE TORQUES PRODUCED IN INDUCTION METERS.

So far no account has been taken of the torque resulting from the eddy currents induced by the current flux reacting on the voltage flux. Several writers contend that the two torques are in opposite directions. The authors do not agree with this contention, and would say that if it were true the meters would not work. In the case of the hypothetical induction meter the mean values of the two torques are exactly equal, and there would obviously be no resultant torque to turn the rotor.

It is easy to show in many ways that the two torques are in the same direction, but perhaps the following method will suffice. Take a magnet system such as that indicated in Fig. 11 and suppose that V and I are in phase. Then Φ_V and Φ_I will be in quadrature. The poles 1, 2 and 3 will come up as, say, N poles in rotation, pole 3 becoming N 180° later than pole 1, and pole 2 90° later than pole 1. Let the fluxes be denoted by Φ_1, Φ_2, and Φ_3, and the eddy currents produced by them by i_1, i_2, and i_3 respectively. In considering the reactions of the eddy currents on the fluxes to produce torque the vector diagram should be drawn as shown in Fig. 11, and it will be clear that the torques are represented by $\Phi_1 \times i_2$ (dotted), $\Phi_2 \times i_1$, $\Phi_2 \times i_3$ (dotted), and $\Phi_3 \times i_2$. These products are all positive, indicating that the torques are all in one direction.

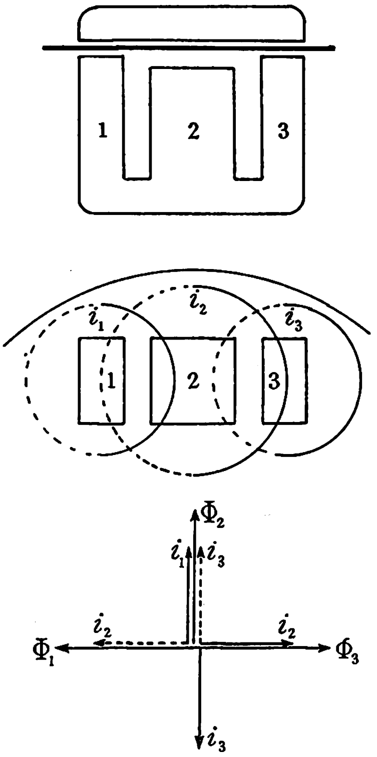

FIG. 11.

Fig. 12 and the corresponding vector diagram indicate that this conception of the direction of the torques is also true where there are only 2 poles instead of 3.

DETERMINATION OF SOME OF THE OTHER PHASE ERRORS IN THE METERS.

When developing the formula to cover both sources of driving torque, it was considered that the results so far obtained were sufficiently good to warrant a rather fuller treatment of the torque formula, taking into consideration as fully as possible the numerous sources of error which arise in an actual meter.

Fig. 13 is the vector diagram assumed for the meter. The combined effect of the iron losses and eddy currents in the iron of the current pole causes the flux to lag behind the current by an angle β.

In a hypothetical meter the voltage flux would be in exact quadrature with the voltage. In an actual meter the resistance of the windings and the losses in the iron core cause the flux to lead exact quadrature, often by an angle of several degrees, and several methods for correcting this lead are in use.

In the Metropolitan-Vickers type " N " meter used in the tests the corrector or quadrature loop is a metal strip or band embracing that part of the voltage pole which is active on the disc. The currents induced in this loop cause an increase in the lag of the voltage flux, and the amount of increase can be adjusted by moving the loop over the voltage pole so as to embrace more or less flux as required.

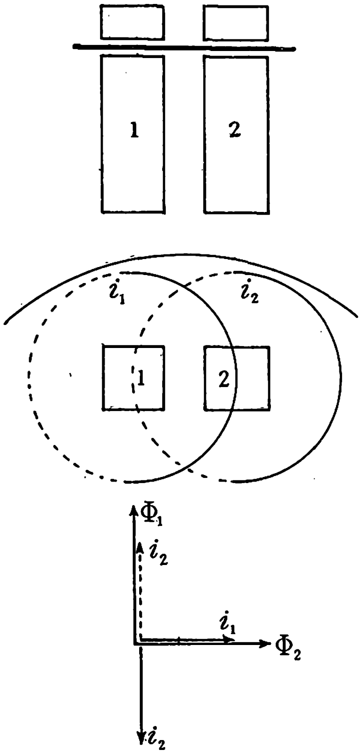

FIG. 12.

In the vector diagram, Fig. 13, it is assumed that the combined effect of the resistance, iron losses and the quadrature loop is to cause the voltage flux to lead exact quadrature by an angle denoted by α. This angle varies and the value to which it is adjusted depends on a number of conditions. The meter is suitable for measuring correctly on low power factors when the position of the quadrature loop is so adjusted that the disc is stationary with the load on the meter adjusted to zero power factor. It is then usually assumed that the voltage flux is in exact quadrature with the voltage. This assumption would be correct, however, only if the disc reactance were zero or negligible, and it has been demonstrated in what has gone before that the reactance is not negligible but may have a very considerable effect on the behaviour of the meter under certain conditions.

One conclusion which was drawn from the frequency tests was that the adjustment of the quadrature loop for standstill at zero power factor would depend on the time-constant of the disc. Tests were made to verify this, and it was found that if the loop was correctly adjusted for the standard aluminium disc, and then the thick copper disc substituted without any other alteration, the copper disc rotated forward. When the loop was correctly adjusted for the copper disc, and the aluminium disc substituted, the disc rotated backward. It therefore appeared that the actual phase of the voltage flux required depended on the time-constant of the disc used, and on the frequency. With the loop removed altogether it was found that at zero power factor at a frequency of 50 the standard aluminium disc rotated backwards, and the thick aluminium disc rotated forwards. It is shown later that the phase of the active voltage flux is not affected by changing the disc, and this suggests that the time-constant of the eddy-current path between the voltage poles is not the same as that between the current poles. That is, θ_V is not of the same value as θ_I. If θ_V were equal to θ_I the position of the power-factor corrector would be the same for all discs.

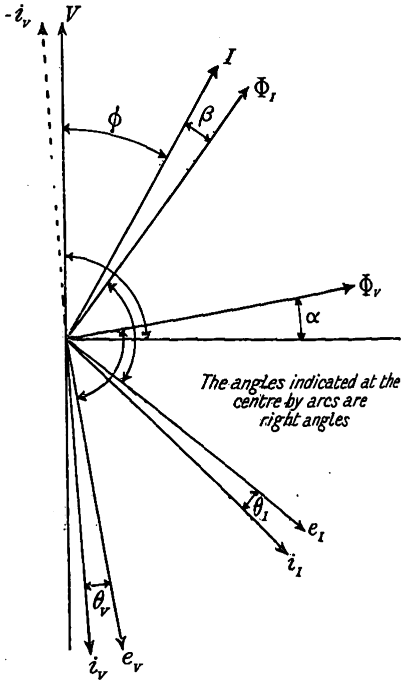

FIG. 13.

Reverting to the vector diagram, the eddy-current paths have time-constants T_V and T_I, not necessarily equal, causing the eddy currents to lag behind the induced e.m.f.'s by angles θ_V and θ_I respectively.

The torque is proportional to

$$\Phi_I i_V \cos(\phi+\alpha+\beta-\theta_V)+\Phi_V i_I \cos(\phi+\alpha+\beta+\theta_I)$$

$$=\Phi_I\frac{e_V}{R_V}\cos\theta_V\cos(\phi+\alpha+\beta-\theta_V)$$

$$+\Phi_V\frac{e_I}{R_I}\cos\theta_I\cos(\phi+\alpha+\beta+\theta_I)$$

and since e_V and e_I are $\propto \Phi_V$ and Φ_I respectively, the torque is

$$\propto \Phi_V\Phi_I\left[\frac{1}{R_V}\cos\theta_V\cos(\phi+\alpha+\beta-\theta_V)\right.$$

$$\left.+\frac{1}{R_I}\cos\theta_I\cos(\phi+\alpha+\beta+\theta_I)\right]$$

Now R_V and R_I are not necessarily equal, but they do not differ by more than a few per cent, and since the curves obtained are not curves of absolute value, but rather curves of change of absolute value, the error in assuming R_V equal to R_I will not be great. This can be seen more clearly, perhaps, from the following:—

The torque is proportional to

$$\Phi_V\Phi_I\left[\frac{1}{R_V}\cos\theta_V\cos(\phi+\alpha+\beta-\theta_V)\right.$$

$$\left.+\frac{1}{R_I}\cos\theta_I\cos(\phi+\alpha+\beta+\theta_I)\right]$$

Assuming that $R_V = R_I$, this becomes

$$\frac{\Phi_V\Phi_I}{R_V}[\cos\theta_V\cos(\phi+\alpha+\beta-\theta_V)$$

$$+\cos\theta_I\cos(\phi+\alpha+\beta+\theta_I)]$$

and the difference in the value of the two equations, due to the change in the value of the cosine terms, will not differ by more than a few per cent—not a serious error, since the changes themselves are small.

Experiments were next carried out to determine the values of the various phase angles assumed. It is obviously best to carry out such tests at or about zero power factor, for here the angles have their greatest effect.

The first experiments were made at zero power factor, as indicated on a Duddell-Mather wattmeter, and the speed of the disc was determined. This method did not prove successful on account of the friction with the heavy discs being comparable with the driving torque. The procedure was therefore altered and the power factor adjusted until the torque on the induction meter was as near zero as could be determined, after which the watts were read on the standard wattmeter. It was found that the removal of the brake magnets greatly increased the ease of working and the accuracy of the determinations and, so far as could be ascertained, did not affect the results.

Let ϕ_S be the phase angle between V and I when the induction meter indicates zero power factor; also let $\phi_S = 90° - \gamma$.

The torque on the disc is zero, and therefore

$$0=\cos\theta_V\cos(\phi+\alpha+\beta-\theta_V)$$

$$+\cos\theta_I\cos(\phi+\alpha+\beta+\theta_I)$$

and $$\phi=\phi_S=90°-\gamma$$

Substituting, we get

$$0=\cos\theta_V\cos(90°-\gamma+\alpha+\beta-\theta_V)$$

$$+\cos\theta_I\cos(90°-\gamma+\alpha+\beta+\theta_I)$$

$$=\cos\theta_V\sin(\theta_V+\gamma-\alpha-\beta)$$

$$+\cos\theta_I\sin(\gamma-\alpha-\beta-\theta_I)$$

If θ_V and θ_I are assumed to be small angles, and their cosines very nearly unity, the equation can be reduced to

$$0=\sin(\theta_V+\gamma-\alpha-\beta)+\sin(\gamma-\alpha-\beta-\theta_I)$$

without incurring any serious error. The solution of this equation is

$$\gamma=\alpha+\beta-\tfrac{1}{2}(\theta_V-\theta_I)$$

This equation and procedure were then used to deduce separately the values of the various phase angles assumed and to determine the effect of frequency on the angles.

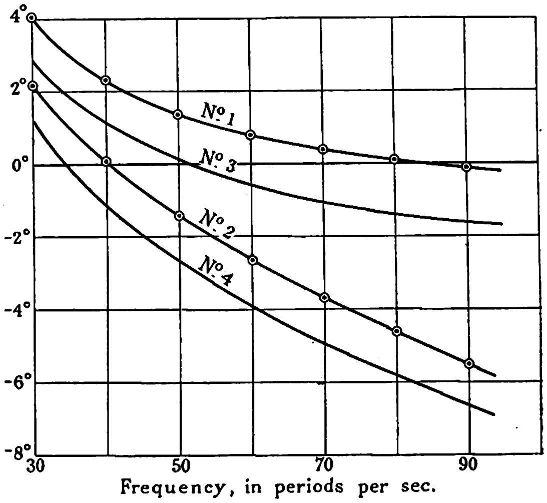

FIG. 14.—Curves of γ/frequency:—

(1) for standard corrugated aluminium disc with power-factor loop removed.
(2) for standard aluminium disc with power-factor loop in position.
(3) for thick copper disc with power-factor loop removed.
(4) for thick copper disc with power-factor loop in position.

Effect of Power-factor Adjustment.—With the power-factor adjustment removed, a curve connecting γ and the frequency was obtained experimentally for the standard corrugated aluminium disc. The power-factor adjuster was then replaced, and a second γ/frequency curve obtained. These curves are shown in Fig. 14, curves 1 and 2.

At any particular frequency the value of β is the same for both curves, and, since the same disc was used in both tests, the values of θ_V and θ_I are the same for both curves. The only change therefore is in the value of α, due to the addition of the power-factor adjuster. Therefore the difference between the two γ/frequency curves gives the effect of the power-factor adjuster on the phase of the voltage flux. This is shown in Fig. 15.

Without altering the position of the power-factor adjuster, this disc was removed and the thick copper disc put in its place. With the power-factor adjuster still in the same position, a γ/frequency curve was obtained. A second γ/frequency curve was obtained after the power-factor adjuster had been removed.

The curves obtained are shown in Fig. 14, curves 3 and 4. Points showing the difference between these two curves are plotted in Fig. 15, and they are coincident with the curve already deduced from the experiments on the standard disc.

The conclusion to be drawn from this is that the effect of the power-factor adjuster on the phase of the voltage flux, for any given position of the adjuster, is not affected by the nature of the disc used in the meter. For any other position of the adjuster the slope of the curve will be different, but it was found that all the curves are practically straight lines passing through the point (O, O).

Effect of Resistance of Voltage Coil.—The inductance and resistance of the voltage coil were determined to be 2·4 henrys and 48 ohms, respectively.

The theoretical effect of the resistance of the winding on the phase of the voltage flux can easily be calculated for any frequency.

The voltage pole shown in Fig. 9 does not carry the total flux produced by the voltage coil, but only a leakage flux. The main flux passes in a good iron circuit, thereby increasing the inductance of the coil without increasing its resistance. In order to determine the effect of the resistance of the coil on the phase of the leakage flux, it was decided to determine the effect of artificially increasing the resistance.

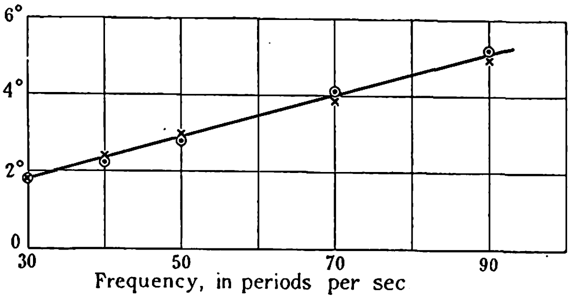

Fig. 15.—Curve connecting the variation in lag of the voltage flux due to the power-factor loop, with frequency. Points marked × are deduced from curves 3 and 4, and points marked ⊙ from curves 1 and 2 in Fig. 14.

The tests were made on a meter from which the power-factor adjuster had been removed. The reason for removing the adjuster was that it is very difficult to replace it in exactly the same position every time.

Curves of γ/frequency for two discs, in the normal meter, have been given already in Fig. 14. Tests for these curves were repeated, but with a resistance of 50 ohms connected in series with the voltage coil. The original curves, 3 and 4, and the new curves, 1 and 2, are shown in Fig. 16. The difference between the two curves for the same disc gives the decrease in lag of the flux due to the increased resistance (Fig. 17).

The resistance of the voltage coil is 48 ohms, and the added resistance 50 ohms. Remembering that at these small angles the sine of the angle is very nearly proportional to the angle, the effect of the added 50 ohms may be considered to be equal to that of the 50 ohms (approx.) of the voltage coil itself.

In Fig. 17 there is given also a curve calculated from the resistance and inductance of the coil. Although the experimental curve is not coincident with the calculated curve, the difference does not appear to be greater than the expected errors of observation.

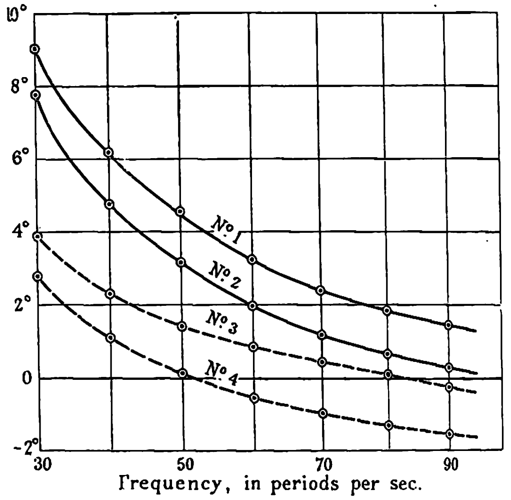

Fig. 16.—Curves of γ/frequency for meter, showing effect of added resistance in voltage circuit:—

(3) standard aluminium disc, no added resistance.
(1) standard aluminium disc, 50 ohms added resistance.
(4) thick copper disc, no added resistance.
(2) thick copper disc, 50 ohms added resistance.

Effect of Iron Losses in Voltage Pole.—This was estimated and found to be negligible.

Effect of Iron Losses in Current Pole.—This makes the flux lag behind the current by an angle which has been denoted by β. To determine this angle, the value of γ was obtained at three loads for each of a number of frequencies. These values of γ were plotted against the load and the curves were extended back to the point at which the load was zero. At this point β is also zero, and therefore any increase in γ is due to the angle β.

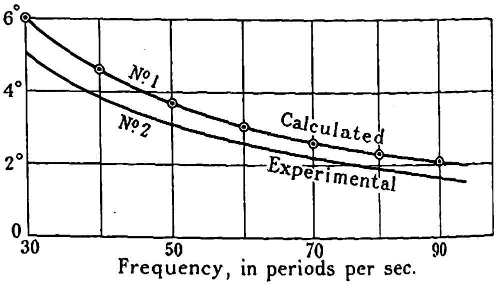

Fig. 17.—Curves showing phase alteration of voltage flux due to resistance of voltage coil.

β appears to be about 0·5° at 30, and 1° at 100 periods per sec. These figures are small and, having regard to the manner in which they are obtained, must be considered as approximate only.

CONCLUSIONS.

From the behaviour of the meters on varying frequency the authors conclude that induction meters may be expected to register slower on distorted than on sinusoidal wave-shapes. The results given in the paper previously referred to * show that all the induction meters tested register slower on distorted waves. In the discussion on the paper, Mr. L. Wild attributed the uniform slow running of the meters on distorted waves to the fact that all the waves used were not smooth waves but had what he termed "architectural features" on them. He himself had found that induction meters registered sometimes faster and sometimes slower on distorted, but smooth, waves than they did on sinusoidal waves. The variations in accuracy obtained by Wild were comparatively small, as were also those obtained by Rosa, Lloyd and Reid at Washington;† and the authors are inclined to attribute them to inconsistencies in the meters themselves, or to changes in the iron losses, or to both.

It would appear from the results and deductions that, in order to reduce the frequency errors in the meters, certain points must be kept in mind in the design. First, the ratio of the active voltage flux to the permanent brake-magnet flux should be kept as low as expediency will permit. Secondly, the time-constant of the eddy-current paths should be as low as possible, consistent with a reasonably high torque. Since a reduction in the active voltage flux would result in a reduced torque, it would appear that the point first mentioned should be effected by means of stronger brake magnets. This would result in lower speeds—a desirable feature in some types of meters.

The authors have not attacked the problem of the additional errors shown by induction meters when working at other than unity power factor at various frequencies. It would appear that the present method of power-factor correction leaves something to be desired. The meters are adjusted at one particular frequency, and it is possible that at higher frequencies the errors introduced by the correctors may be equal to, if not greater than, those which they are intended to eliminate.

The usual theory of induction watt-hour meters assumes that certain factors, such as the phase of the voltage flux and the time-constant of the eddy-current paths, are practically those that would hold in an ideal meter. The authors have shown that these assumptions are not justified even in modern, well-designed meters. In the case of the thick copper disc and the thick aluminium disc the time-constant is about 0·0008, and at a frequency of 50 the current would lag by an angle of about 14°. At a frequency of 100 the angle would be about 27°, and these angles are comparatively large.

The authors wish to express their indebtedness to the Principal and Governing Body of the Manchester College of Technology for facilities for carrying out the experiments described in the paper.

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* *Loc. cit.*

† *Bulletin of the Bureau of Standards*, vol. 1, p. 421.

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 7TH MARCH, 1930.

Mr. E. Fawssett: The figures given on page 1029 are remarkably accurate. Two very small differences between large quantities, which in one case are less than 2 per cent apart, are divided one into the other. The result obtained is found to be within 2 per cent of the theoretical value. On page 1030 the effect of altering the compensation is considered, and it follows from the tests described that where a meter has good shunt-coil and magnetic characteristics it is possible to choose a disc requiring no other compensation at all. This has actually been done and a meter with good inherent characteristics, requiring no extra compensation whatever, was the result. The curves of Fig. 14 show very clearly that the best meter is the one with the smallest initial inherent errors for which compensation has to be made. Similarly, Fig. 16 indicates that a meter with a shunt coil of the minimum resistance gives the best performance, and, incidentally, why the high-class British meter has an advantage over the Continental meter, which is usually equipped with a shunt coil of much higher resistance. At the end of the paper angles of 14° and 27° are given for the lag of the eddy currents in the thick discs at 50 and 100 cycles; as these values seemed to be large, I tried to think of a way of checking them experimentally. Mr. Richardson, one of my technical assistants in meter development work, suggested a method which employed a Metropolitan-Vickers meter of the type used by the authors, with its disc and compensator in place. The latter was adjusted for correct quadrature at zero power factor, the disc was removed, and a wound rotor consisting of two coils wound in opposite directions and held in place by two thin mica discs was substituted. A current (which represented the eddy currents and occupied the same position in space) was led in from outside by flexible ligaments, the substituted rotor being sufficiently free to move to a position of balance. The power factor was varied until the zero-torque point was reached with the coils at the maximum position, at which stage the phase of the disc eddies should have been 91° behind that of the series current, or 1° behind that of the voltage which induced them. For the disc mentioned by the authors the corresponding figure was 14°, and in case the discrepancy was due to the absence of the disc one of these was inserted as well. A change of less than 1° was the result, so that the angle obtained seemed to be very much less than that given in the paper. I should be glad if the authors could point out the cause of the divergence. On the general question of the effect of frequency change at unity power factor, the performance of the meters available on the British market is exceedingly variable. On the North-East Coast some 100 000 existing meters will have to be changed over from 40 to 50 cycles per sec. before long, and it has been necessary to choose types that can be left in circuit until the individual periodic change of each is due to take place. On 11 types of meters, British and foreign, selected from those which are available in this country, it was found that when the power factor adjustment had been set correctly for 40 cycles per second the error at the higher frequency varied from 2·1 per cent fast to 2·3 per cent slow; thus the various meters fall on different parts of the authors' characteristic curves. I agree with them that the torques in an induction meter are both positive and not opposing. To explain this, consider a meter circuit in which the main current I and the main voltage V are in phase (see Fig. A). The flux due to I is substantially in phase with it, but that part which cuts the disc lags slightly behind and induces an e.m.f. in the disc which lags by 90°. The eddy currents (b) due to the latter lag slightly more and these, which we may call "disc series eddies," are acted upon by the disc shunt flux (a) so as to produce a torque proportional to the vector product of (a) and (b). These vectors are substantially, but not in all cases necessarily, exactly in phase. The disc shunt flux (a) also induces an e.m.f. in the disc which lags by 90°, and the resultant eddy currents (d) have a further slight lag. These, which we may call "disc shunt eddies," react with the disc series flux (c), and it is because the two vectors are in opposition that the idea of the negative torque has grown up. It has, however, been overlooked that these eddy currents are displaced 180 electrical degrees in position on the disc; thus a flux having a given direction at any moment is in this case reacting with the opposite side of the eddy ring, so that this torque is proportional to $cd \cos (180 - \phi)$ or $c'd \cos \phi$, where ϕ is a small angle such that θ and ϕ together exercise the minimum effect at unity power factor in the circuit. Both torques are positive at unity power factor (see Fig. B): they are portions of sine curves, 90° apart, and their resultant has a peak of twice the frequency. I have endeavoured to give an alternative way of regarding this problem, which has apparently puzzled electrical engineers for some time, and I hope that my presentation confirms the authors' argument. I have always believed their solution to be the true one, and that the theory championed in books by well-known authorities, to the effect that the torques were opposing, was really founded upon a misconception.

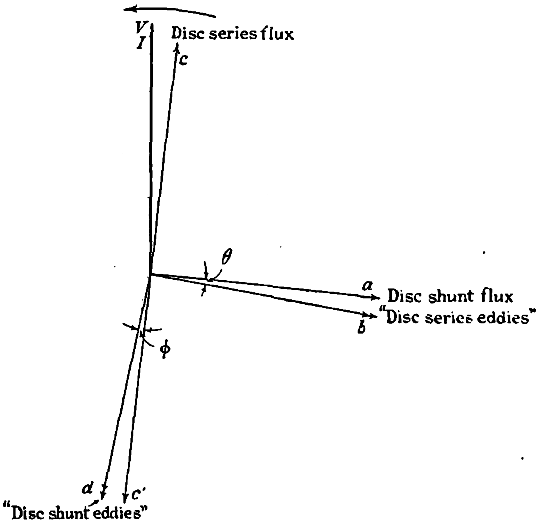

FIG. A.

Mr. W. Lawson: I have been familiar for many years with this phenomenon of variation in induction meters with changes of frequency, and some time before the War carried out experiments in connection with it. I selected two meters designed for 25 cycles per sec. (one was manufactured by Metropolitan-Vickers, Ltd., while the other was of foreign origin), and tried the effect of increasing the frequency to 27 cycles per sec. With the Metropolitan-Vickers meter the change was + 0·8 per cent at unity power factor and + 5·5 per cent at 0·25 power factor. Under the same conditions the other meter registered changes of + 1·4 per cent and + 13·7 per cent respectively. The results afforded striking evidence as to the effect of changes of frequency. Recently I had to deal with the unusual case of a supply system which was temporarily on 25 cycles per sec. and after about two months was to be changed over to 50 cycles. The district had only recently been opened up and a considerable number of meters had to be fixed immediately. Only 50-cycle meters were available and it was decided to adjust these temporarily for 25 cycles. The shunt coils became rather hot but fortunately they were able to stand the conditions, and of course the meters ran very slow. The braking system of these meters consisted of a pair of brake magnets with their poles opposed, and in order to reduce the flux across the gaps a wedge-shaped piece of strip iron was used to bridge across the poles of the magnets situated above the disc. All the tester had to do was to move the strip until the correct position had been reached. When the supply was changed from 25 to 50 cycles per sec. it was only necessary to remove the piece of iron and the meter was then adapted to suit the new conditions. The method was rather rough-and-ready and might be open to criticism on account of the change in the brake flux. No undue risk was, in fact, taken as the meters themselves were ultimately all removed, but it is interesting to note that on appreciable permanent alteration in the meters had taken place. The question of wave-form is undoubtedly connected with this subject. At the time of the paper by Messrs. Ratcliff and Moore [*] it was thought, and

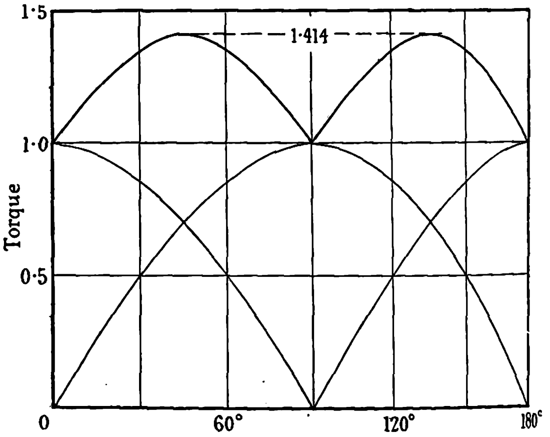

FIG. B.

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[*] *Loc. cit.*

rightly so, that meters susceptible to change of frequency would turn out also to be susceptible to changes of wave-form. At that time I had contemplated the purchase of a 3-phase double generator set for a.c. meter testing, but as the oscillograph proved the wave-form to be very irregular I was rather dubious about acquiring such a machine. In order to come to a definite conclusion, I decided to carry out tests with this machine on some meters that were much affected by changes of frequency and compare the results with similar tests on the same meters carried out with the machine at the National Physical Laboratory, the wave-form of which was beyond question. The greatest difference in an average of about 6 readings in each series was of the order of 0·18 per cent. I consider the test to be proof that the wave-form of the machine was satisfactory. The method formed a practical way of dealing with testing apparatus the wave-form of which was in doubt, and the machine in question, judged by the standard of the N.P.L. and most of the manufacturers, is undoubtedly quite suitable for its purpose. Before carrying out the test it was necessary to test the meters for constancy, and this took about 4 months. I first found that the frequency of the supply on which they were being tested was subject to variation, then that there were very small variations in the indication of the wattmeter, and finally that the stop-watch which I was using was not at all times reliable. Having eliminated all the sources of error, a very large number of readings was taken before I could be satisfied as to the constancy of the meters. The effects of variations of frequency, as shown by the curves given in the paper, are interesting and it is clear that the better performance of the thin discs is due to the fact that the higher resistance tends to swamp the reactance of the disc. The reactance produces the drooping curve and the employment of a thin disc delays this effect until the higher frequencies are reached, as shown in Fig. 8B, which gives the curves for an aluminium standard disc and a thick Eureka disc. With regard to the theory of the induction meter, it appears to me that the meter follows essentially the same law as the induction motor. The chief difficulty is in visualizing a rotating magnetic field, and it would appear that this expression is misleading, for what we have, in effect, is an oscillating field. Taking the case of the permanent-magnet brake system, we have here a reverse torque produced by a disc passing through a gradually increasing and then gradually diminishing magnetic field. If the permanent magnet were rotated it would drag the disc along with it and produce rotation. The actions of the voltage and current fluxes would appear to produce a field which sweeps along the disc in waves of varying intensity, and so creates a condition which will generate the eddy currents necessary to produce driving torque.

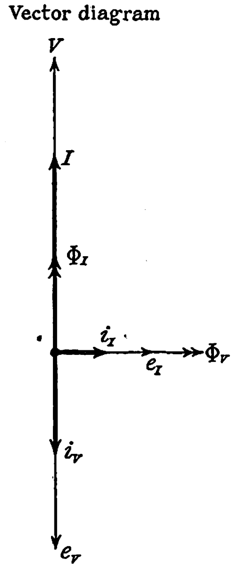


FIG. C.

LIST OF SYMBOLS.

V = applied voltage.
I = current in series coils.
Φ_V = flux due to applied voltage (V).
Φ_I = flux due to current (I).
e_V = induced voltage in disc due to Φ_V.
e_I = induced voltage in disc due to Φ_I.
i_V = induced current in disc due to Φ_V.
i_I = induced current in disc due to Φ_I.

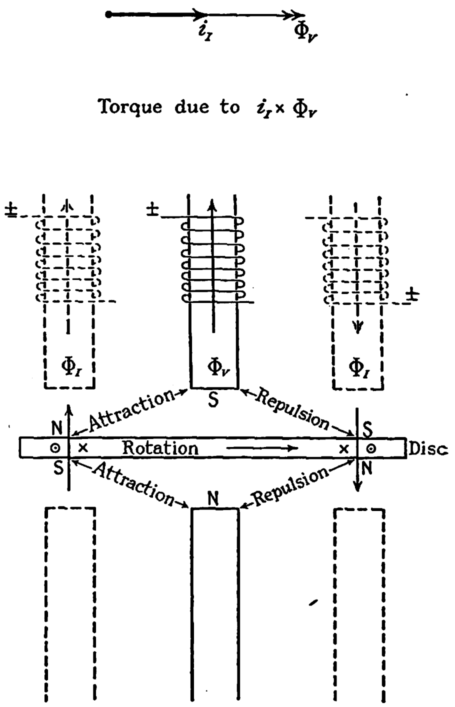
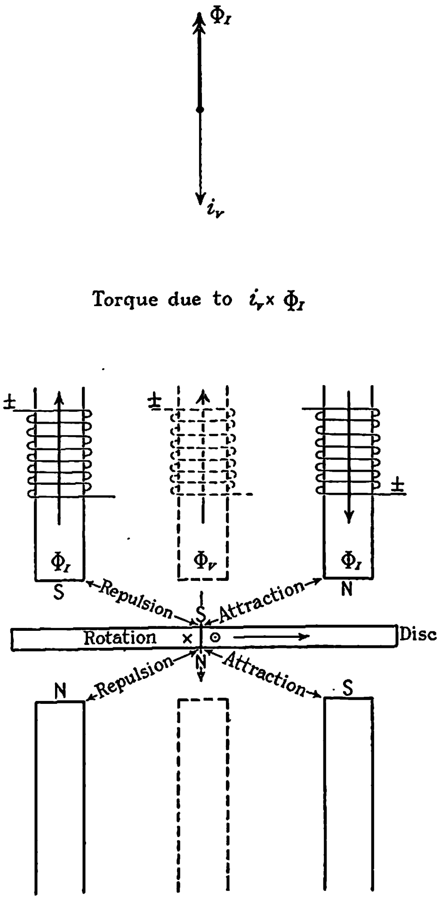


FIG. D.

Mr. G. F. Shotter: According to the authors, several writers contend that the two torques, produced by the action of the shunt flux on the flux due to the series eddy-currents and the series flux on the flux due to the shunt eddy-currents, respectively, are in opposition. I endorse the authors' contention that this is not so and that the torques are in the same direction. I should like to put forward an explanation of my own theory of the induction watt-hour meter. In Fig. C is given the general vector diagram of the voltages, currents and fluxes of a perfect meter under unity power-factor conditions. It will be understood, however, that the imperfections of a commercial meter do not in any way interfere with the reasoning on which I base my theory. To simplify matters, Figs. D and E show the fundamental magnetic elements of an induction watt-hour meter consisting of one main shunt-magnet excited from the source of potential and two magnets excited from the current, which is in phase with the source of potential.



Torque due to $i_V \times \Phi_I$

Fig. E.

A little consideration will show that the potential and current elements could be interchanged without any alteration to the theory. It will be seen from the vector diagram that the flux from the shunt element is in quadrature with the applied e.m.f. Before proceeding with the explanation of the diagrams it will be as well to consider the following points: (1) A continuous torque can only exist between two in-phase fluxes. (2) Although an instantaneous torque does exist between two fluxes 90° apart, the resultant torque over one complete cycle is zero. (3) Any two fluxes can be split up into in-phase and out-of-phase components, but only the in-phase components can be considered. It is, of course, assumed that these fluxes are not coincident in space. (4) Alternating fluxes in phase can be replaced, for simplification, by magnets excited by direct current or by permanent magnets. (5) It should be noted that a continuous torque-producing flux can be either in phase or 180° out of phase, the effect being produced by attraction instead of repulsion, or vice-versa. The relationship between the torque-producing fluxes will be observed from the vector diagrams of Figs. D and E. These figures are self-explanatory and give the correct polarity not only of the windings but also of the fluxes concerned. Figs. D and E further show that the two continuous torques produced by $i_I\ \Phi_V$ and $i_V\ \Phi_I$ are in the same direction and, in the case of a disc of dimensions sufficient to cause no restriction to the eddy lines, the two torques should be practically equal. Since putting forward this theory I have carried out an experiment in an attempt to prove its correctness. This is illustrated in Figs. F and G. The experiment was carried out on a commercial meter in which the metal disc was replaced by a mica one. Upon this were placed three copper rings in such a position that two of these came under the series iron and the other—at the opposite side of the disc—could be brought separately under the shunt iron. It was found that in both cases the rotation was always in the same direction, and also that the torques produced by the two causes were approximately the same. It will be seen from the expression of the torque values that the equality of the torques is independent of the relative values of the shunt and series fluxes. It is interesting to point out that the torque impulses on the disc are of four times the frequency. In connection with the effect of wave-form the authors will, I think, agree that it is generally accepted that the errors are due to (*a*) the pure frequency effects, and (*b*) saturation. This explanation, however, seems difficult to apply to the results which I obtained a few years ago on one particular type of meter having variations as large as 2 per cent at 1/20th full load, the variation being approximately inversely proportional to the load. The wave-form of the supply was not abnormal, but it probably contained a third harmonic, as it was from a delta/star power transformer. It appeared to be produced entirely by the shunt system and to be due to the use of solid return paths. I should be glad to know whether the authors have noticed any phenomena of this nature.

Mr. Wilfred Holmes: All supply stations in this country will shortly be operating at 50 cycles per sec. It would therefore appear, on first consideration, that the frequency error in meters is not now very important. The author rightly points out that the study of frequency variation is a key to the solution of the problem of wave-form error in meters. He does not deal in detail with the effect of the quadrature loop (the lagging coil or copper stamping which usually goes round the shunt pole) upon frequency errors. For some time a meter manufacturer in this country made meters without quadrature loops. In one design the pole pieces were of cast iron and the quadrature adjustment was made by adding resistance in series with the potential circuit. This meter had a curve similar to curve II, Fig. 1, except that the fastest point was at 83 cycles. I refer to this fastest point as the " frequency-curve peak." In another design of meter the fastest point was at 33 cycles.

This meter had laminated poles and no quadrature loop, the quadrature adjustment being made by means of a specially shaped tongue-piece placed between the two series poles and carrying part of the shunt flux. This latter meter was designed for use in cases where accuracy on both 25 cycles and 50 cycles was required, and although it was fast on 33 cycles it was particularly useful for supply stations which were to change over from 25 cycles to 50 cycles. In meters generally, in order to comply with B.E.S.A. requirements regarding change of frequency, it was found necessary to vary the thickness of the discs, and thus 20-mil discs for 100 cycles, 40-mil discs for 50 cycles and 60-mil discs for 25 cycles had to be supplied. The authors have explained why this was necessary and have shown the theory to be in line with practice. It is well known that an induction meter should be accurate on change of frequency, because, as has been pointed out, the potential coil acts like an iron-cored impedance coil and with a fixed voltage the flux decreases with increased frequency; as the eddy currents in the disc are proportional to flux × frequency, the torque should not alter with frequency. This is clearly explained on page 1025 of the paper, and it is shown that the speed variation produced by a change of frequency is due to the voltage flux acting as a brake on the disc. The braking can only occur if the disc rotates, so that from this point of view it would be more accurate if the meter could register with the disc stationary. The obvious solution is to reduce the speed, and that is why the modern meters run at 12 instead of at 40 r.p.m. This is confirmed on page 1033 of the paper.

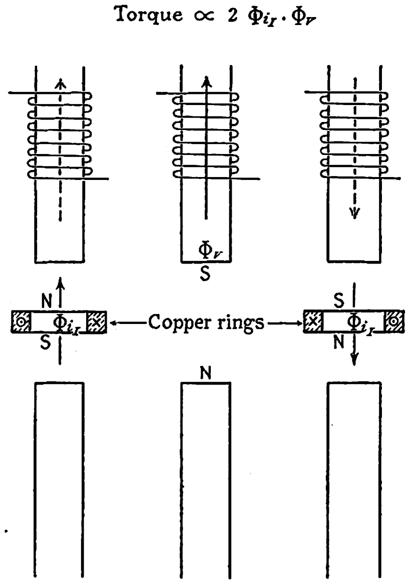


Fig. F.

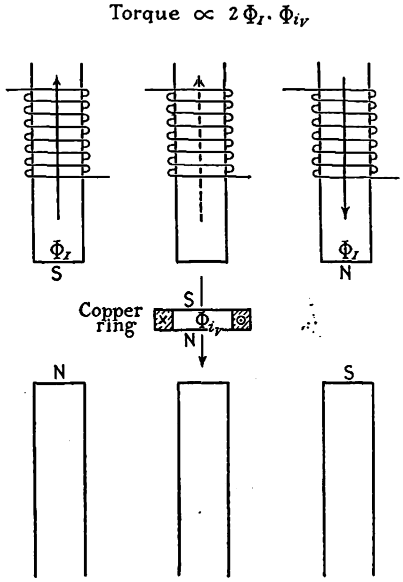


Fig. G.

Let $\Phi_V = \Phi_{i_V} = 100$ units, and $\Phi_I = \Phi_{i_I} = 10$ units.
Then $2\,\Phi_{i_I}\,.\,\Phi_V = 2\,000$ units, and $2\,\Phi_I\,.\,\Phi_{i_V} = 2\,000$ units.

Mr. S. Garbutt (*communicated*): The authors refer to tests carried out in 1911 on induction watt-hour meters with alternating currents of different wave-shapes. The meaning of this does not become clear until actual reference is made to the paper quoted, which points out that the wave-forms of both voltage and current of the supply used in the tests were distorted. This is a different problem from the distortion of only one of the wave-forms, and it has been shown by Mr. R. G. Isaacs * that in a circuit where the voltage wave-form is sinusoidal, but the current wave-form is badly distorted, the registrations of induction watt-hour meters are within the usual limits of accuracy. The initial examination of the curves in Figs. 1 and 2 leads to the opinion that, although the induction watt-hour meters may conform to the usual limits of accuracy when tested at their rated frequency, they are appreciably inaccurate if the wave-forms of pressure and current of the supply are distorted. Further comparison of the curves for meters I and II respectively shows that under certain conditions the errors may balance each other to some extent, but that meter No. III would under-register in any circumstance of distorted wave-form. If meters register in the consumers' favour, due to distorted voltage and current wave-forms, in the near future the majority of supply undertakings will be purchasing their electrical energy in bulk supply through meters. A suggestion of practical value was put forward by Mr. J. T. Irwin (who is referred to on page 1023)—to the effect that "each type of meter should be tested at frequencies much higher than those at which it is to be used, and rejected if not up to a definite standard." I should like to ask the authors whether they know what is the wave-form of the current in the pressure coil of an induction watt-hour meter when the voltage applied to the coil has a sinusoidal wave-form.

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* *Proceedings of the Meter Engineers' Technical Association*, 1928, vol. 2, p. 80.

Messrs. A. E. Moore and **W. T. Slater** (*in reply*): The discussion shows that there is general agreement with our contention that the theory of the induction meter, when treated from the point of view of alternating fluxes stationary in space, shows that the two resultant torque components are in the same direction. It would appear that the fallacy of the theory of opposing torques is due to vector diagrams which show only the time phase of the fluxes and currents, whereas to obtain the directions of the resultant torques it is necessary to consider not only the time phase but also the space phase of the fluxes and currents. The theory of the meter responds equally to the moving-field conception and the same conclusions obtain, as, of course, they should do.

Mr. Fawssett supports our conclusions that the best performance is obtained on meters requiring least compensation. It may be noted that the theory of the perfect induction meter shows that the behaviour of the instrument is quite independent of frequency and wave-shape. Mr. Fawssett questions the probability of the angle of lag of the eddy currents in the thick copper disc being of the order of 14° at 50, and 27° at 100 periods. The angles are calculated in the usual way from the value determined for the time-constant of the disc, and the frequency, and it may be noted that the values have been used in the calculations for the curves given in Fig. 7. The conditions obtaining in the wound rotor and in the disc may be quite different, since in the wound rotor the eddy-current path is defined whereas in the disc it is not. Presumably, the torque will depend upon the position of the currents in the disc, and it may be that, with higher frequencies, the eddies spread out into paths of greater radius. Such a change in position could not take place in a wound rotor; but what effect this consideration would have on the theory which we have set forth has not yet been investigated. That some makes of meters run faster and some slower when the frequency is increased above the normal for the meters can be deduced from the curves given in Figs. 1, 2 and 3.

The figures given by Mr. Lawson for the variation in accuracy of meters when the frequency is changed from 25 to 27 periods per sec. may be expected, and may be deduced from the theory of the meters. The variations are usually greater in those meters normally designed for 25 periods than in meters for, say, 50 periods. A first-class induction watt-hour meter, correctly adjusted, gives excellent results when used at the frequency for which it has been adjusted, but it may have large errors if used at other frequencies, particularly if the power factor is not unity. One of the authors has occasionally had to test induction meters which have been used in tests on loads at frequencies considerably different from that for which the meters have been adjusted. In some cases, small changes in the frequency or in the power factor have resulted in such large changes in accuracy that it has been impossible even to approximate to the correct results. Mr. Lawson's account of his procedure with reference to the change-over meters indicates some of the problems presented to the meter engineer and his ingenuity and resource in meeting them.

Mr. Holmes refers to what he terms the "frequency-curve peak" and cites cases where this occurs at frequencies of 83 and 33 respectively. A study of the theoretical curves given in Fig. 7 explains why the peak occurs at different frequencies with different shunt magnets and discs. The use of different discs for different frequencies is interesting and, as Mr. Fawssett points out, our experiments show that it would be possible to select a self-compensating disc for a particular meter.

With reference to the point raised by Mr. Garbutt in connection with the wave-form errors in induction meters, we would point out that the conclusions attributed to R. G. Isaacs were indicated by J. T. Irwin in the 1911 paper.* We do not quite understand the object of Mr. Garbutt's question relative to the wave-shape of the current in the shunt coils. The wave-shape may easily be determined by means of an oscillograph, but it is the wave-shape of the shunt flux which is of importance. Provided that the iron and copper losses in the shunt system are small, then with a sinusoidal wave of voltage there will be a sinusoidal wave of flux. If the winding were highly resistive there would be a tendency for the shunt-current wave to be sinusoidal with a sinusoidal voltage and, since the permeability of the iron is not constant, the resultant flux wave would not be sinusoidal. It may be that the bad effect of distorted waves on some meters is due in some measure to the distortion of the shunt-flux wave brought about by a highly resistive shunt coil.

Mr. Shotter gives another interesting method of explaining the theory of the induction meter. We do not quite understand what is meant in the last part of his remarks by a certain meter "having variations of 2 per cent at 1/20th full load," since he does not state whether the meter was tested on more than one source of supply.

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* *Loc. cit.*

SOME DEVELOPMENTS OF THE THERMIONIC VOLTMETER.*

By E. B. Moullin, M.A., Associate Member.

(*Paper first received* 28*th January, and in final form* 22*nd April,* 1930.)

Summary.

In this paper the various ways are considered in which a 3-electrode valve should be used in a thermionic voltmeter, and the accumulated experience is described of several years' work by the author in making valve voltmeters for various purposes. No one arrangement can possess every desirable property, and it is shown how to produce a voltmeter to fulfil specified requirements. The effective input resistance of the various arrangements, and the harmonic currents produced by grid current, are considered analytically and experimentally. The effect on range and sensitivity of providing additional batteries is also discussed, extra batteries being found to be an advantage only in very low-range instruments.

The effect on the calibration of a change in the valve and in temperature is found to depend on the form of the rectifier used. In general, a thermionic voltmeter cannot read R.M.S. values. The wave-form error of various systems is investigated; with one arrangement the reading is proportional to the peak voltage and in another to the mean. The possibility of a frequency error is discussed; tests show that the error is negligible for frequencies up to 1 000 kilocycles per sec., whilst from indirect tests it would appear that the error is probably negligible for frequencies up to 30 times this value.

(1) Introduction.

A rectifier, such as a crystal or thermionic valve, may be used to make an alternating voltage perceptible to a polarized galvanometer, and in recent years these have been combined to produce a satisfactory voltmeter. The thermionic valve, with either two, three or four electrodes, possesses great potentialities for voltmeter use, and this paper explores some of the most desirable.

The ideal a.c. thermionic voltmeter should possess the following properties. It should be as portable as a d.c. ammeter and be permanently calibrated; it should possess great sensitivity and wide range and be unaffected by a steady voltage between its terminals; its input resistance should be infinite, and its readings should be proportional to the R.M.S. value of any wave-form and unaffected by frequency.

By a suitable choice of valve, batteries and galvanometer, most of these desirable attributes can be secured, but they cannot all be secured simultaneously. Simplicity and portability are two of the most desirable attributes: the fixed location inevitable with a table full of semi-portable apparatus imposes severe limitations on the use of a thermionic voltmeter, and therefore it must be worth while to design portable instruments, even though they may possess limitations which are well understood. The same consideration underlies much of the art and skill of instrument design; for example, the silver voltameter and current balance may be the most perfect ammeters known, yet their sphere of application is vastly more limited than that of a direct-reading pivoted instrument.

We shall now consider how to make portable thermionic voltmeters having the least number of features which will in general be undesirable.

(2) Elimination of Unessential Batteries and Method of Reproducing Calibration Conditions.

A thermionic voltmeter must have a battery to heat the filament and to this extent cannot be as portable as a moving-coil voltmeter. But this battery need not supply more than, say, $0 \cdot 1$ amp. at 3 or 4 volts; it can therefore be a small dry battery and the inconvenience of this is not overwhelming. Additional batteries are not essential to the working of the voltmeter. We shall therefore postulate a problem as follows: Given a galvanometer, thermionic valve and filament battery, to produce a voltmeter which shall possess the greatest possible number of desirable qualities.

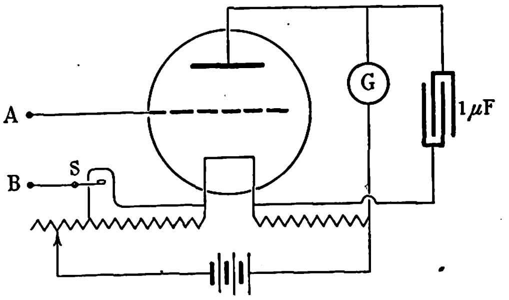

Fig. 1.

The instrument is to be permanently calibrated and provision must therefore be made to reproduce the conditions, in respect of filament current, anode and grid potential, which obtained at the time of calibration. If connections basically like those depicted in Fig. 1 are used we may reproduce the exact calibration conditions by adjusting the filament rheostat until the galvanometer in the anode circuit deflects to a marked point on the scale. It is convenient to provide a testing switch (marked S in Fig. 1) which temporarily removes the grid bias and so enhances the test-point deflection. The sensitivity of the galvanometer must at least be sufficient to produce an adequate deflection for the test point. With ordinary valves, this usually entails that the galvanometer shall be as sensitive as it is possible to make a portable unipivot instrument.

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(3) LIMITATIONS OF RANGE.

Consider the system of Fig. 1. An alternating voltage applied between A and B produces an increase of mean anode current which is proportional to the square of the applied voltage when this voltage is very small. The lower limit of range depends, therefore, on the sensitivity of the galvanometer; in a portable voltmeter equipped with a unipivot instrument the smallest detectable current is of the order of 0·25 μA, and this will be produced by an applied p.d. of about 0·1 volt (R.M.S.) Provision of additional anode potential will not alter this sensitivity appreciably but will extend the square-law portion of the scale. Greater sensitivity can be obtained only by using several valves in parallel or by adding an amplifier. The upper limit of range is imposed by the available anode potential, and in Fig. 1 this is supposed to be 4·5 volts positive to the negative end of the filament. When the grid becomes appreciably more positive than the anode the grid current will exceed the anode current, which tends to a limiting or maximum value. This is illustrated by the curve of Fig. 2 (which relates to a P.M.4 valve connected as in Fig. 1 but with zero grid bias). Fig. 2 shows that if the applied voltage exceeds about 12 volts maximum (8·4 volts R.M.S.) the anode current increases very slowly, and it becomes necessary to move the galvanometer to the grid circuit and use the valve as a diode. Such an arrangement would be undesirable because the voltmeter would take considerable power from the source and so have a low effective resistance. Therefore the negative grid-bias must be increased, but if extra batteries are precluded this must be done by some automatic process. Two such methods are shown in Figs. 3 and 4, and of these Fig. 3 has the great advantage of isolating the voltmeter from steady voltages and so confers one of the desirable attributes postulated in the Introduction. In Fig. 3 the spurts of rectified grid current divide between the parallel paths provided by the condenser and the grid leak. The capacity of the condenser is so large that sensibly all the alternating components flow through it, leaving a substantially steady p.d. between its terminals. The combination of large capacity and high resistance is therefore precisely equivalent to a battery giving a negative bias to the grid and, moreover, a bias which increases in proportion to the applied a.c. voltage. The saturation effect of Fig. 2 will now be delayed and anode current will flow during a portion only of the positive half-cycle of voltage.

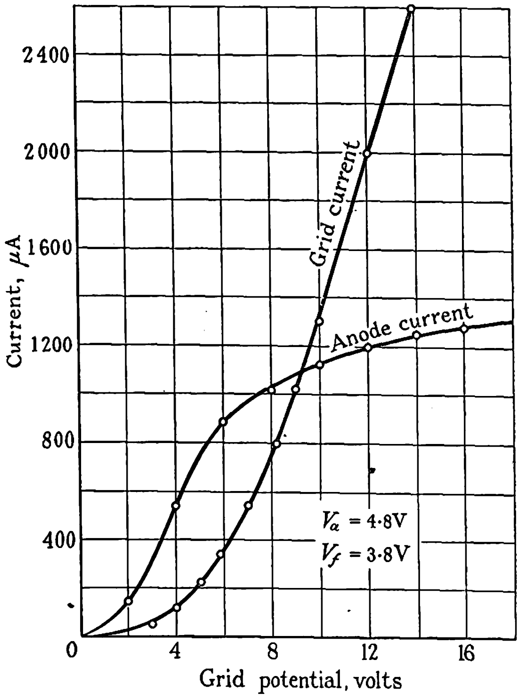

FIG. 2.

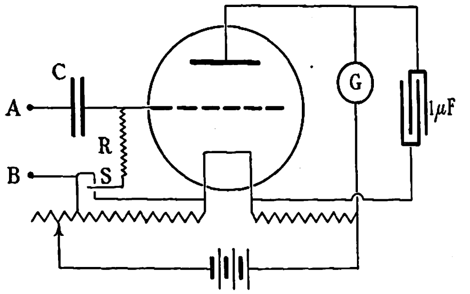

FIG. 3.

In the system of Fig. 4 the positive voltage applied to the grid is but a small fraction of the voltage applied between A and B, and this fraction depends on the ratio of the effective resistance of the grid-filament path compared with that of the grid leak in series with it. Here anode current will flow during the whole of the positive half-cycle of voltage, but in effect the voltmeter is fed from a potential divider. Since no current flows during the negative half-cycle, the resistance is infinite for that period and so the system is preferable to a potential divider; moreover, the variable conductivity of the grid provides a potential divider in which the tapping point is lowered automatically as the applied voltage is increased. The systems shown in Figs. 1, 3, and 4 take power from the source; we shall now consider the effective input resistance of voltmeters which use any one of these three systems.

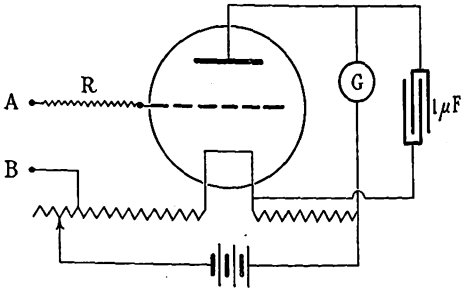

FIG. 4.

(4) EFFECTIVE INPUT RESISTANCE.

The effective input resistance may become finite from any or all of four independent causes; namely, energy transferred from the grid to the anode circuit, dielectric losses in the valve cap and instrument generally, losses in the grid leak, and losses due to grid current flowing during a part or the whole of the positive half-cycle of applied voltage. The energy is transferred from grid to anode by means of the grid-to-anode capacity and is wasted in the resistance of the anode circuit impedance (galvanometer, etc.). The anode circuit impedance should be shunted by a large capacity, say 1 μF, and then the anode is in effect short-circuited to the filament and the anode potential does not fluctuate. The grid-anode capacity is then in parallel with the grid-filament capacity and contributes only to the input capacity without contributing anything to the input resistance. We shall presume that the anode is so connected to the filament and that then the first-mentioned cause of loss is removed.

The dielectric losses are reduced by removing the valve cap and intelligently disposing the valve and terminals in the instrument case; dielectric loss cannot be eliminated, and is troublesome to measure. The results obtained on a voltmeter constructed as in Fig. 1, but without the calibrating switch, may be quoted as an example. A circuit having an inductance of 1·14 mH was tuned to a frequency of 212 kilocycles per sec. ($\lambda = 1\,420$ m), and by plotting the resonance curve the inherent decrement was found to be 1·80 per cent. The complete voltmeter (of the type depicted in Fig. 1) was then connected across the whole of the inductance, but, to prevent grid damping, the filament was not switched on. The circuit decrement was determined again with the voltmeter connected to the circuit and was now found to be 1·85 per cent, so that the presence of the voltmeter had increased the apparent resistance of the coil by 3 per cent. But some of this 3 per cent increase is due to the capacity of the voltmeter increasing the apparent resistance of the coil in a manner analogous to self-capacity.

The two resonance curves showed the apparent input capacity of the voltmeter to be 5·5 $\mu\mu$F and it may be calculated, from the value of L and the frequency, that the tuning capacity was 485 $\mu\mu$F. Now if a condenser of capacity C_1 shunts a coil L, which is in series with a condenser of capacity C_2, and the system is tuned to resonance, it is well known that C_1 increases the apparent resistance of the coil in the ratio $[(C_1 + C_2)/C_2]^2$: in this case the ratio is $(485/479\cdot 5)^2 = 1\cdot 023$. Thus practically all the observed increase of decrement could be accounted for if the power factor of the voltmeter were zero. In this instrument the valve cap had been removed and the grid was connected to the input terminal by a bare lead only about 3 cm long, otherwise so small a capacity as 5·5 $\mu\mu$F would not have been achieved. As a contrast, a similar voltmeter containing a similar valve, but in which the valve cap was intact and placed in a moulded ebonite valve-holder and the grid lead was long and heavy, may be quoted. This instrument had a capacity of 19 $\mu\mu$F, and increased the apparent resistance of the same circuit by 20 per cent. It may be calculated that the shunting effect of 19 $\mu\mu$F would increase the apparent resistance of the coil by 8·2 per cent, so the residue of 11·8 per cent must be attributed to bad power factor. From the stated values of L, C, f and δ, it may be calculated that an increase of 11·8 per cent would be produced by a resistance of 2 MΩ shunting the coil. It will also be found that the impedance of 19 $\mu\mu$F at the relevant frequency is 1/25·3 MΩ, so that the power factor of the voltmeter was 0·02. If the same process is applied to the rather inadequate difference observed for the capless valve, a power factor of 0·005 will be deduced: on the other hand, if the effect of the capacity had been ignored the voltmeter would have been held to have a power factor of 0·017. So it is clear that if the cap is removed and all due precautions are taken the power factor need not exceed 0·01, and if the cap is not removed it will be about 0·02.

Concerning the power factor of valve capacities, a paper* by G. W. Sutton should be consulted. Sutton finds, for valves without their caps, power factors which range from 0·003 to 0·02, and concludes that "it should be sufficient merely to remove the cap from an ordinary receiving valve for use as a valve voltmeter."†

When the system of Fig. 3 is used, conditions are made worse both because of the conductance of the grid leak and also because of the poor power factor inevitably associated with the grid leak and condenser. As an example, a carefully constructed voltmeter arranged as in Fig. 3, but with some switching arrangements on the filament side of the leak (of resistance 1 MΩ) had an apparent capacity of 31 $\mu\mu$F and raised the decrement of the test circuit from 1·8 per cent to 3 per cent. The enhanced capacity is due partly to some switching arrangements, but is partly inevitable from the earth capacity of the rather bulky grid condenser and leak connections. It may be found that the capacity of 31 $\mu\mu$F increases the apparent resistance of the coil by 13·8 per cent and so leaves a residue of 52 per cent to attribute to the grid leak and to power factor. It may be found that this increase would be produced by a shunt resistance of 0·5 MΩ, but this is due partly to the real resistance of the 1-MΩ leak, and so the power factor is equivalent to a shunt resistance of 1 MΩ. Combining this with the impedance of 31 $\mu\mu$F at 212 kilocycles per sec., the power factor of the voltmeter is 0·024. A voltmeter arranged as in Fig. 4 and having an unshunted grid leak of 1 MΩ had an apparent capacity of 25 $\mu\mu$F, and increased the resistance of the same test circuit by 25 per cent.

In general, therefore, a voltmeter will have a power factor between, say, 0·01 and 0·03, and the capacity will approach that of the electrodes only with the arrangement of Fig. 1. Probably the power factor is substantially constant at all frequencies, so to obtain a high value for the effective resistance at radio frequencies it is important to keep the capacity small. Viewed in this way it is more important to keep the capacity small than would appear from considering the ratio of this capacity to the other capacities of the system. In default of an actual measurement of resistance, we may estimate its value by arbitrarily assigning a power factor of, say, 0·02 to the measured value of the input capacity.

Grid current must flow in the arrangement of Figs.

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* "The Power Factor and Capacity of the Electrodes and Base of Triode Valves, with special reference to their use in Thermionic Voltmeters," *Proceedings of the Physical Society of London*, 1927, vol. 40, p. 14.

† See also Bibliography, (8), p. 592, Table 2.

3 and 4 in order that their purpose may be fulfilled, and it will flow in the arrangement of Fig. 1 when the peak value of the applied voltage exceeds the grid bias of about 1·2 V.

We may deduce the wave-form of grid current for the system of Fig. 1 from a static characteristic connecting the steady voltage between the terminals of the voltmeter and the resultant grid current. Such a static curve taken from a complete voltmeter of a well-known pattern,* typified by Fig. 1, is shown in Fig. 5. From this curve we may readily obtain the wave-form of grid current which results from a sinusoidal applied voltage. Four such wave-forms are exhibited in Fig. 6, and correspond respectively to an applied p.d. of 0·71, 1, 1·42 and 2 volts (all R.M.S.). The other half of the positive half-cycle is, of course, an exact replica of that shown by Fig. 6, and the current is zero throughout the negative half-cycle. If the ordinates of the curves of Fig. 6 are multiplied by the corresponding ordinates of their appropriate voltage wave, a curve of input power may be plotted: the effective resistance can then be deduced from the mean height of this curve taken over a whole cycle of applied p.d. This has been done for the four curves of Fig. 6, and Fig. 7 exhibits the effective resistance plotted as a function of the R.M.S. value of the applied p.d. The full-scale deflection for this pattern of voltmeter is usually fixed at 1·5 volts (R.M.S.), and hence the effective resistance for grid damping does not fall below 0·4 MΩ.

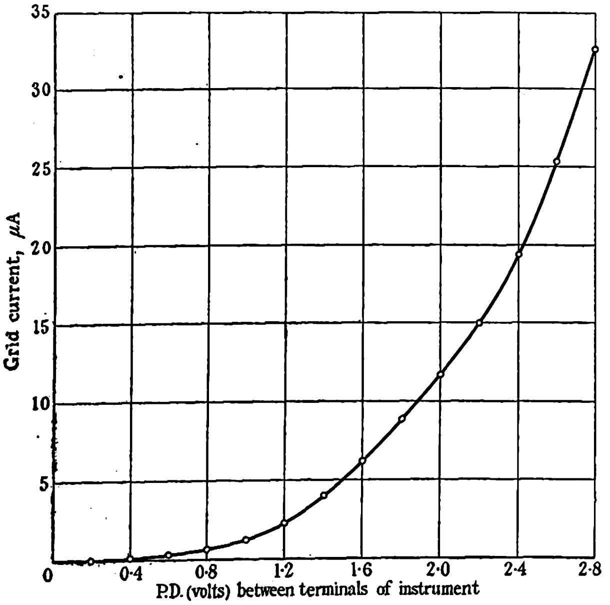

FIG. 5.

Though it is preferable to deduce the effective resistance from curves such as Fig. 5, the resistance can be measured by observing the decrement which the voltmeter adds to a tuned circuit. As an example of such a measurement may be quoted an experience from the same measuring circuit described previously. This had an inherent decrement of 1·8 per cent at 212 kilocycles per sec. With the voltmeter across the whole of the 1·14-mH coil the decrement was increased to 3·4 per cent, and from this it follows that the effective resistance of the voltmeter was about 0·31 MΩ. This figure is in fair agreement with the deduced figure of 0·4 MΩ; and also the measurement was not made on the same instrument from which Fig. 5 was obtained. Since the resistance is a function of the applied voltage, the voltmeter will distort slightly the top of the resonance curve of the circuit to which it is attached.

The effective resistance due to power factor will vary roughly as the reciprocal of the frequency, whereas the resistance due to grid current is independent of frequency. Assuming that the resistance at full scale is 0·4 MΩ for grid current and 14 MΩ for dielectric loss at 212 kilocycles per sec. (i.e. power factor of 0·01 with capacity of 5·54 $\mu\mu$F), we obtain the resistance-frequency values collected in Table 1.

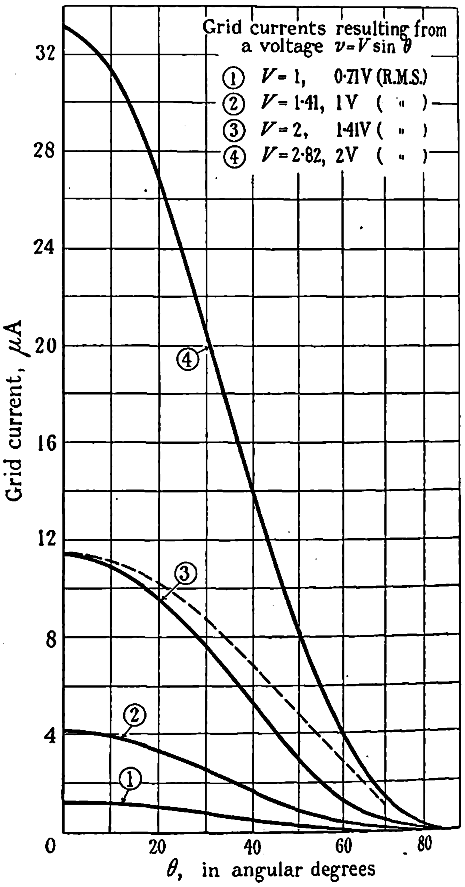

FIG. 6.

In addition to adding effective resistance the voltmeter also creates harmonic currents and it is of some interest to estimate their value. The fundamental amplitude can be obtained at once from the deduced values of effective resistance. Thus for the four curves of Fig. 6 the maxima of the fundamental components are respectively 11·3, 4·4, 1·23, and 0·435 μA when the positive peak values were respectively 33, 11·5, 4·2 and 1·2 μA, and the ratio of positive peak to fundamental amplitude does not differ much from 3. It is scarcely worth while to make a Fourier analysis of the curves of Fig. 6, but they approximate roughly to the form $y = (1 - \cos 2x)$ from $x = 0$ to $x = \pi$ and $y = 0$ from $x = \pi$ to $x = 2\pi$, and this is the equation of the dotted curve near (3) of Fig. 6. The Fourier series representing this curve is

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* Moullin Voltmeter, Pattern A, No. L22474.

$$y = \frac{1}{4} + \frac{4}{3\pi}\left(\sin x - \frac{3\pi}{16}\cos 2x - \frac{1}{5}\sin 3x - \frac{1}{35}\sin 5x \ldots\right)$$

According to this the second harmonic is 59 per cent and the third harmonic 20 per cent of the fundamental. If we had supposed the curves of Fig. 6 to be sine curves during the positive half-cycle and zero during the negative half-cycle, it may be shown that the second harmonic would have been 48 per cent and the third harmonic 8 per cent. Evidently the size of the second harmonic is not very sensitive to the exact shape of the curve, and we may assume roughly that the second-harmonic current through the voltmeter is about 50 per cent of the fundamental: from this we may estimate roughly the second-harmonic current in the remainder of the circuit.

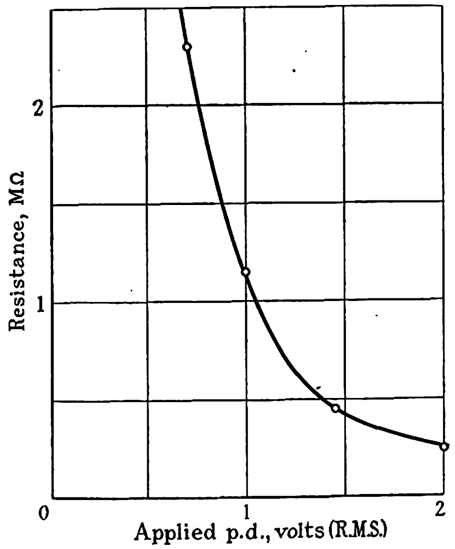

FIG. 7.

TABLE 1.

Frequency	λ	Resistance
kilocycles per sec.	m	MΩ
1	300 000	0·4
100	3 000	0·395
1 000	300	0·376
10 000	30	0·17
30 000	10	0·08

We now consider the effective resistance due to grid current in the arrangement of Fig. 3. A 6-volt filament battery will permit a negative bias of at least 1·4 volts. We shall assume that this has been provided and then there will be no grid current until the applied voltage exceeds 1·0 volt (R.M.S.). The current flowing in this condition has been studied closely by S. E. A. Landale,* who shows there that if the equation of the grid current curve is taken to be a parabola, then the mean grid current may be predicted accurately from 0·10 volt (R.M.S.) up to any value. Reference to this paper will show how to determine the effective resistance accurately, but we shall do this roughly for the voltmeter having the static characteristic represented by Fig. 8. Over the range covered in this figure we shall assume the grid-current curve to be straight, starting at 1·4 V and having a slope of 15 μA/V. Let us take a grid leak of 2 MΩ and a permanent bias of − 1·4 V. Consider Fig. 9, which shows a positive half-cycle of voltage of maximum value V. Grid current flows during that portion of the cycle only which is shown shaded. Let the mean grid current be I, then grid current will begin to flow at

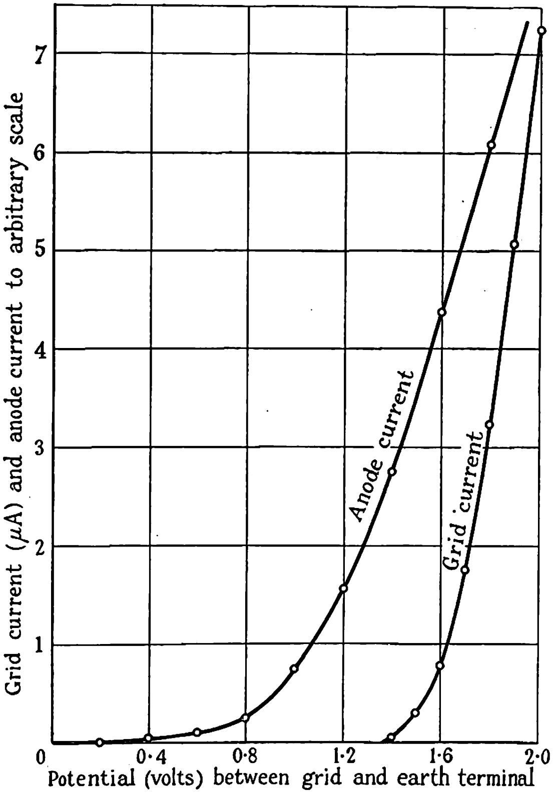

FIG. 8.

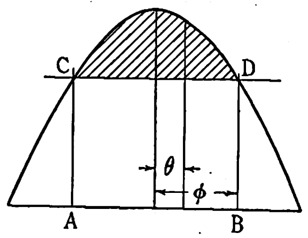

FIG. 9.

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* See Bibliography, (15).

the moment of the cycle when the voltage rises to a value AC given by the equation $RI + 1{\cdot}4 = V \cos \phi$. Now $I = Ab/2\pi$, where b is the slope conductance of the grid characteristic and A is the area of the shaded cap. From this we have

$$\frac{bRV}{\pi}(\sin \phi - \phi \cos \phi) + 1{\cdot}4 = V \cos \phi$$

Taking $b = 15\,\mu\text{A/V}$ and $R = 2\,\text{M}\Omega$, we have

$$\frac{30V}{\pi}(\sin \phi - \phi \cos \phi) + 1{\cdot}4 = V \cos \phi$$

On substituting in this $\phi = \pi/10$, $\pi/8$ and $\pi/6$, we find that $V = 1{\cdot}64\,\text{V}$, $1{\cdot}92$ V and $3{\cdot}3$ V respectively. The instantaneous grid current is $i = V(\cos \theta - \cos \phi)b$ and the instantaneous rate of working is

$$\begin{aligned} W &= iV \cos \theta \\ &= bV^2 (\cos^2 \theta - \cos \theta \cos \phi) \end{aligned}$$

$$\therefore \quad \frac{\int_0^\phi iV \cos \theta \,.\, d\theta}{\pi} = \frac{bV^2}{2\pi}\left(\phi - \frac{\sin 2\phi}{2}\right) = \frac{V^2}{2R}$$

where R is the effective resistance

$$\therefore \quad R = \frac{\pi}{b(\phi - \frac{1}{2}\sin 2\phi)}$$

Giving ϕ the values $\pi/10$, $\pi/8$ and $\pi/6$ we find that R has the values 10, 5 and $2{\cdot}3$ MΩ respectively. This effective resistance is in parallel with a grid leak of 2 MΩ, and so the net effective values are $1{\cdot}68$, $1{\cdot}43$ and $1{\cdot}07$ MΩ respectively.

In accordance with our previous working we shall take the effective resistance due to imperfect power factor as equivalent to $1{\cdot}25$ MΩ at 212 kilocycles per sec. (i.e. power factor of $0{\cdot}02$ with a capacity of 30 $\mu\mu$F) and so obtain the resistance/frequency values collected in Table 2.

TABLE 2.

Frequency	λ	Resistance (MΩ)		
		$V = 1{\cdot}64$	$V = 1{\cdot}92$	$V = 3{\cdot}3$
kilocycles per sec.	m			
1	300 000	1·68	1·43	1·07
100	3 000	0·1	0·93	0·73
1 000	300	0·22	0·22	0·20
10 000	30	0·026	0·026	0·026

Comparing this with Table 1 we see that the grid-leak system of Fig. 3 is better than the arrangement of Fig. 1, except for frequencies which make the effect of imperfect power factor all-important. This is a point worth careful notice and is of general application in radio work. Since we find ϕ is a small angle, we can approach the matter more simply and in a way which leads to a simple experimental method of determining the effective resistance. Since grid current does not start to flow until the voltage has reached the value $V \cos \phi$, and since $\cos \phi$ is very nearly unity, we can write

$$\frac{\int_0^\phi iV \cos \theta \,.\, d\theta}{\pi} \doteqdot \frac{V\int_0^\phi i \,.\, d\theta}{\pi} = VI$$

where I is the mean grid current.

$$\therefore \quad VI = V^2/2R$$

whence $$R = \frac{V}{2I} = \frac{V_{R.M.S.}}{\sqrt{2}I}$$

If, therefore, a curve connecting rectified grid current and R.M.S. voltage be plotted from experiment the effective input resistance is found by dividing the voltage by $\sqrt{2}$ times the corresponding mean grid current. For large applied voltages, say $V > 14$, the curve of grid current and voltage becomes a straight line which just does not pass through the origin, and then I approaches very closely to the value $I = V/R$, where R is the grid-leak resistance. This is very nearly true for all valves and all reasonable values of R.*

Then we have $$\begin{aligned} R &\doteqdot V/(2I) \\ &\doteqdot \tfrac{1}{2}R \end{aligned}$$

and so the effective resistance tends to a limiting value equal to half that of the grid leak. This simple formula must always under-estimate the effective resistance, because I is always a little less than V/R and not all the grid current flows at quite the full voltage V. Hence the effective resistance must be more than half that of the grid leak. Since this effective resistance is in parallel with the grid leak the net effective resistance must always be greater than $\frac{1}{3}R$. If, therefore, the voltmeter has a 3-MΩ grid leak the effective resistance cannot fall below 1 MΩ and must always be less than 3 MΩ. In parallel with this there is the effective resistance due to imperfect power factor, and this is a function of frequency, probably varying inversely as the frequency. S. E. A. Landale calculates (*loc. cit.*, Table 3) the effective resistance due to grid current for a certain D.E.L. 410 valve combined with a 1-MΩ grid leak and finds the values shown collected in Table 3.

TABLE 3.

Applied p.d.	Effective resistance
volts (R.M.S.)	MΩ
63·1	0·57
20·6	0·58
7·74	0·62
1·77	0·72
0·24	1·75

Table 3 shows that the limiting value of $\frac{1}{2}R$ is approached very slowly and that it is more appropriate to take a figure of about $0{\cdot}65$ than one of $0{\cdot}5$.

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* Bibliography, (11), p. 887; also Bibliography, (15).

The oscillograms shown in Figs. 10 (*a*) and 10 (*b*) are instructive in illustrating the foregoing analysis. Fig. 10 (*a*) shows the current flowing through the grid leak for an applied voltage of 12 volts (R.M.S.) and with a permanent bias of $-1\cdot 0$ V. The top edge of the thick black line is the zero of the record and the oscillograph spot would lie on this when no voltage was applied. It will be seen that the current flowing is sensibly a sine curve superposed on a steady current. A thin line has been drawn half-way between the tops and bottoms of the sine curve, and the distance between this line and the top of the black zero line represents the mean rectified current which we have called I. Measurement on the oscillograms shows that I is 86 per cent of the maximum superposed alternating current, and this illustrates the truth of our approximate equation $I = V/R$. Grid current would flow during those portions of the sine curve which lie above the zero line. Fig. 10 (*b*) is an oscillogram of the current entering the condenser from the source, that is, the input current to the voltmeter, and the mean value of this current is zero. If the grid current were zero this would be a sine curve equably disposed above and below the zero line, and if a grid-bias battery of voltage RI had been placed between the grid leak and the filament the curve would still have been a sine curve disposed equably above and below a zero line depressed an amount proportional to RI. In reality, spurts of grid current flow and are shown in Fig. 10 (*b*) by the high peaks above the zero line; the duration of these peaks corresponds to the duration of the shaded cap in Fig. 9. To obtain the requisite sensitivity (the currents being but a few microamperes) it was necessary to use an Einthoven galvanometer of relatively low natural frequency; consequently the wave-form of the peaks is not faithful and is distorted by the oscillograph.* Rough measurements from Fig. 10 (*b*) show that the grid current lasted for about one-sixth of the whole cycle, and this corresponds to $\phi = 30°$ in Fig. 9.

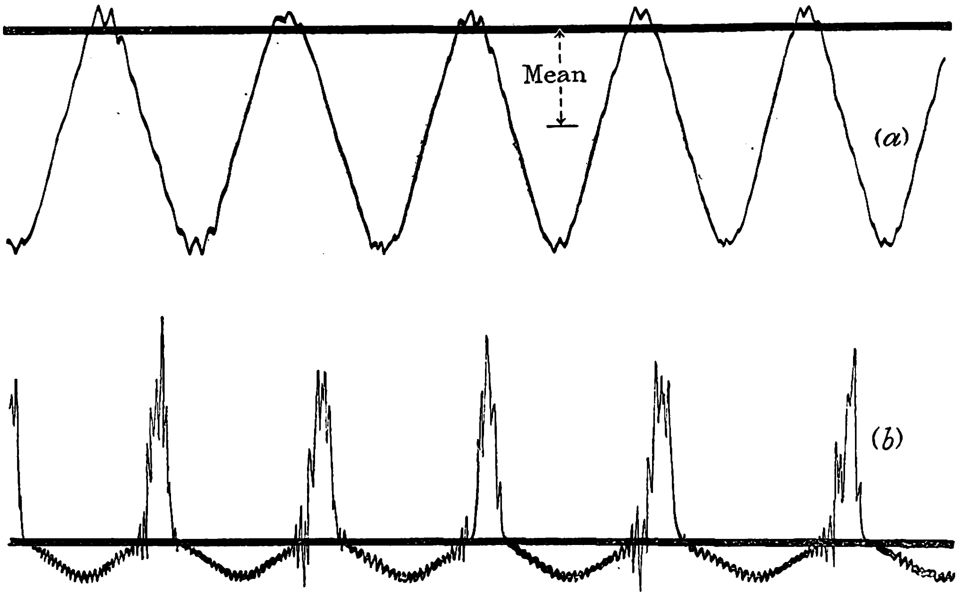

FIG. 10.

To make a rough estimate of the harmonic currents produced by the voltmeter, we shall assume the wave-form of the current passing from the grid into the filament to be that shown in Fig. 11. The Fourier series which represents this is

$$y = \frac{a\pi}{144}\Big\{1 + 3\cdot 25 \sin x + 13 \cos 2x - 13\cdot 3 \sin 3x + 6\cdot 5 \cos 4x - 3 \sin 5x \ldots\Big\}$$

where, of course, $a\pi/144 = I \doteqdot V/R$.

According to this, at the moment of maximum voltage there is a fundamental component of current equal to $3\cdot 25\ V/R$ entering the grid and passing to the filament, and a fundamental component of current equal to V/R entering the grid leak and passing to the filament. The fundamental component entering the condenser is therefore equal to $4\cdot 25\ V/R$ and this leads to an effective resistance of $0\cdot 236\ R$. This value is less than our lower limit of $\frac{1}{3}R$, partly because, in reality, ϕ is much less than 30°. According to the assumed wave-form the second harmonic will be $13/4\cdot 25 = 3$ times the fundamental, the third harmonic will have about the same value and the fourth harmonic will be about $1\frac{1}{2}$ times the fundamental. We may therefore regard the voltmeter as being roughly equivalent to a resistance $\frac{1}{4}R$ and taking a second- and third-harmonic current of value about $9\ V/R$.

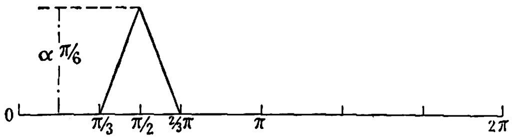

FIG. 11.

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* The author is indebted for these oscillograms to the courtesy of the research department of Messrs. Cambridge Instrument Co., Ltd., London and Cambridge.

We shall now consider the grid current taken by the arrangement of Fig. 4, and this system presents much less difficulty than either of the other two. If the voltage is applied to the grid in Fig. 4 through a resistance of the order of 1 megohm, the valve itself adds to this resistance a negligible amount when the grid is positive and an infinite amount when the grid is negative. This is capable of very definite experimental proof as follows: Let a curve be plotted connecting the grid current with the steady voltage applied between the terminals A B. The result is a straight line which misses the origin by only a small fraction of a volt.* The slope of this line will differ inappreciably from the resistance of the grid leak. (In the example quoted above, the voltage-drop across the valve was in general less than 2 per cent of the applied p.d. when the grid leak had a resistance of 1·65 MΩ.) Consequently the grid current will be $i = (V/R)\sin pt$ during the positive half-cycle and zero during the negative half-cycle. The static curve is, of course, sufficient to substantiate this, but a further check can be obtained from an a.c. measurement as follows. The maximum grid current will have the value V/R and the mean during a half-cycle will be $2/\pi$ of this, and so the mean during a whole cycle will be $I = V/(\pi R)$. An example of such a test, in which R was 1·65 MΩ, is shown by the figures given in Table 4.

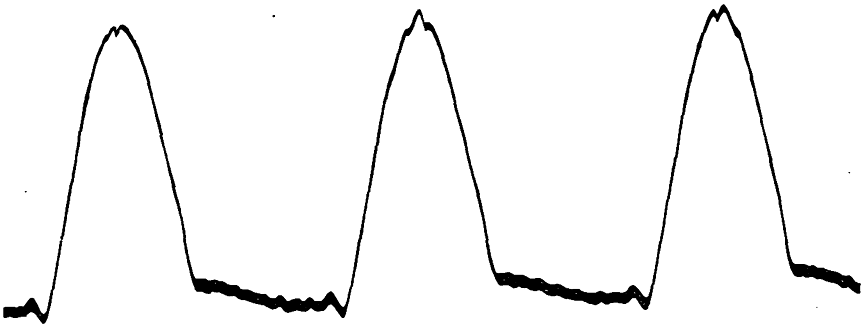

FIG. 12.

The oscillogram of Fig. 12 shows the wave-form of grid current for 100 volts (R.M.S.), and the half-sine curves followed by blank spaces are apparent. The dark line which falls below the zero is due to the overshoot of the underdamped Einthoven fibre.

We obtain the effective resistance $R_{eff.}$ as follows.

$$\text{Mean power} = \frac{\int_0^\pi (V^2/R)\sin^2 x\,dx}{2\pi}$$

$$= \frac{V^2}{4R} = \frac{V^2_{\text{R.M.S.}}}{2R}$$

$$\therefore\quad R_{eff.} = 2R$$

The harmonic analysis of the grid current is here very definite and is

$$i = \frac{V}{\pi R}\left[1 + \frac{\pi}{2}\sin pt + \frac{1}{8}\sin 3pt + \frac{1}{24}\sin 5pt + \frac{\sqrt{5}}{3}\sin(2pt + \lambda_2) + \frac{\sqrt{5}}{15}\sin(4pt + \lambda_4)\right]$$

The voltmeter therefore behaves as a constant resistance of value $2R$ and passes a second-harmonic current of amplitude $0{\cdot}235\ V/R$ and higher harmonics of negligible amplitude.

(5) USE OF THE ANODE CURRENT AND CONSIDERATIONS WHEN TO USE EXTRA BATTERIES.

Grid current flows in each of the three systems considered, and in that of Figs. 3 and 4 it is essential for the purpose of extending the range beyond that suitable for Fig. 1. If, therefore, there is a rectified grid current, should it not be used to actuate the indicating galvanometer? This turns very largely on the sensitivity of the galvanometer to be used as the indicator, and also partly on the desired scale shape. The most sensitive portable galvanometers require about 20 μA for full-scale deflection, and the a.c. voltage required to give this rectified current will dictate the range of the most sensitive voltmeter we can make. Referring to Fig. 5, we may estimate that 2 volts (R.M.S.) would produce a mean grid current of about 8 μA, and 1·4 volts (R.M.S.) a mean grid current of about 2·5 μA. This system is unsuitable for voltages above 1·5 volts (R.M.S.) because the input resistance then becomes inconveniently small, so that if the grid current is indicated we could not get more than about 15 per cent of the available deflection. The rectified anode current is, however, much larger than the rectified grid current, and for the bright-filament valve to which Fig. 4 refers full-scale deflection may be obtained for 1·5 volts (R.M.S.). In this case, therefore, it is essential to use the anode current. Conditions would not be much improved by using an anode battery of considerable voltage. If this were provided, the anode current with no applied a.c. voltage would be considerable and a balanced

TABLE 4.

Applied p.d.	Measured value of I	Deduced value of R
volts (R.M.S.)	μA	ohms
240	65	1·66
200	55	1·64
180	48	1·68
80	21	1·70
46	12	1·71

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* For an example of such a curve see Bibliography, (11), Fig. 8.

system would have to be used. The rectified anode current (μA) would be given approximately by the equation $I = 16\ V^2$* and so there would be about 35 μA for 1·5 volts (R.M.S.) applied. We could then obtain full-scale deflection for 1·1 volts instead of 1·5 volts, but the scale would be of the square-law type, which in general is inconvenient. There would be but a trifling increase of sensitivity and considerable loss of portability and convenience.

Let us turn now to the arrangement of Fig. 3. Since the negative bias automatically increases with the applied voltage, it will be still more necessary to use the anode current with Fig. 3 than with Fig. 1. Since the bias grows progressively with the applied voltage, ultimately there will result an anode current which flows during only a portion of the positive half-cycle, this portion being slightly wider than the shaded cap of Fig. 9. This is illustrated by the oscillogram of Fig. 13, which shows the spurts of anode current with an applied p.d. of 12 volts. The combination of this effect with the effect illustrated by Fig. 2 causes the rectified anode current to reach a limiting value for an applied voltage of about 70 volts (R.M.S.). But for voltages of the order of 70, the rectified grid current will be ample to indicate directly since it is sensibly equal to the maximum of the applied voltage divided by the grid-leak resistance. Thus with a 3-MΩ grid leak (giving the voltmeter an effective resistance of about 1 MΩ) full-scale deflection of 20 μA will result from an applied p.d. of 42 volts. The scale will be accurately linear and will be useful for voltages above about 5. If we are content with a leak of 1 MΩ (effective resistance $\frac{1}{3}$ MΩ) we can obtain a full-scale deflection for 14 volts and the scale will be useful for voltages greater than about 1·5. The system of Fig. 3, but with the galvanometer in series with the grid leak, therefore becomes naturally the next step of the range to that of Fig. 1. The decision of when to use grid current in preference to the anode current is associated with the desired input resistance, but it is probably correct to say that the grid current should be used when measuring voltages greater than about 5. Using dull-filament valves in the arrangement of Fig. 3, it is convenient to make a two-range voltmeter having a range of 0–5 volts with the galvanometer in the anode circuit, and a range of about 0–30 with the galvanometer in the grid circuit.

Is it any advantage to provide additional batteries for the system of Fig. 3? If the voltmeter is to be unaffected by steady voltages—and this was one of the desirable attributes postulated—the input system of Fig. 3 must be used. To obtain the greatest possible input resistance, grid current must be prevented by adding a grid bias battery of voltage exceeding the peak value of that applied. This battery will increase the input resistance from $\frac{1}{3}$ R to R for acoustic frequencies, but for very high frequencies the effect of imperfect power factor will swamp the advantage gained. We shall, therefore, surely decide to abandon a separate grid-bias battery. If grid current is permitted, the decrease of mean grid potential is roughly equal to the peak value of the applied voltage, and this is substantially true even down to 0·3 volt (R.M.S.).* With an anode battery of adequate voltage there need be no rectification of anode current and the decrease of mean anode current will be g times the decrease of grid potential, where g is the mutual conductance of the valve. Taking g as 2 mA/V it should be possible to get a decrease of anode current of about 2·8 mA for an applied voltage of 1 volt (R.M.S.) and the scale will be approximately linear. This is in striking contrast with the previous best figure of 16 μA for 1 volt (R.M.S.) with a square-law scale. The initial anode current will, however, now be several milliamperes and a balanced system is imperative. Also this arrangement is not capable of an extensive range, for the linear portion of the anode-current characteristic will soon be exceeded and the mean grid potential will correspond to zero anode current. Rectification of anode current will counteract the decrease of mean grid potential and there will be some applied voltage for which the indicator readings will commence to reverse. This condition can be delayed by an increase of anode battery, but it cannot thereby be postponed indefinitely.

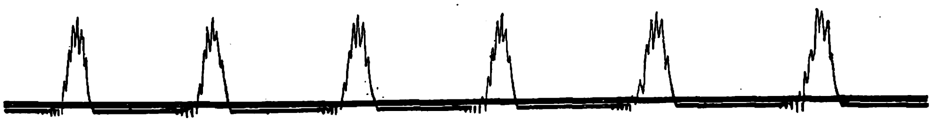

FIG. 13.

So it seems that additional batteries are advantageous and worth while only for voltmeters in which full-scale deflection is to be produced by a small fraction of a volt. If a full-scale deflection for 1·5 volts (R.M.S.) is sufficient sensitivity, then it is both unnecessary and very inconvenient to use any batteries other than the 6-volt accumulator for the filament. Coming now to the arrangement of Fig. 4, the effective resistance of which is 2 R and in which $I = (\sqrt{2})V/(\pi R)$, it will be sufficient if R is 1 MΩ and then we shall have $I = 20\ \mu$A for $V = 45$ volts, and the grid current should be indicated for voltages greater than about 5. There are some advantages, in respect of scale shape, in indicating the anode rather than the grid current; these are discussed in the appropriate section. If a high-voltage anode battery is used with this system, there would result sinusoidal decreases of anode current and a relatively small increase having a complex wave-form. The mean decrease of anode current would be given approximately by $I = (\sqrt{2})Vg$. This relation would hold over a limited range only. For very small applied voltages the decrease would not vastly dominate the increase of anode current, and for values of V of 1 or 2 volts the anode current would be decreased to zero before V had reached its negative maximum. The scale would there fore be linear over a limited range, and in this range its slope could be about 1 mA per volt applied. The arrangement would require a balanced system but might be useful in very special circumstances. As a general purpose voltmeter there is nothing to be gained by using an anode battery with the system of Fig. 4.

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* See MOULLIN: "Radio-Frequency Measurements," chap. 2, p. 32.

* See Bibliography, (15).

(6) FREQUENCY ERROR, PERMANENCE OF CALIBRATION AND EFFECT OF TEMPERATURE.

The indications of the system of Fig. 1 are independent of frequency up to a very high value, because the time of flight of an electron from the filament to the grid or anode is short compared with a micro-second. The lower limit of frequency is imposed by the periodic time of the galvanometer movement. If, therefore, the voltmeter is calibrated at, say, 50 cycles per sec. the calibration probably remains unaltered up to many millions of cycles per second. It is not easy to make a direct test of the validity of this statement, both because electrometers of like sensitivity are not readily arranged and because their readings are not necessarily correct at the upper end of the present spectrum of frequency. A direct comparison has been made with an electrometer for frequencies up to 1 megacycle per sec.* The accuracy of comparison was such that a disagreement of 1·5 per cent could have been detected and this was not observable at any frequency up to 10^6 cycles per sec. Fig. 14 shows a resonance curve taken at a frequency of $30 \cdot 5 \times 10^6$ cycles per sec. ($\lambda = 9 \cdot 83$ m). The ordinates are the readings of a voltmeter coupled loosely to the measuring circuit, and the abscissæ are the values of the total circuit capacity. Inspection of the shape of the resonance curve shows that relative calibration has remained correct up to frequencies of over 30 megacycles per sec. Since the absolute value of the calibration has remained correct over a change of frequency from 50 to 10^6 cycles per sec., it has probably remained absolutely correct in the change from 10^6 to 30×10^6 cycles per sec., since we have experimental proof that the relative calibration has remained unchanged. We may regard such a voltmeter as the standard at such frequencies, for the capacity of an electrometer would often prohibit its use and the inductance of its suspension would probably vitiate its readings.

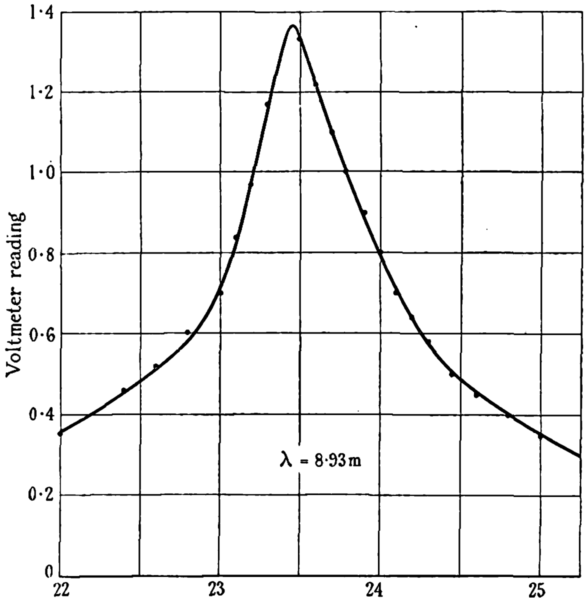

FIG. 14.

If these voltmeters are used at frequencies of the order of 30 megacycles per sec. a deflection may be found when the terminals are short-circuited. Apparently this is due to a voltage induced in the grid-bias coils, and the deflection is removed by shunting them by a suitable capacity. Voltmeters so provided may be used with as little care at 30 megacycles per sec. as at 100 kilocycles per sec.

The calibration of the system of Fig. 3 is also independent of frequency: so far as the response of grid or anode current to change of grid potential is concerned this follows from the tests of the system of Fig. 1. We have then to consider only whether the a.c. voltage applied to the grid remains the same fraction of that applied between A and B at all frequencies. This condition is fulfilled by making the impedance of the grid condenser sufficiently small at the lowest frequency to be used: as the voltmeter and grid leak in parallel have an effective resistance $\frac{1}{3}$ R we must so arrange C that $\frac{1}{3} R >> 1/(pC)$. If we make $\frac{1}{3} R = 5/(pC)$ at, say, 50 cycles per sec., then the calibration made at 50 cycles will be 2 per cent low at an infinite frequency. If $R = 3$ MΩ this condition is fulfilled when $C = 0 \cdot 016\ \mu$F. A voltmeter of the pattern typified by Fig. 1 was connected in parallel with one typified by Fig. 3 and the readings of the two instruments were compared for different frequencies up to 6×10^6 cycles per sec. No difference was detectable at a deflection of 1·5 volts. In comparing two voltmeters connected in parallel at frequencies of the order of 6 megacycles per sec., due attention must be paid to the inductance of the lead to the grid-leak instrument, for this may easily cause the p.d. applied to the grid to differ from that applied to the other instrument, even though the two are separated by but a few inches.

The distributed capacity of the resistance R makes the calibration of instruments of the pattern typified by Fig. 4 dependent on frequency. At very high frequencies this distributed capacity will be sufficient to convert Fig. 4 effectively into Fig. 3 and thus increase the mean grid current from $I = (\sqrt{2}) V/(\pi R)$ to $I = (\sqrt{2}) V/R$, and a direct test shows that the factor π has sensibly been reached at a frequency of 2 megacycles per sec. There will be an intermediate range of frequency where the correction factor may behave in a complicated manner; however, this pattern of voltmeter is not intended for use at frequencies above a few kilocycles per second.

The permanence of calibration depends on the permanence of the valve characteristic and also on that of the grid leak (when there is one). The patterns of voltmeter typified by Figs. 3 and 4 are almost independent of the valve if this is used as a diode: this follows because $I = (\sqrt{2}) V/R$ and $I = (\sqrt{2}) V/(\pi R)$ respectively. Also it is capable of simple experimental proof, for it will be found that the calibration is independent of filament current over an enormous range: the range is so great that it is superfluous to provide a test-point condition and it is sufficient to use an accumulator of the correct nominal voltage. For these patterns, ageing of the valves need not be considered, but the permanence of calibration is directly proportional to the permanence of the resistance of the grid leak. Modern grid leaks are very permanent in value but have an appreciable temperature coefficient, and for this reason it is difficult to guarantee an absolute accuracy of closer than ± 2 per cent. It should, however, be noticed that even large changes of grid-leak resistance will not alter the relative calibration of the scale.

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* See E. B. MOULLIN: "Radio-Frequency Measurements," chap. 2, p. 38, Table 3.

The permanence of calibration of the pattern typified by Fig. 1 does depend on the permanence of the valve characteristic, but experience shows that the calibration remains permanent for many years, provided the valves are aged for a few hours before calibration and are run with less than the rated filament current. A certain voltmeter tested by the author seven years after calibration was found to be unchanged between 1·5 V and 0·4 V, but below this the calibration had changed slightly. Possibly the satisfactory permanence of calibration is due partly to the method of adjusting the instrument zero by bringing the anode current to a predecided initial value: perhaps the filament current necessary to produce this increases by a very small amount as the valve gets older, but if this be so there is evidently no appreciable change of shape of the characteristic. When the anode current is indicated in the systems of Figs. 3 and 4, then calibration will depend on the permanence of the valve.

The effect of temperature has been studied by enclosing the voltmeter in a large case in which the air could be raised to various temperatures between + 8° C, and + 40° C. A given air temperature was maintained for a considerable period of time and it was then assumed that the whole voltmeter had reached the air temperature. An instrument typified by Fig. 3 and used as a diode was found to have a mean temperature coefficient, between 14·5° C. and 40° C., of 0·23 per cent per deg. C. An instrument typified by Fig. 4 and used as a triode was found to have a mean temperature coefficient, between 8° C. and 40° C., of 0·15 per cent per deg. C. A temperature coefficient of about + 0·2 per cent per deg. C. is probably about an average value for grid-leak voltmeters, and therefore their absolute accuracy should be reliable to ± 2 per cent if they are not exposed to a temperature range of more than ± 10 deg. C. from 15° C. Voltmeters typified by Fig. 1 have no measurable temperature coefficient.

(7) Dependence of Calibration on Wave-Form.

It is usual for an a.c. voltmeter to read the R.M.S. value of a wave of any shape, but a thermionic voltmeter does not generally do this. If the equation relating the instantaneous current i through the valve with the instantaneous value v of the applied voltage is $i = bv + cv^2$, then the mean current $I = cV^2$, where V is the R.M.S. value of the applied voltage. Valve characteristics approximate to a parabola over a very limited range, and so at best the voltmeter reading will be only roughly proportional to the R.M.S. applied voltage. If the system of Fig. 1 is provided with a suitable anode battery the indicator readings will be proportional to the R.M.S. voltage if the peak value does not exceed 2 or 3 volts,* but with ordinary valves it is difficult to extend this range very much. It must be recognized that ordinary thermionic voltmeters do not measure the R.M.S. value and it is merely fortuitous good fortune if their readings are approximately proportional thereto. It so happens that the indications of the system of Fig. 1, when employed with bright-filament valves, are not very sensitive to wave-form so long as the wave-form is not extraordinarily non-sinusoidal, for example, not more so than that ordinarily obtained from dynamos or from the magnetizing current of saturated iron. A test of this is recorded† on a wave having an in-phase third harmonic of about 30 per cent, and then the true R.M.S. value was about 1 per cent greater than that recorded by the voltmeter. A test of the curve connecting anode current and applied d.c. voltage shows that the equation is sensibly parabolic over the range ± 1 V, and so the convenient property of this pattern is explained. If the applied wave contains even harmonics the positive and negative peaks are likely to have different values, and then a reversal of connections to the voltmeter will generally yield different readings and little useful information can be deduced from either. As an example, a voltmeter of the type of Fig. 1 was connected across a resistance to measure the input current to a voltmeter of the type of Fig. 3. With the valve in type 3 switched off, the voltmeter reading was 0·52 V, from which it was deduced that the grid-leak resistance was 1·64 MΩ (the value measured by a bridge was 1·63 MΩ). With the valve switched on, this reading became 1·4 V or 1·62 V, according to the sense of connection. Reference to the oscillogram, Fig. 10 (*b*), will at once explain the difference of readings but does not suggest how to interpret them.

If the anode current is indicated in the system of Fig. 3, the reading must be very sensitive to wave-form and quite uninterpretable in terms of R.M.S. value. The anode current flows only during portions of a cycle (see oscillogram, Fig. 13), and the indications will be some function of the shape of the crest of the wave and quite independent of the shape of its main portion.

The mean anode current in the arrangement of Fig. 4 will also be dependent on wave-form, but is not nearly so dependent as in Fig. 3 because it will flow during the whole of the positive half-cycle of applied voltage. Experiment shows that the calibration is roughly independent of wave-form for such wave-forms as are ordinarily produced by dynamos. Thus a wave-form having an 8 per cent fifth harmonic‡ produced a deflection 1·8 per cent less than was produced by a sinusoidal voltage of the same R.M.S. value. But a wave-form having an anti-phase third harmonic of 34 per cent and an anti-phase fifth harmonic of 8 per cent § produced a deflection too small by 5 per cent. The shape of the scale makes the fractional change of voltage indicated greater than the fractional change of deflection. Experiment shows that the relative values of the calibration are unaffected by wave-form.

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* See Moullin: "Radio-Frequency Measurements," chap. 2, p. 32, Fig. 21, and G. W. Sutton: *loc. cit.*, Fig. 3.

† See Moullin: *Ibid.*, p. 36, Fig. 29.

‡ See Moullin: *Journal I.E.E.*, 1928, vol. 66, p. 891, Fig. 11b.

§ See Moullin: *loc. cit.*, Fig. 11a.

When, however, the systems of Figs. 3 and 4 are used as diodes, such voltmeters measure specified properties of the wave-form and yield more information than if they measured the R.M.S. value. The relation $I = \sqrt{2}V/R$ for Fig. 3 shows that the mean grid current is proportional to the peak value of a sine curve, and it is evident from a consideration of Fig. 8 that it will be roughly proportional to the peak value of any wave-form. This has been examined experimentally in a paper by the author,* where it is shown that the readings of several very complex wave-forms are proportional to the peak value to an accuracy of better than ± 3 per cent. These experiments are supported by a rough analysis, but a more exact analysis† shows that the voltmeter must measure the peak value with an accuracy even greater than that deduced by experimental methods.

The system of Fig. 4 necessarily measures the mean value of a half wave, and this follows from the linear relation between grid current and applied d.c. voltage. The only cause of error would be from a higher harmonic of frequency sufficient to convert Fig. 4 effectively into Fig. 3, but as a given harmonic contributes to the mean in the inverse ratio of its order number the magnitude of this possible error is very small.

Sometimes the inability to read R.M.S. values with a thermionic voltmeter is annoying, and sometimes it is helpful. The times when it is annoying are very few. Low-range voltmeters are required mostly at radio frequencies where the available power and permissible capacity are small; at radio frequencies most measurements are made in resonant circuits having a low decrement and these necessarily filter away harmonics to very minute values. If a high-range voltmeter (say for more than 40 V) is being used at acoustic frequencies, presumably it is preferred to an electrometer because it has the power of indicating distortion of wave-form. To sum up, therefore, we may say that "wave-form error" is very seldom troublesome or deceptive so long as thermionic voltmeters are operated by those who understand their properties and characteristics.

(8) The Scale Shape and Multi-Ranging.

The most desirable shape of scale depends on the purpose for which the voltmeter is required. If it is used mainly as an indicator of a maximum, then a square law is convenient, but the useful range is very limited. To obtain a wide range on one scale it is preferable for the scale to be open at the start and to close up towards the top. The information contained in this paper should suffice to show how to deduce from the static characteristic the scale shape for any type of thermionic voltmeter. The scale shape for voltmeters of the type of Fig. 1 is roughly parabolic, but the openness of the upper part of the scale can be curbed by inserting a high resistance in the anode circuit; by this means about 50 per cent of the scale can be made linear. The same result can be achieved more elegantly and usefully by the reflex system of Medlam and Oschwald,* illustrated diagrammatically in Fig. 15. Here the anode-circuit resistance R not only lowers the anode potential but also provides an increasing negative bias to the grid. It should be noticed that this system cannot be used without a separate anode battery, and it will be subject to wave-form errors roughly corresponding to Fig. 3 used as a triode. When the systems of Figs. 3 and 4 are used as triodes the scale closes towards the top. The range 0–60 V is readily covered on two scales: the low range is useful from 1 to 4 V, and the second scale has an overlap on the first of 15 per cent of the maximum deflection. This arrangement is undesirable if wave-form error is important, and then it is best to achieve the second scale by using the valve as a diode. The first scale then remains 1–4 V and the second scale is linear from 0 to 16 V, with an overlap of the first of about 10 per cent of full deflection.

The system of Fig. 4, when used as a triode, is very convenient for obtaining an enormous range by simply shunting the galvanometer. The range 0–200 V may be covered in three stages, viz. 0–4–20–200 V; the overlap between the first and second range is 35 per cent of full deflection and between the second and third is 25 per cent. Width of range in three stages is the only reason for using the arrangement of Fig. 4 as a triode. When the arrangements of Figs. 3 and 4 are used as diodes the calibration is linear.

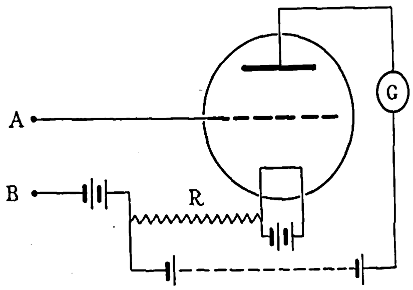

Fig. 15.

The convenience of a voltmeter is enhanced enormously if the scale is engraved directly and so obviates an appeal to a calibration chart. It is undesirable to have more than two scales on one dial, and it is desirable that a change of range can be charted by a constant multiplying factor over the whole of at least one scale. It can be shown that this condition is fulfilled only if the equation connecting deflection θ with applied voltage V is of the form $\theta = AV^n$, where the index n has any real value. It is therefore possible to test whether one scale can be used for two ranges by making a logarithmic plot of θ and V and choosing that portion, if any, which becomes a straight line. It happens that the arrangement of Fig. 4 used as a triode does conform very closely to this condition over the range from about 5 to 200 V. Of course the scale does not conform precisely to the equation $\theta = AV^n$, and it is impossible to use one scale for two ranges in a voltmeter which has to meet an overall accuracy guarantee. However, the correspondence is quite close enough for many practical purposes, and the possibility of obtaining an enormous range, at the sacrifice of some accuracy, is worth remembering. We are confronted by the same difficulty when using the systems of Figs. 3 and 4 as diodes, for though the calibration is linear, it is a line which does not pass through the origin. By experiment with either instrument we have $\theta = a(-5 + V)$ from 10 volts upwards.* Suppose that θ is full scale for 100 volts and the galvanometer is shunted so that it is again full scale for 200 volts. If we now apply 100 volts we shall obtain a deflection corresponding to 51·2 V, so the two scales disagree at that point by 2·4 per cent. Alternatively, if we make 100 volts applied to the upper range produce the deflection marked 50 on the dial, then 200 volts will produce the deflection marked 97·5 V; the instrument will then be 2·5 per cent low at full scale. If the two ranges are made to agree at about $\frac{3}{4}$ scale and if the high range is never used unnecessarily, then we could use only one scale and never have an error of more than ± 1·2 per cent. Such a makeshift would be intolerable in a voltmeter which had to meet a general guarantee of accuracy, but it would be no serious disadvantage to an intelligent operator.

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* *Journal I.E.E.*, 1928, vol. 66, p. 893, Table 6.

† See S. E. A. Landale: *Proceedings of the Cambridge Philosophical Society*, 1929, vol. 125, section 4.

* Bibliography, (10), p. 664.

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* Bibliography, (11), Figs. 3 and 9.

RECENT DEVELOPMENTS IN DIRECTION-FINDING APPARATUS.

By R. H. Barfield, M.Sc.(Eng.), Associate Member.

(*Paper first received 8th December,* 1929, *and in final form* 3*rd March,* 1930; *read before the* Wireless Section *2nd April,* 1930.)

Summary.

Part (1) describes a four-aerial direction-finding system erected at a site near the Radio Research Station, Slough, and gives details of the tests carried out on this apparatus at wavelengths of 300 to 600 m. The system is based on the Adcock principle, but a modification has been introduced to correct for the asymmetry of the aerial system with respect to its upper and lower portions which is unavoidable if the operating hut is at ground-level.

In the first test the performance of the new direction-finding system was compared with that of a rotating-loop direction-finder over a prolonged period which included conditions of most severe "night effect." In the second test a calibration of the system was made by means of a transmitter attached to a kite which provided a source of downcoming waves of known angle of incidence and polarization.

The results of the tests show the new system to be considerably superior to the closed-loop system for conditions of "night effect." They indicate, however, a residual instrumental error of the system in the presence of downcoming waves. Finally, a further modification of the system by which it is hoped this will be eliminated is described.

Part (2) describes two distinct types of portable short-wave direction-finding apparatus and gives details of the methods by which they were tested and compared under working conditions at wavelengths of 12 to 60 m.

The first instrument is of the totally-screened closed-loop type.

The second instrument is of the rotating Adcock type consisting of a single pair of spaced vertical aerials pivoted about a vertical axis.

The tests described are divided into four sections:—

(*a*) Tests for instrumental error with a local transmitter situated first on the ground and then elevated 40 ft. above the ground with its aerial at various angles to the vertical to give waves of varying polarization.

(*b*) Tests on the effects of the immediate surroundings of the receiver.

(*c*) Direction-finding observations on the "ground ray" of a transmitter up to the maximum distance at which the ray is detectable.

(*d*) Long-range tests at which only downcoming waves were being received.

Test (*a*) showed the Adcock to be much superior to the loop in the presence of downcoming horizontally polarized waves, while (*b*), (*c*) and (*d*) show that for observations on the ground ray both instruments are equally satisfactory and that with due precaution in the choice of a site their performance is much the same as that of longer-wave apparatus. For observations just outside the range of the ground ray both systems are equally useless, while at greater ranges (beyond the "skip distance") the results again demonstrate the superiority of the Adcock to the loop.

It is shown that the results generally confirm the conclusions with respect to the nature of the propagation of the waves arrived at by Eckersley [*] from somewhat similar experiments.

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Part 1. MEDIUM WAVES (300 TO 600 M).

(1) Introduction.

It is well known that direction-finding apparatus based on the closed-loop principle such as the Bellini-Tosi single- or double-coil systems—in fact all existing systems which are employed in a practical capacity as an aid to marine or aerial navigation—are subject to a very serious inherent limitation or defect. They determine not the direction of travel of the waves but only that of the resultant horizontal magnetic field of the waves. When it is a question of taking measurements on the ground ray of a wave alone these two directions are at right angles, but when, on the other hand, it is a question of receiving waves which have travelled via the Heaviside layer, some of which arrive from the upper atmosphere with horizontally polarized components, there is no necessary relationship between them. In fact these systems are entirely unreliable as direction-finders under such conditions.

The first attempt to produce an instrument not subject to this limitation was made in 1916 by Adcock,[*] who pointed out that a directional receiving system consisting of spaced vertical aerials should theoretically determine the true direction of travel under all circumstances. Adcock actually constructed such an apparatus and demonstrated the improved nature of the results to be obtained with such a system, though this work was not actually published until after the lapse of several years.

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[*] T. L. Eckersley: "Short-Wave Wireless Telegraphy," *Journal I.E.E.*, 1927, vol. 65, p. 600.

[*] F. Adcock: "Improvement in Means for Determining the Direction of a Distant Source of Electromagnetic Radiation," British Patent No. 130490 (1919). *See also* R. L. Smith-Rose and R. H. Barfield: "The Cause and Elimination of Night Errors in Radio Direction-Finding," *Journal I.E.E.*, 1926, vol. 64, p. 831.

During this time attempts were being made at Slough to produce a direction-finder free from the defect described above, which might be conveniently designated " horizontal effect "—a direction-of-travel-finder as distinct from a direction-of-field-finder.

A system based on Adcock's principle was in due course produced which gave almost complete freedom from " horizontal effect." The system, however, relied for its success on the suspension of the hut containing the operator and apparatus at a height of some 20 ft. above the ground. An account of this work is given in an earlier publication by Dr. Smith-Rose and the author.

The subsequent work described in this paper has been devoted to the development of the Adcock principle as a practical system for medium waves by removing the drawback of an elevated hut, and to the construction of portable apparatus (described in Part 2). A considerable amount of attention has been devoted to testing and calibrating.

(2) Description of Balanced Adcock System.

The system differs from that described in the earlier paper[*] in three respects:—(1) The hut containing the apparatus is on the ground, (2) balancing condensers are inserted in the earth leads to compensate for the lowering of the hut, and (3) the aerial system is supported by a single central mast instead of four separate masts (see Fig. 1).

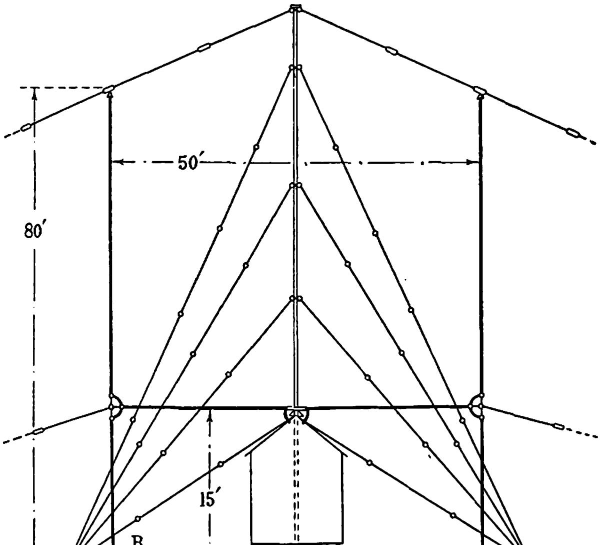

Fig. 1.—Aerial system.

B = box containing balancing condenser.

Operating Hut.—The hut is 15 ft. square and is thoroughly screened by means of 1-inch mesh wire netting with which the outside is covered. The 100-ft. mast passes up through the centre of the hut in order to ensure an equal effect on all four aerials.

Aerial System (*see Figs.* 1 *and* 2).—The four aerials approximately 80 ft. high are suspended from four radial stays of stranded steel which are anchored to the ground at points 400 ft. out from the mast. These stays are " broken " by suitable insulators into 20-ft. lengths.

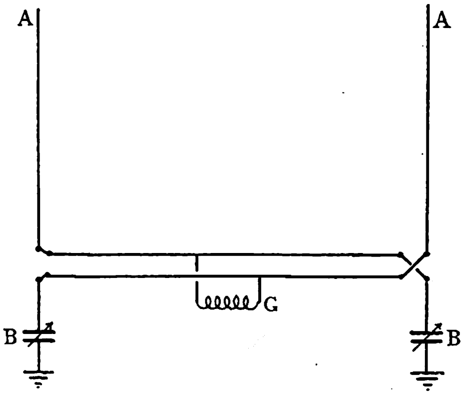

Fig. 2.—Diagram of aerial connections.

G = field coil of goniometer.
B = balancing condensers.
A = aerial.

The system of stays supporting the mast is also broken up by insulators into lengths not exceeding 15 ft. Each aerial is stretched tight to anchor pegs in the ground vertically under its point of support, and is broken at a point 15 ft. above the earth by an insulated length containing the spacing element for the horizontal leads.

Horizontal Leads.—The twin horizontal lead-in wires are attached to the insulators on the spacing piece in the aerial wire, which keeps them 6 in. apart in a horizontal plane. They are strained to insulators attached to battens on the mast at a point just above the roof ridge of the hut. Connections are made to the aerial by soldered " tags." A separate down-lead is attached to each of the eight horizontal wires and these are

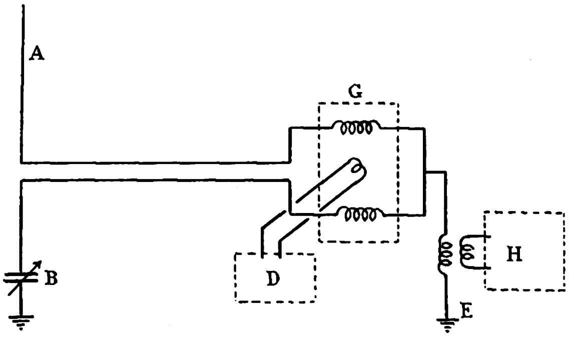

Fig. 3.—Method of obtaining balance.

A = single aerial of Adcock system.
B = balancing condenser.
D = amplifier, etc.
E = earth of centre of system.
G = goniometer.
H = local high-frequency source.

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[*] *Journal I.E.E.*, 1926, vol. 64, p. 831.

passed through the roof of the hut by means of lead-in insulators.

Earth Connections.—Each earth connection consists of four cylindrical holes 4 ft. deep and 2 ft. apart, arranged symmetrically round the foot of the aerial. Each hole contains a piece of metal sheet bent in the form of a cylinder to fit the hole. The holes are then filled in and rammed down. The four wires are "commoned" and soldered to the earth terminal of the balancing condenser.

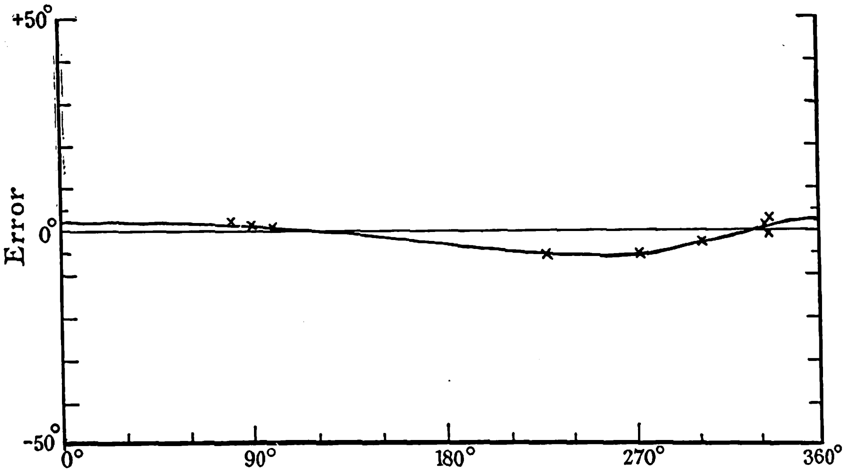

Fig. 4.—Calibration curve for ground waves.

TABLE 1.

Comparison of Standard Deviation for Balanced Adcock and Direction-Finding Loop.

Date	Time (G.M.T.	Station	D.F. loop		Adcock (Bal.)	
			Number	S.D.*	Number	S.D.*
3. 5.28	19.15–20.15	Bournemouth	28	30·6	81	10·44
10. 7.28	18.40–21.30	Bournemouth	65	29·2	73	1·1
11. 7.28	19.15–21.50	Bournemouth	100	25·9	65	0·5
17. 7.28	19.15–22.00	Daventry	37	0	41	0·12
19. 7.28	19.30–22.00	Daventry	87	1·51	59	0·08
24. 7.28	19.00–21.25	Manchester	87	14·95	118	7·4
25. 7.28	19.45–21.30	Manchester	72	33·1	59	3·3
15.10.28	17.10–18.50	Bournemouth	—	†	88	8·8
14.11.28	17.25–18.25	Daventry	84	0·72	50	0·08
27.11.28	17.15–18.30	Langenberg	120	9·1	85	3·2
29.11.28	16.53–19.00	Langenberg	218	12·5	151	3·0
11. 1.29	18.30–19.05	Hamburg	44	0·97	35	1·25
23. 1.29	17.30–18.30	Hamburg	102	1·7	43	0·7
28. 6.29	20.45–21.15	Glasgow	45	4·6	24	0·93
11. 7.29	20.15–21.30	London	121	0·62	60	0·29
18. 7.29	20.15–21.30	London	117	0·63	71	0·3
9. 8.29	19.25–20.00	Cardiff	45	25·6	47	3·95
15. 8.29	19.10–20:00	Cardiff	40	19·46	48	2·23
22. 8.29	19.40–20.20	Dublin	60	3·84	58	1·98

* S.D. = standard deviation. † Night error too severe to take standard deviation (see Fig. 5c).

Note:—The standard deviation is obtained by taking the root-mean-square value of the variation of individual observations from their arithmetical mean.

Balancing Condensers (*see Fig.* 2).—These are variable condensers* (maximum capacity 0·0003 μF) of commercial pattern entirely enclosed in a metal "plymax" box (10 in. × 10 in. × 8 in.) which is fixed to wooden pegs driven into the ground. A short-circuiting switch is mounted on the outside of the box. When the aerial system is correctly balanced these condensers have a value of approximately 60 $\mu\mu$F.

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* These condensers may be replaced by fixed condensers as soon as the correct value has been found: they do not have to be readjusted on changing wavelength unless the natural wavelength of the aerial is approached.

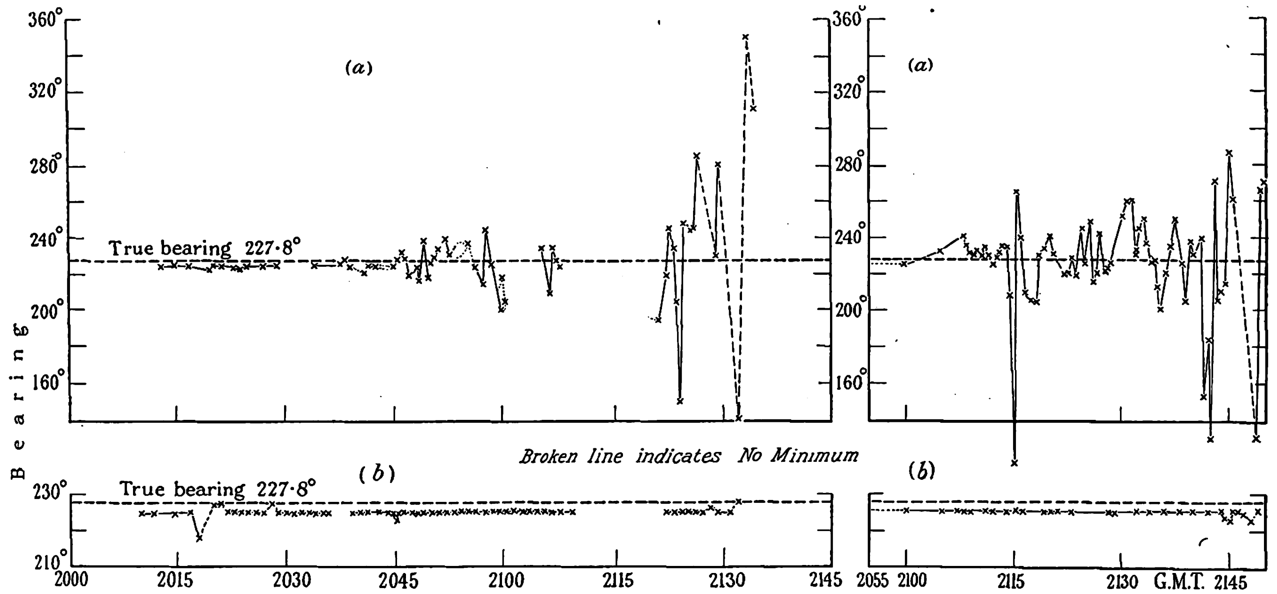

FIG. 5A.—Comparison of simultaneous bearings on (a) direction-finding coil system, and (b) Adcock system. Transmitter: Bournemouth (329 m). Left-hand 10.7.28; right-hand 11.7.28.

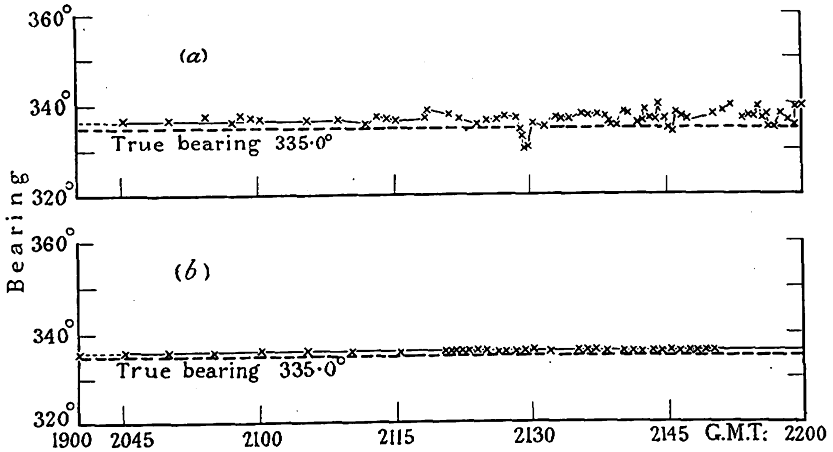

FIG. 5B.—Comparison of simultaneous bearings taken on (a) direction-finding coil system, and (b) Adcock system. Transmitter: Daventry (491 m), 18.7.28.

Interior Connections.—The interconnections between the horizontal leads necessary to complete the arrangement shown in Fig. 2 are made inside the hut at roof-level. Each lead, however, is broken at the point of entry into the hut by means of a switch controllable from the ground by means of a rod. The four down-leads to the goniometer are brought down the sides of the mast.

Goniometer and Receiver Apparatus.—These do not differ in any important way from the installation of a standard Bellini-Tosi direction-finding system.

Balancing the System.—As explained later, the object of the balancing condensers is to make the impedance of the lower half of the system equal to that of the upper half with respect to e.m.f.'s generated in the horizontal members of the aerial system by the horizontal electric component of the received waves. This is achieved on each aerial separately by the device shown in Fig. 3. Each of the four aerials in turn is connected to its earth through both field coils of the goniometer in the manner shown, and the point of junction of the field coils is connected to an earth at the centre of the aerial system; actually the screening wire of the hut is good enough. A local carefully-screened high-frequency source is set going to inject an e.m.f. into this centre earth-lead, thus sending a current which branches off into each field coil. One branch passes along one horizontal lead into the aerial, and the other passes along the other horizontal lead to earth through the balancing condenser. The relative intensity of these two currents can now be determined from the position of the search coil necessary to obtain a "minimum" from this local signal, and by adjusting the balancing condenser until this minimum occurs with the search coil at 45° to each field coil they are made of equal intensity. The system is then balanced.

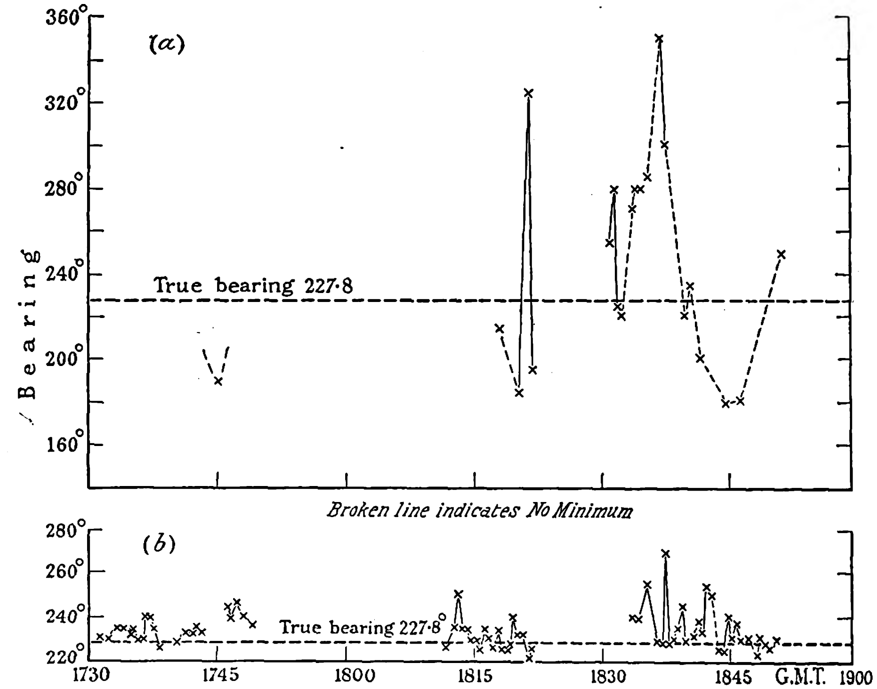

FIG. 5c.—Comparison of simultaneous bearings taken on (*a*) direction-finding coil system, and (*b*) Adcock system. Transmitter: Bournemouth (329 m), 15.10.28.

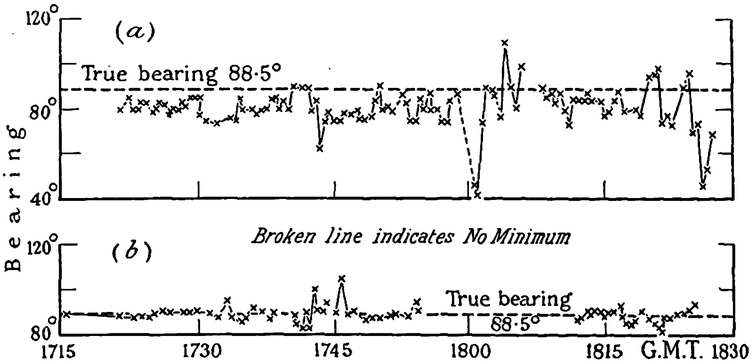

FIG. 5d.—Comparison of simultaneous bearings taken on (*a*) direction-finding coil system, and (*b*) Adcock system. Transmitter: Langenberg (468·7 m), 27.11.28.

(3) TESTS.

The apparatus was subjected to the following tests:—

(*a*) Calibration for ground waves and range tests.

(*b*) Tests during "night effect."

- (i) Comparison with closed-loop direction-finder.
- (ii) Effect of balancing condensers.

(*c*) Calibration by means of downcoming waves from kite transmitter.

A description of these tests, with their results, is given in this section.

(*a*) ***Calibration for Ground Waves and Range Tests.***—This test was carried out in the usual manner by taking bearings of a number of distant transmitting stations in as many different directions as possible. Broadcasting stations in the United Kingdom were for the most part observed and the observations were made in the daytime when ground waves only were being received. The calibration curve is shown in Fig. 4 and compares favourably with those obtained from other forms of direction-finding systems under these conditions. No difficulty was experienced in obtaining sharp minima. The range of the installation with standard forms of amplifier appeared to be not noticeably different from the Bellini-Tosi or other system.

(*b*) *Tests during "Night Effect."*

(i) A series of observations of bearings of distant transmitting stations extending over a period of about 18 months have been made in which the performance of the Adcock system, as described in this paper, was compared with that of a rotating-coil direction-finder under conditions of "night effect." Most of the observations were taken over a period of one or two hours just after sunset.

Table 1 gives a complete summary of all the results obtained during these tests. It gives the standard deviation for each period of observation and for each type of direction-finder. The curves in Figs. 5A, 5B, 5C, 5D, and 5E show the observed bearings plotted with respect to time of observation in a few selected cases chosen to include both the best and worst from the point of view of the Adcock direction-finder.

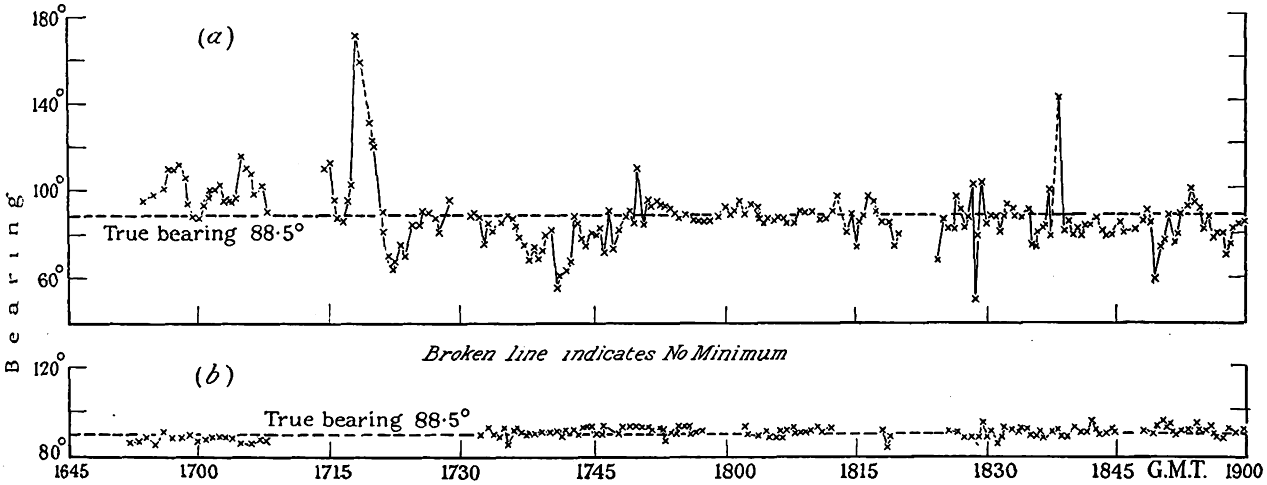

FIG. 5E.—Comparison of simultaneous bearings taken on (*a*) direction-finding coil system, and (*b*) Adcock system, 29.11.28.

Both the tables and the curves show in an unmistakable manner the superiority of the Adcock system over the loop system, and little further comment is necessary. It should be pointed out, however, that in cases where the night effect is very severe, this method of presenting the results tends to underestimate the magnitude of the disturbance on the loop, since, in these cases, no reading whatever can be obtained on the loop over large portions of the period of observation. With the Adcock, on the other hand, such lapses are so extremely rare that the curves and the table give a just account of its performance. It should further be borne in mind, when considering the Adcock results by themselves as an indication of its suitability for a practical direction-finding system, that the particular circumstances in these tests were deliberately chosen to be those of the worst possible "night effect" obtainable. Thus, for example, on longer waves or over sea, nothing so marked as the state of affairs indicated by Fig. 5C is ever experienced.

(ii) Separate tests were made to prove the efficacy of the method of "balancing" introduced in this system. These tests consisted in taking alternative sets of observations on the Adcock only, of about ¼-hour duration each, with and without the balancing condensers in the earth leads (see Fig. 2). The results are shown in Fig. 6 and in Table 2, and clearly indicate the improvement obtained by the use of the condensers.

TABLE 2.

Comparison of Standard Deviation for Balanced and Unbalanced Adcock.

Date	Station	Unbalanced		Balanced	
		Number	S.D.*	Number	S.D.*
10.10.28	Bournemouth	5	9·52	27	5·77
25.10.28	Bournemouth	16	10·29	37	2·07
1.11.28	Bournemouth	20	28·1	49	8·1
25.7.28	Manchester	51	14·9	59	3·3

* S.D. = standard deviation.

Returning to a consideration of Fig. 5, it will be noticed that most of the curves show a residual error of a few degrees obtained on the Adcock system, while in one case (Fig. 5C) during the occurrence of exceptionally bad "night effect" on the loop direction-finder the maximum error of the Adcock was as high as 40°. The question naturally arises whether these errors are instrumental and curable or whether they are due to actual lateral deviation and therefore incurable. Some advance towards answering this question is given by the tests with artificially produced downcoming waves, which will now be described.

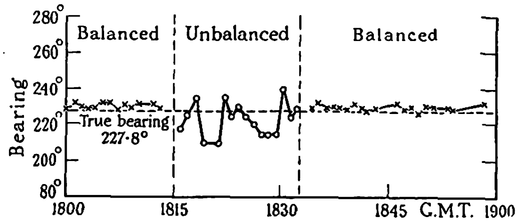

FIG. 6.—Effect of balancing condensers.

(*c*) *Calibration by means of Downcoming Waves from Kite Transmitter.*—In order to arrive at the cause of the residual errors experienced in the Adcock system during "night effect," it was necessary to calibrate the system with a source of artificially produced downcoming waves with a known and suitable degree of horizontal polarization. These waves were produced by means of a transmitter raised several hundred feet above the receiver by means of a kite. The transmitter consisted of the simplest form of valve oscillator directly coupled to a light flexible aerial wire 100 ft. long, twisted in with the string of the kite. The arrangement is shown diagrammatically in Fig. 7.

In order to reduce weight the high-tension and the valve filament-current were supplied from small dry cells of the grid-bias or flash-lamp type. The capacity of these cells was enough to give at least 6 hours' running, and this was enough for the purpose of one test. The whole transmitter weighed about 2½ lb. The kite was borrowed from the Meteorological Office and is the type used for carrying up scientific instruments. With the complete arrangement it was possible to work with the transmitter 200 or 300 yards away from the Adcock aerial, and with waves arriving at an angle of incidence varying from 80° to 30°. The inclination to the vertical of the transmitting aerial, which corresponded to the angle of the kite string, varied from about 30° to 60°, and this varied the angle of polarization of the waves in a corresponding manner.

A complete set of measurements consisted in a simultaneous determination of:—(1) The true bearing (ϕ) of the transmitter, (2) the apparent bearing (A) as observed on the Adcock system, (3) the angle of incidence (θ) of the downcoming waves, and (4) their angle of polarization (α). Of these, ϕ was measured with sufficient accuracy by means of a sighting arm pivoted about a vertical axis and provided with a pointer and scale, and θ and α by sighting through a transparent protractor fitted with a plumb bob.

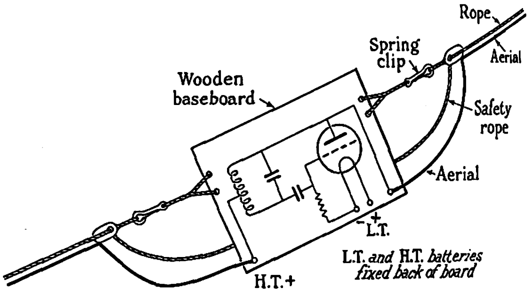

FIG. 7.—Kite transmitter.

In Fig. 8A are shown the results of these tests, the error (ϕ − A) being plotted against the angle of polarization of the transmitter for various angles of incidence. On each curve is also plotted the corresponding error for the closed-loop direction-finder, as calculated theoretically and verified experimentally. A careful study of these curves, which should be compared with those in Fig. 17, gives a clear impression of the extent to which each system is affected by abnormally polarized waves, and shows again the superiority of the Adcock system. To take one example, Fig. 8A(*c*) shows that a wave arriving with an angle of incidence of 75° (15° to the horizontal) and polarized with its electric force at an angle of 60° to the vertical, will give rise to an error of 24° on the loop direction-finder but only 7° on the Adcock.

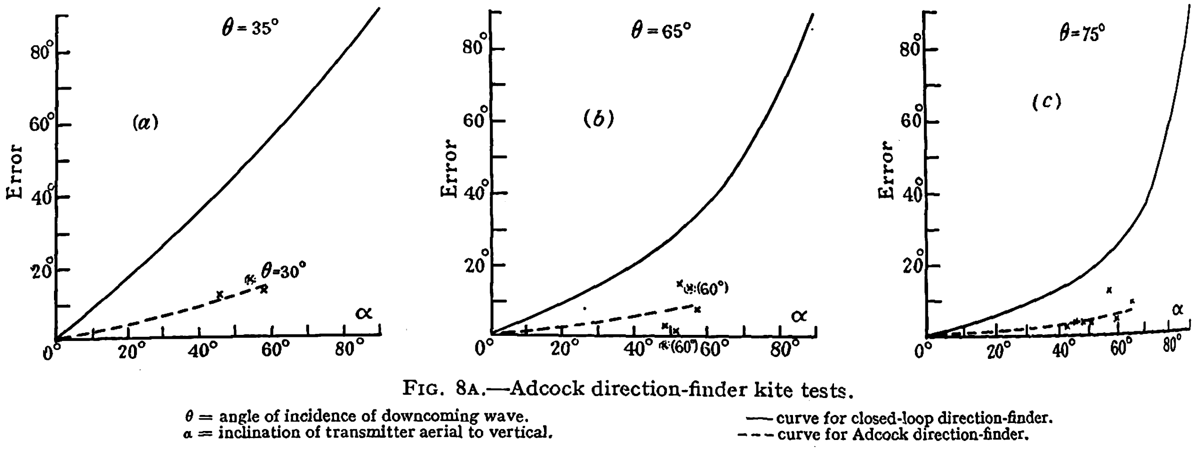

FIG. 8A.—Adcock direction-finder kite tests.

θ = angle of incidence of downcoming wave.
α = inclination of transmitter aerial to vertical.
—— curve for closed-loop direction-finder.
– – – curve for Adcock direction-finder.

On the other hand these kite experiments show that residual experimental errors do exist, so that, considering the two tests together, it would appear that the residual errors experienced at night are likely to be due to a predominatingly large extent to instrumental error and are therefore curable. This conclusion is of some importance as it points to the desirability of a careful theoretical consideration of the system with a view to its further successful development.

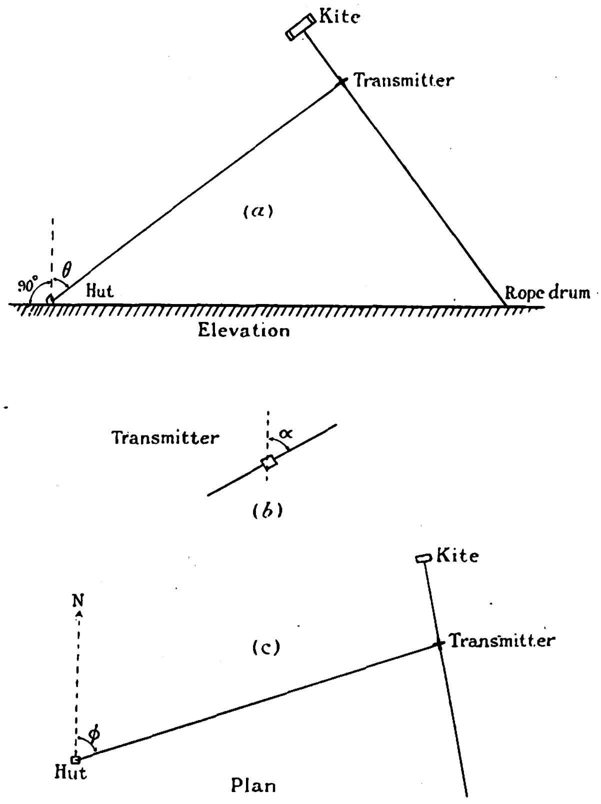

FIG. 8B.

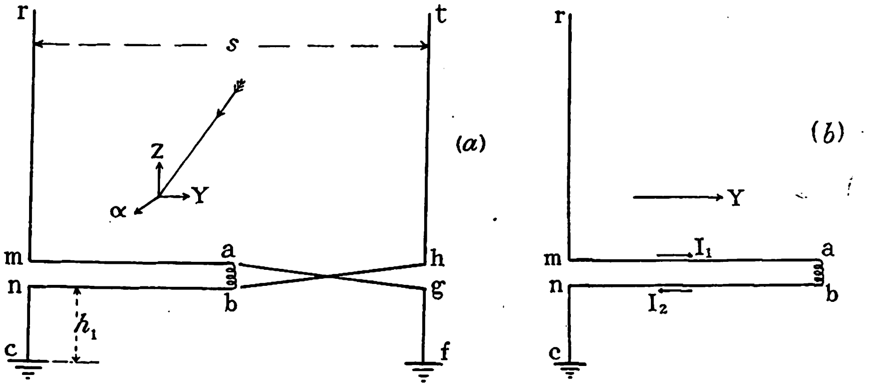

FIG. 9.

THEORY OF BALANCED ADCOCK SYSTEM.

The circuit shown in Fig. 9(*a*) represents a balanced Adcock "element" under the influence of a downcoming wave with horizontal polarization. The condition for correct balancing of the system is that the horizontal electric component of the received field shall induce no current through the field coil "a b." This implies in the first place that the impedance Z_1 of the circuit "r m a b h t" shall be equal to that (Z_2) of the circuit "c n b a g f." If the aerials are untuned with natural wavelength well below that of the working wavelength, this condition is achieved by making the capacity of the balancing condensers equal to that of the aerial circuits. It is interesting to note that the values of the condensers found by the practical method of balancing described above confirm this.

Let I_Y = current through field coil due to Y, due to abnormally polarized wave,
Y = abnormally polarized electric component,
a = horizontal magnetic component at right angles to Y, and
Z_3 = impedance of circuit "c n b a g f."

Then we have for the current through "a b"

$$I_Y = \frac{Y_s}{Z_1} - \frac{Y_s}{Z_2} + \frac{\omega a s h_1}{c Z_3}$$

when Z_1, Z_2 are the impedances defined above and h_1 is the height of the horizontal portion above the ground. By balancing up the condensers we make $Z_1 = Z_2$ but we are still left with the component produced by the magnetic field of the downcoming wave in the loop "c n b a g f," and, since the ratio a/Y varies with the angle of incidence of the wave and the magnetic components are not necessarily in phase with the electric components, it appears impossible to balance this out.

It would at first appear that this component could be eliminated by making h very small, i.e. by having the horizontal leads very close to the ground. Unfortunately, however, in doing this, the capacity to earth of the horizontal limbs becomes no longer negligible, with the result that the balancing condensers are seriously "short-circuited" by distributed capacity to earth along the wire. There is probably, however, a most favourable height which could be found by a series of careful experiments or possibly by calculation.

We have considered the balancing of the circuit "r m a b h t" against the circuit "c n b a g f." It remains to consider the behaviour of the circuits "r m a b n c" and "t h b a g f," both representing possible paths for currents generated by the Y component. Fig. 9(b) shows one of these circuits drawn separately.

It would at first appear that, so far as this circuit is concerned, since the Y component induces equal and opposite e.m.f.'s in the two limbs "m a" and "n b," no current due to this field component would flow through the field coil "a b" under any conditions. This would only be the case if the circuit under consideration were a closed circuit.

In an open circuit, owing to the dominating importance of "displacement currents" which originate, so to speak, at all points on the aerial and result in an unequal distribution of current over the aerial, it is clear that equal e.m.f.'s introduced into the circuit at different points will give rise to unequal currents at any specified point in the aerial. Hence the Y component, although inducing equal and opposite e.m.f.'s in "m a" and "n b" respectively, actually will in general give rise to a residual resultant current in the circuit which passes through the field coil and is thus a possible source of errors. It will be noted, however, that equal e.m.f.'s in "m a" and "n b" will induce equal currents if the current distribution curve is symmetrical about "a b," i.e. if, when the aerial is normally excited, the current maximum occurs at the centre of the field coil. Fortunately, this can be achieved by inserting a balancing condenser in the earth lead just as before, and the value of the balancing capacities required in the two cases appears to be approximately the same.

It is extremely difficult to calculate the extent of the error produced under any given circumstances, but the following cases give some idea of their importance.

Case 1. *Unbalanced System.*

(a) *Effect of Magnetic Component* (a).

Let I_Z = current through field coil produced by normally polarized field (Z),
I_a = current through field coil produced by abnormally polarized magnetic component (a),
X_a = impedance of aerials, and
X_b = impedance of loop.

Then

$$\left.\begin{aligned} I_Z &= \frac{\pi s}{\lambda}\cdot\frac{Zh}{X_A} \\ I_a &= \frac{\omega a s h_1}{c X_b} \end{aligned}\right\} \quad \ldots\ldots \quad (1)$$

If $\mathcal{E}$ be the error in degrees we have (neglecting phase differences)

$$\tan\mathcal{E} = \frac{I_a}{I_Z} = \frac{a}{Z}\cdot\frac{X_A}{X_B}\cdot\frac{h_1}{h}\cdot\frac{\omega\lambda}{c\pi} \quad \ldots \quad (2)$$

Take $h_1 = 10$ ft.; $s = 50$ ft.; $h = 60$ ft.;

$X_A = 1\,000\omega$; $R_A = 30$ ohms; $X_B = 400$ ohms (approx.)

Practical experiments have shown that a/Z frequently exceeds the value $a/Z = 0\cdot5$. It is found from (2), using this value, that errors exceeding 10° may result from a system of this type.

(b) *Effect of Electric Component.*—The first effect of the electric component referred to is not readily calculable, but the second effect is more manageable and this may be termed the "current distribution effect."

Neglecting the mutual capacity of the two horizontal leads in Fig. 9(a) it is permissible to assume sinusoidal current distribution along the aerial according to a law

$$I = K\sin\frac{2\pi x}{\lambda}$$

where x is the distance of the point under consideration from the top of the aerial and K is a constant depending on the height of the aerial and on the amount of series inductance.

It is now necessary to make the assumption that the residual current induced by the Y component is equal to the difference between the *mean currents* in horizontal limbs produced by a "lumped" e.m.f. of the same value acting alone in the middle of each limb, or symbolically that

$$I_Y = K\left(\sin\frac{2\pi x_1}{\lambda} - \sin\frac{2\pi x_2}{\lambda}\right)$$

where x_1 and x_2 are the respective distances of the centre points of the horizontal limbs from the aerial tip, and the constant K is given by

$$K\sin\frac{2\pi h'}{\lambda} = \frac{Ys}{2X_A} \quad \ldots\ldots \quad (3)$$

where h' = total length of aerial.

As before, $$I_Z = \frac{\pi s}{\lambda}\cdot\frac{Zh}{X_A}$$

so that

$$\tan\mathcal{E} = \frac{I_Y}{I_Z} = \frac{K\left(\sin\frac{2\pi x_1}{\lambda} - \sin\frac{2\pi x_2}{\lambda}\right)}{(\pi s/\lambda)\,(Zh/X_A)} \quad . \quad (4)$$

Since $\lambda >> h$ and $x < h$ we may write sines equal to angles, so that, substituting for K in (4), we obtain

$$\begin{aligned} \tan\mathcal{E} &= \frac{(Ys/2X_A)\,(\lambda/2\pi h)\,.\,\left[2\pi/\lambda(x_1 - x_2)\right]}{(\pi s/\lambda)\,(Zh/X_A)} \\ &= \frac{Y}{Z}\cdot\frac{x_1 - x_2}{h'}\cdot\frac{\lambda}{2\pi} \\ &= \frac{Y}{Z}\cdot\frac{\lambda}{2\pi h}\cdot\frac{x_1 - x_2}{h'} \quad \ldots\ldots\ldots \quad (5) \end{aligned}$$

It is possible to evaluate this as follows:—

$\lambda = 300$ m; $h = 20$ m; $h' = 40$ m;
$x_1 = 16$ m; $x_2 = 7$ m; $x_1 - x_2 = 9$ m.

Former experiments show that Y/Z may frequently exceed the value $Y/Z = 0\cdot5$.

Hence $$\tan\mathcal{E} > 0\cdot5\cdot\frac{300}{2\pi 20}\cdot\frac{9}{40}$$

which shows that this effect under the particular circumstances may give rise to errors exceeding 14°.

Case 2. Balanced System.

Effect of Electric Component (Y).—If the balancing has been properly carried out the effects of the Y component should now be negligible either on the circuits "rmabnc" and its pair or on the circuits "rmabht" and "cnbagf."

Effect of Magnetic Component.—We are, however, still left with the magnetic component acting on the loop "cnbagf." The error from this source is given as before by

$$\tan \mathcal{E} = \frac{a}{Z} \cdot \frac{X_A}{X_B} \cdot \frac{h_1}{h}$$

The value of X_A for the aerial system in question has already been given as about 1 000 ohms. The value of X_B is obtained from the value (C_B) of the balancing condensers, and the inductance (L) of the loop "cnbagf" and that of the field coil. The inductance of the loop is of the order 8×10^{-5} henry; the capacity of the condensers is of the order $1{\cdot}0 \times 10^{-10}$ farad, making the total impedance approximately 2 500 ohms.

Hence $$\frac{X_A}{X_B} = \frac{1}{2{\cdot}5} \cdot \frac{h_1}{h} = \frac{1}{6}$$

Again taking the maximum value of a/Z to be $0{\cdot}5$, we have

$$\tan \mathcal{E} = 0{\cdot}029$$

and the possible error is less than 3°.

This theoretical comparison of the balanced Adcock with the unbalanced Adcock shows the latter to be liable to errors of much greater magnitude than the former, and is, in general, in agreement with the experiments.

(4) CONCLUSIONS AND FUTURE WORK.

Considering the work as a whole, it is seen that the type of direction-finder described, which may be called a balanced Adcock direction-finder, constitutes a simple practical form of direction-finder which, compared with present existing practical types, has greatly improved characteristics with regard to downcoming waves. In other words it constitutes a system which, although not more complicated than other systems or more difficult to operate, is far less subject to night effect or to "aeroplane effect." The actual extent of the improvement is well represented by the kite tests shown in Fig. 8 and the night-effect tests of Fig. 5, while the degree to which this improvement is due to the addition of the balancing condensers is shown by Fig. 6.

Both theory and experiment, however, show that the system is not entirely free from what may be termed "avoidable error," that is, error caused by the polarization of the waves as distinct from the unavoidable error which would be caused by their actual deviation from the straight path.

Future development work clearly lies in the direction of removing the residual error which is still inherent in the system, i.e. in devising a system for which the curves of Fig. 8 show zero error for all values of θ and α.

Now an extension of the theory outlined above to other forms which the Adcock principle may take shows that any unbalanced Adcock system in which the vertical aerials are connected to the goniometer by continuous horizontal leads is liable to errors resulting from the action of horizontally polarized waves.

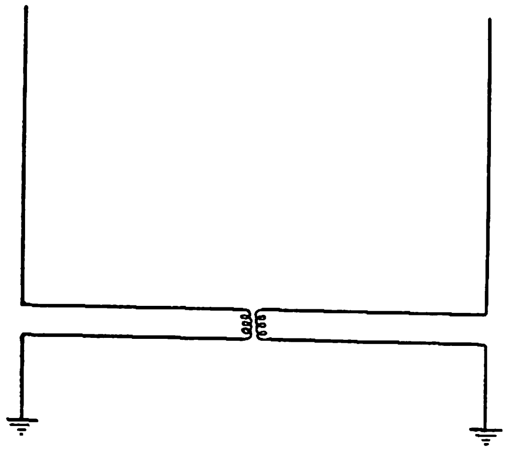

FIG. 10.

Four ways may be distinguished in which this action may take place:—

(*a*) The action of the horizontal electric field on a long horizontal pair of conductors which are in circuits of different impedance, but both in series with the field coil of the goniometer.

(*b*) The action of the horizontal electric field on a long horizontal pair of conductors forming part of the same circuit containing a field coil, but in which the current distribution is not uniform.

(*c*) The action of the horizontal electric field on a long pair of horizontal conductors giving rise to currents in the vertical aerials by virtue of the *electrostatic* coupling between the horizontal conductors and the vertical aerial.

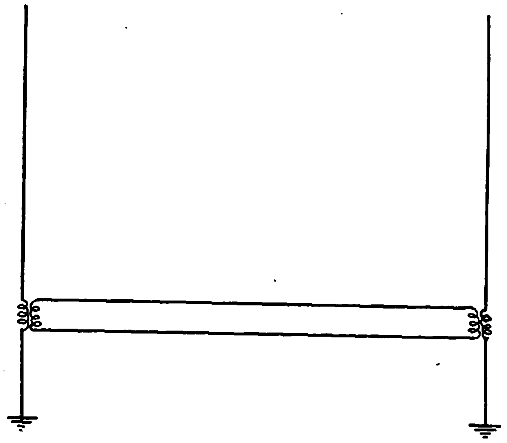

FIG. 11.

(*d*) The action of the horizontal magnetic field on the closed loop formed by a single conductor, the ground and the lower parts of the vertical aerials when this closed loop contains a field coil.

These effects are not all present in any given system. At least three types of circuit exist which come under the above classification of an unbalanced Adcock system, and each behaves differently in this respect:—

(1) *Direct-coupled Type*.—This is as shown in Fig. 3 of Adcock's patent specification,* in which the aerials are directly connected to each other and to the field coil of the goniometer. This is subject to errors of classes (*a*), (*b*) and (*d*).

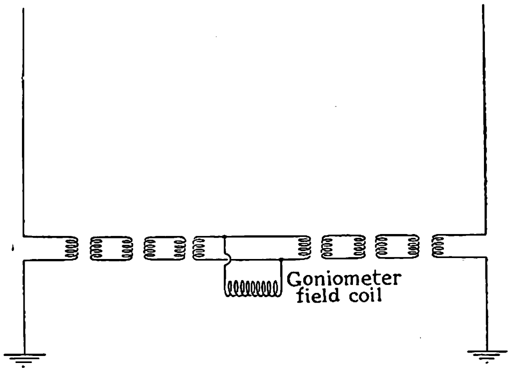

FIG. 12.—" Chain "-coupled Adcock direction-finder.

(2) *Loose-coupled Type* (*Fig*. 10).—In this the aerial circuits are magnetically coupled to the field-coil circuits, the coupling coils being at the centre of the system. This is subject to errors of class (*b*) only.

(3) *Loose-coupled Type* (*Fig*. 11).—In this the arrangement is the same as (2) except that the coupling coils are situated near the aerials. This is subject to errors of class (*c*).

Thus each type is subject to error of some form. In every case it is the horizontal leads which give rise to the error, and although balancing by condensers results in great improvement it has been demonstrated in at least one case to leave residual imperfections. It therefore appears that a perfect system would demand the abolition of these leads altogether. This may be virtually achieved by substituting for these leads a series of magnetically coupled circuits, each circuit occupying a comparatively short length of space between the aerial pairs. Fig. 12 illustrates the general principle. The actual number of " links " in the chain here shown has no special significance; theoretically the greater the number the more perfect the system becomes. Fig. 13 shows a particular arrangement when the new principle is introduced in its most practical form. Here the number of links is reduced to two for the sake of avoiding technical difficulties.

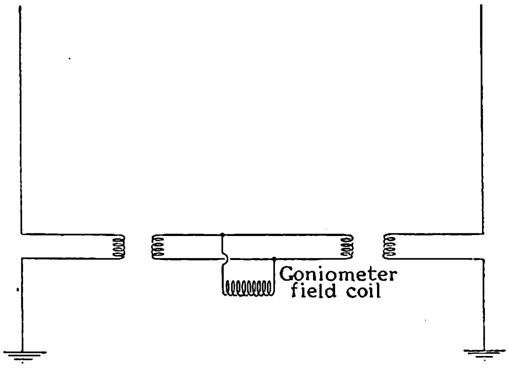

FIG. 13.—Simplest arrangement of chain coupling.

Development of the Adcock system therefore involves in the first instance the testing of this principle and this will be attempted if occasion arises.

Part 2. SHORT WAVES (12 TO 60 M).

(1) Description of Closed-Loop Direction-Finder.

The loop consists of a single conductor forming a square with a side of 3 ft. This conductor is stretched tight at the centre of an enclosing brass tube of 1 in. square section. The 3 ft. square frame formed by the brass tube is electrically continuous except at the centre of the top side, where there is a gap ⅛ in. wide, the frame being kept rigid at this point by a small ebonite junction-piece fitting tightly into the ends of the tube.

The mechanical construction is shown in Fig. 14. The frame is welded to a hollow brass vertical axis A 1½ in. diameter which rotates in the fixed brass bearing B and carries the pointer P. The leads L from the single-turn loop are brought down the interior of this axis and terminated on the slip-rings S. Before this is done the wire is strained tight so that it remains rigid in all parts of the tube. At the corners of the brass frame the wire passes over ebonite spacing-pieces E, which allow the wire to slip over them when it is tightened.

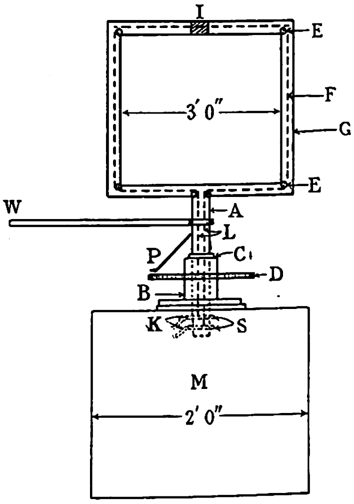

FIG. 14.—Rotating-loop direction-finder for short waves.

A = brass vertical axis 1¼ in. diam.
B = brass bearing 3 in. internal diam.
C = brass collar.
D = aluminium scale.
E = ebonite spacing-pieces.
F = direction-finding loop.
G = outer brass pipe.
I = insulated gap.
K = brushes.
L = leads.
M = metal-lined box with amplifiers, tuner, etc.
P = pointer.
S = slip-rings.
W = wooden handle.

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* *Loc. cit.* (same as Fig. 2, without balancing condensers).

The bearing B consists of a brass cylinder with bottom flange of 3 in. inside diameter and 8 in. long. The inside of the cylinder forms the bearing for the vertical axis, while the outside of the cylinder is machined to take the circular aluminium scale-plate D (8 in. dia.) which is marked off in degrees. This can be rotated relatively to B by undoing a locking screw on occasions when it is required to set the scale to read true bearings. The bearing B is bolted to the centre of the top of a double metal-lined box (plymax) 2 ft. cube and a hole is cut in the top of the box sufficiently large to allow the slip-rings on the vertical axis to pass through. The metal-shielded loop is erected by simply placing the axis in the bearing B so that it rests on the collar C. The lower part of the axis with the slip-rings then projects about 3 in. down into the interior of the box and makes contact with the brushes K, which are "sprung" aside while the loop is lowered into position. The lid of the box is at the side and has a 1-in. overlap. In order to ensure good contact, however, two clamps are mounted on each of the four sides of the box and are screwed up when the lid is in position. The frame is rotated by means of a light wooden handle W clamped to the vertical axis. The slip-ring brushes are connected to the terminals of the coupling coil which forms the input of the amplifier.

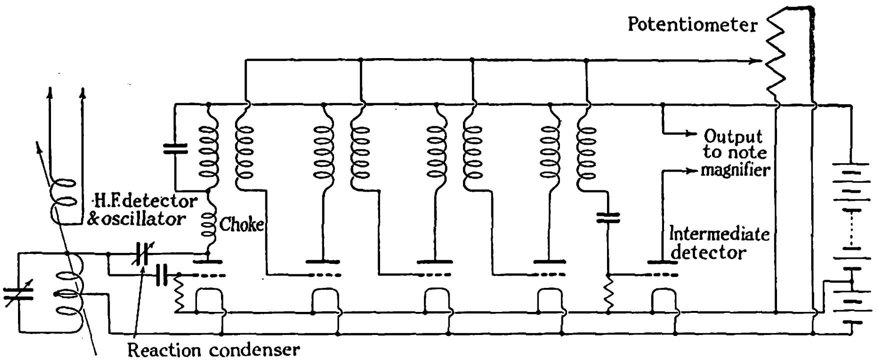


FIG. 15.—Circuit diagram of direction-finder supersonic amplifier.

The amplifier is mounted on a wooden shelf about 1 ft. from the top of the box, the battery being placed beneath. It consists of a 6-valve super-heterodyne receiver of commercial pattern, the valve filament being supplied from a 2-volt cell. A single-stage magnifier unit is also employed. The single tuning condenser is controlled externally by a suitable extension rod. The receiving loop remains untuned, being simply loose-coupled to the inductance of the rectifying and oscillating valve of the super-heterodyne. Heterodyne reception of continuous-wave stations is effected by allowing the intermediate-frequency stage to oscillate and controlling it to maximum sensitivity by means of a potentiometer. The receiver as a whole is exceptionally simple to operate, there being only one tuning control. The circuit diagram is given in Fig. 15.

The advantages and suitability of this instrument for short-wave working lie mainly in the form of screening employed, and are:—

(1) Complete absence of antenna effect, resulting in very sharp and accurate bearings.
(2) Robustness of loop, since it is enclosed in a metal pipe.
(3) Loop may be approached and, on the higher wavelengths, the screen even touched without appreciably altering bearing or weakening signals.

(2) DESCRIPTION OF ROTATING ADCOCK DIRECTION-FINDER.

The system consists of two spaced vertical aerials fixed at the ends of a rotating horizontal arm, the aerials being connected in opposition as shown in Fig. 16(*a*). Each aerial is made up of two 5-ft. lengths of $\frac{3}{4}$-in. dia. aluminium tube. The horizontal arm is in two 5-ft. lengths of $1\frac{1}{2}$-in. dia. brass tube, the two lengths being joined at the centre by a brass sleeve or union piece [Fig. 16(*c*) and (*d*)]. In a later model a single length of tube is used for the arm. The twin horizontal leads connecting the two aerials together are stretched tight in the brass tube at a distance of $\frac{3}{4}$ in. apart and at the centre are brought out to two terminals for connecting to the primary of the transformer.

The transformer and its mounting are shown in Fig. 16(*b*). The primary and secondary windings are separated by an "electrostatic" screen E which serves also as a mechanical support for the former. The screen consists of a cylindrical cage (8 in. high × 4 in. dia.) of fine vertical wires spaced $\frac{1}{8}$ in. apart. The method of winding the cage is perhaps of some interest. At the top the wires are supported by an ebonite disc which is carried on three brass legs fixed at their lower end to a brass ring to which the lower ends of the cage wires are all commoned. This ring is screwed to an 8-in. square brass baseplate (6) which carries the structure for supporting the 10-ft. horizontal arm. This brass plate is fixed to a brass tube (9) which forms the bearing, rotating about a fixed inner brass tube (10). This tube (10) has the down-leads spaced inside it and carries the transformer secondary at its top end, while its lower

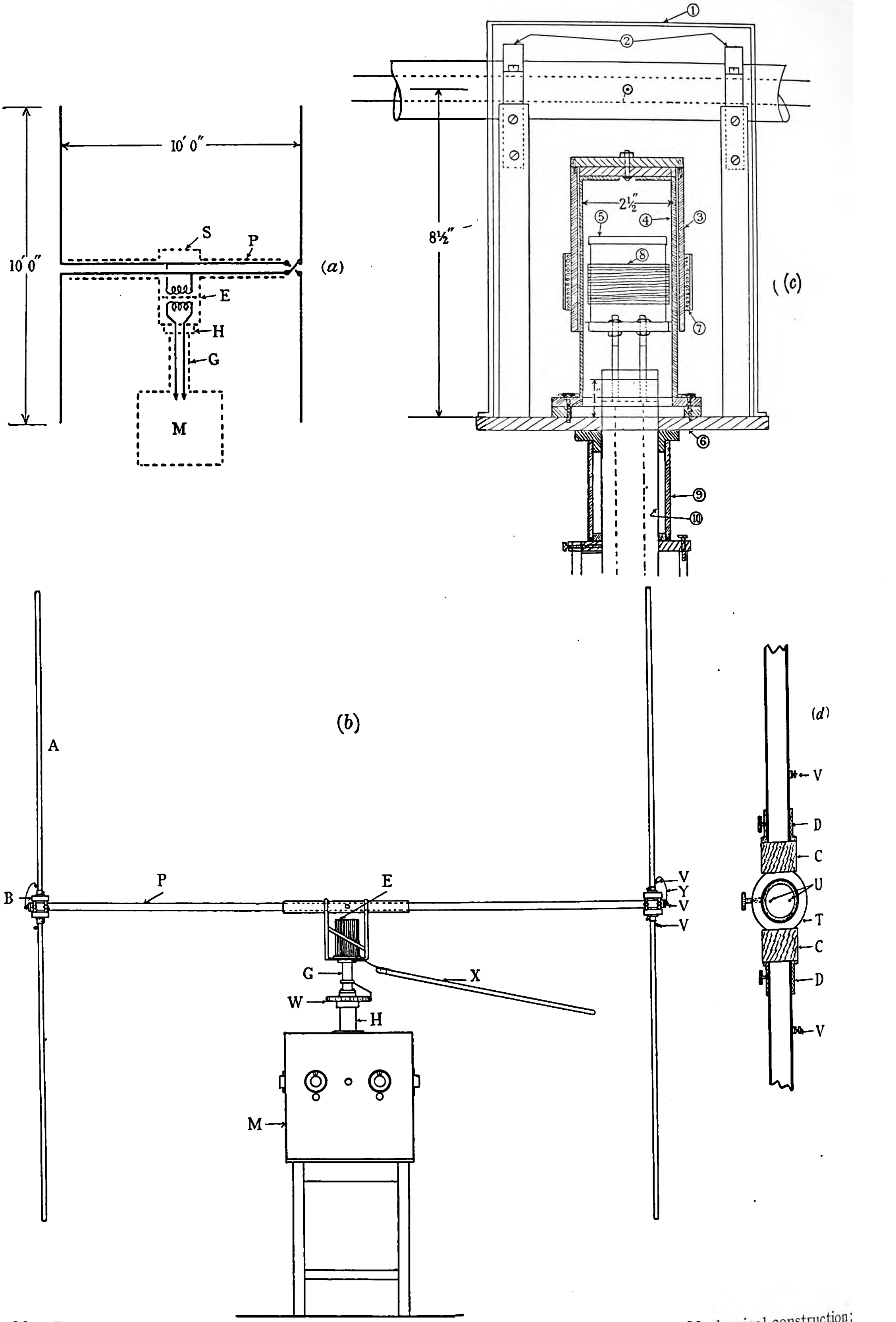
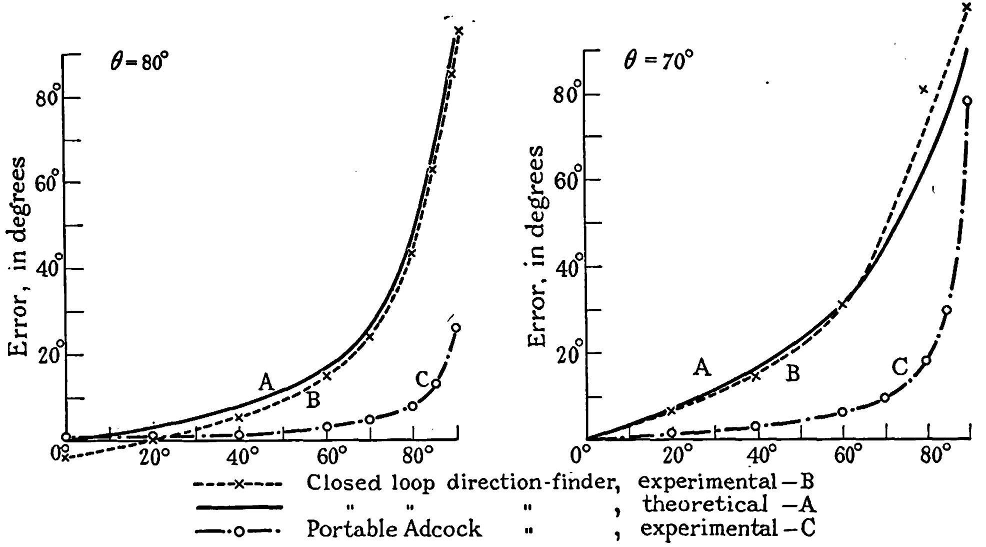


FIG. 16.—Rotating Adcock direction-finder. (*a*) Circuit and screening arrangements; (*b*) Mechanical construction; (*c*) Details of centre transformer; (*d*) Details of aerial junction-pieces.

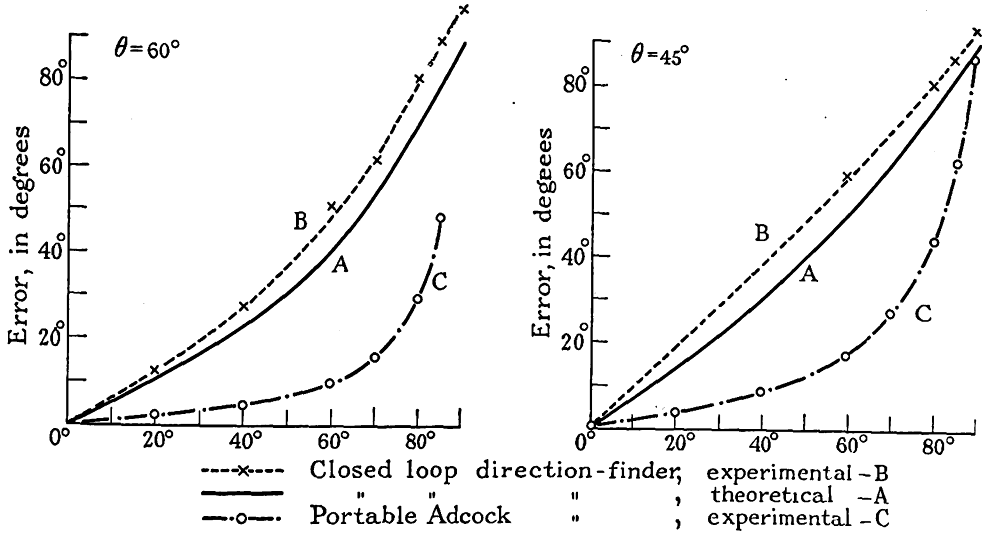
A = aluminium rod aerial. B = junction pieces. C = ebonite spacing block. D = brass socket. E = electrostatic screen. G = brass tube with down leads. H = bearing. M = metal-lined box with amplifiers, etc. P = metal pipe. S = screen. T = brass ring with clamping screw. U = horizontal leads. V = terminals. W = scale and pointer. X = handle (projecting at right angles to horizontal arm). Y = connecting leads. (1) metal screening cover. (2) supports for horizontal pipe. (3) ebonite former for primary. (4) electrostatic screen. (5) ebonite former for secondary. (6) brass baseplate. (7) primary winding. (8) secondary winding. (9) outer rotating tube. (10) inner fixed tube.

end projects downwards into the top of the amplifier and tuner box. The secondary coil (8) consists of a few turns wound on a 2-in. dia. ebonite former (5) which plugs into valve sockets on the top of the fixed tube (10). The primary coil (7) is wound on a 4-in. dia. former (3) which slides over the screen (4). Thus the primary coil rotates with the aerial system but the secondary remains stationary, and since the coils are concentric there is no change in the mutual inductance. In this way direct mechanical connection between the rotating and fixed portions of the system is avoided.

The amplifier, its box, scale and scale mounting (B in Fig. 14) are actually the same as used for the screened direction-finding loop already described, though in this case the brass cylinder B no longer acts as a bearing but as a mounting for the scale and a support for the tube (9) which is locked inside it.



FIGS. 17 and 18.—"Aeroplane effect" direction-finding tests. $\lambda = 21$ m.



FIGS. 19 and 20.—"Aeroplane effect" direction-finding tests. $\lambda = 21$ m.

The aerial rods fit into brass sockets screwed to ebonite blocks mounted on brass collars sliding over the ends of the horizontal arm. The aerial rods carry terminals at their lower ends, and these are connected to the horizontal leads.

(3) Description of Tests.

The two types of direction-finders which have been described above have been subjected to a series of tests with the object of ascertaining their performance under varying circumstances. In particular, an attempt has been made to calibrate these instruments with respect to their behaviour when under the influence of downcoming waves of abnormal polarization.

As in the case of the medium-wave Adcock direction-finder described in Part 1, these latter tests are of two kinds:—(i) Tests with natural downcoming waves by observations on commercial transmitting stations at varying ranges and times of day, and (ii) tests with artificial downcoming waves provided by an elevated local transmitter—in this case not on a kite but fixed on the top of a 40-ft. telegraph pole.

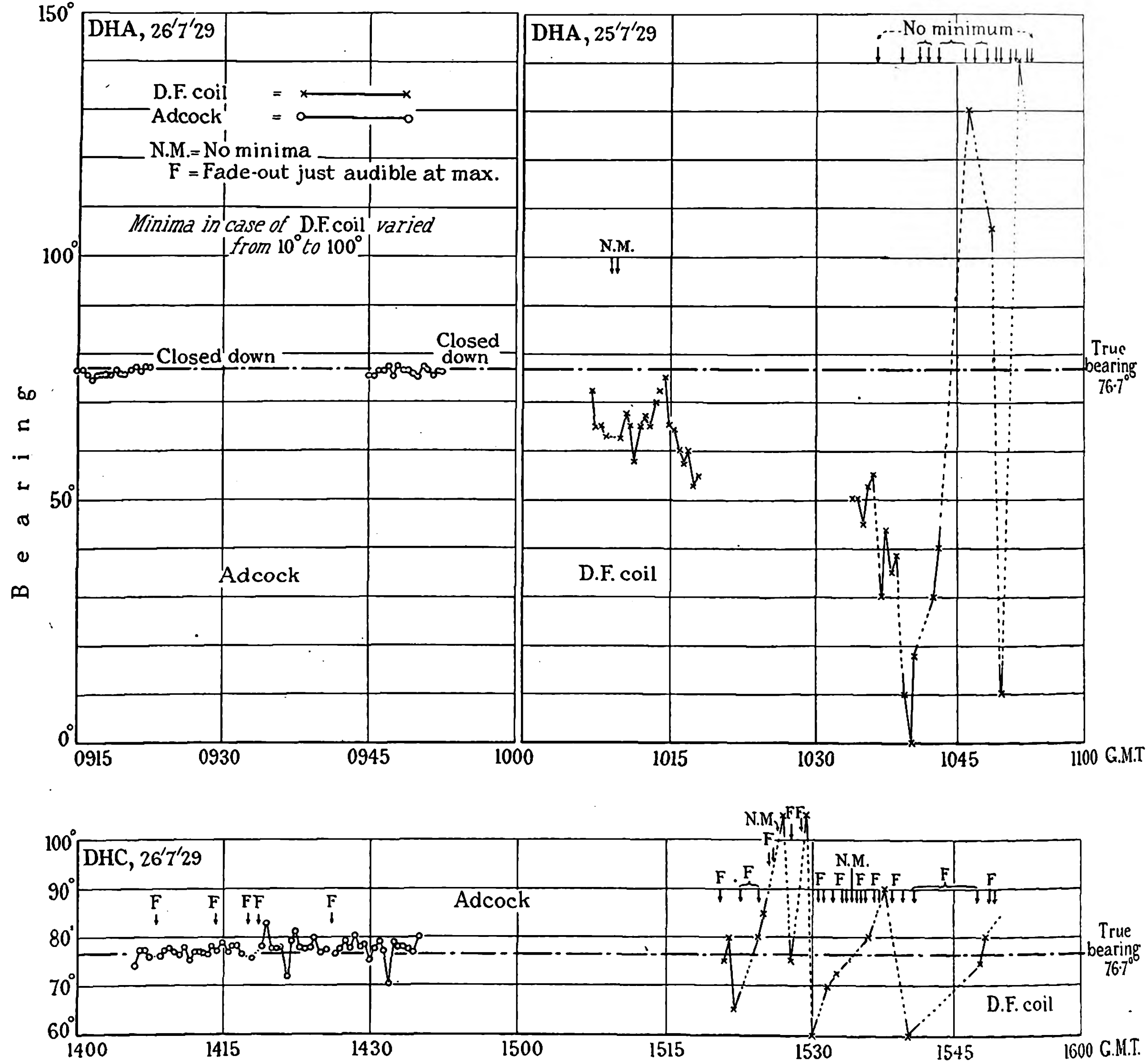


FIG. 21.—Comparisons of bearings on short waves taken by portable direction-finding coil and portable Adcock coil. Transmitters: Nauen [DHA (26·2 m) and DHC (22·7 m)].

The tests are divided into the following sections:—

- (a) Tests with local transmitter.
  - (i) Transmitter on ground.
  - (ii) Transmitter elevated 40 ft. above ground.
- (b) Effect of immediate surroundings.
- (c) Tests up to limit of ground-ray range.
- (d) Long-range tests.

Test (a)(ii) gives the inherent liability of the direction-finding sets to instrumental error, while the remainder give practical information about the conditions under which the sets can be effectively used. A consideration of the two tests together enables some conclusions to be drawn with regard to the nature of the propagation of short waves.

Tests (a) (i) and (b) were made with the loop direction-finder only but they may be assumed to hold good for both instruments, for the two were frequently compared at close range from ground transmitters and found to behave similarly under these conditions.

(a) *Local Transmitter Tests.*

(i) With a low-power transmitter situated in the middle of a large, flat, open space and at a distance of 100 yards from the direction-finding set, the maximum error was 2·0° on all wavelengths from 16 to 40 m.

(ii) An important test carried out with the local transmitter was that of working with the transmitter in the air in order to provide a source of downcoming waves.

The transmitting aerial consisted of an aluminium rod 15 ft. long fed at the centre from a simple form of valve oscillator. This aerial was pivoted on a horizontal axis on the top of a telegraph pole 40 ft. above the ground. Directional observations were made on the ground at different distances from the foot of the pole with both types of direction-finding apparatus, in order to ascertain the error in observed bearing produced by the horizontally polarized component of the downcoming waves. The distances between transmitter and receiver were altered in successive stages to correspond to angles of incidence of the downcoming wave of 80°, 70°, 60° and 45° respectively, and at each site a series of observations was made for different inclinations of the transmitting aerial varying from 0° (vertical) to 90° (horizontal), thus providing waves of varying polarization.

The error ($\mathcal{E}$) which should theoretically be produced on the loop direction-finder in any given case is given by a simple calculation as

$$\tan \mathcal{E} = \tan \alpha \, . \cos \theta \, . \frac{1 + \rho_h}{1 + \rho_v} \quad . \quad . \quad . \quad (1)$$

where $\mathcal{E}$ = observed error,
θ = angle of inclination to vertical of transmitting aerial (polarization angle),
α = angle of incidence of downcoming wave, and
ρ_h/ρ_v = reflection ratio of ground to horizontally and vertically polarized waves respectively.

The results of the tests are summed up in the set of curves given in Figs. 17 to 20. Each figure is for a different angle of incidence (θ), and the curves each show the direction-finding error with respect to α, (*a*) being the theoretical error curve for the loop, (*b*) the experimental error curve for the loop obtained from (1), and (*c*) the experimental curve for the Adcock direction-finder.

The theoretical loop curves agree very closely with the practical loop curves, and in all cases the Adcock errors are seen to be notably less than the loop errors. The extent of the superiority of this type of Adcock direction-finder over the loop type for observation on downcoming waves is exactly represented by these curves and cannot be expressed in any better way. It is of interest, however, to write down one or two examples. Thus, for a wave arriving at an angle of incidence of $\theta = 80°$ (10° to horizontal) and polarized with its electric force at $\alpha = 45°$ from the vertical, the error on the loop is 10°, while on the Adcock it is less than 2°. Again, for $\theta = 45°$, $\alpha = 60°$, the error on the loop is 60° and that on the Adcock 18°.

The cause for the existence of the residual error revealed in Figs. 17–20 is probably the asymmetry introduced by the earth's surface. A successful attempt was made to reduce these residual errors by shortening the lower limbs of the aerials. The curve obtained by cutting 2 inches off these aerials is shown in Fig. 22 for one angle of incidence. Tests with other angles of incidence, however, still showed an improvement, but not so great.

(*b*) *Effect of Immediate Surroundings.*—These tests were undertaken mainly to provide information affecting choice of site for short-wave working. Observations were made to determine the effect of local contour variations, villages, individual houses, boundary walls, etc. The general conclusions arrived at were that, provided the same precautions as to choice of site were taken that are taken with longer-wave direction-finding apparatus, the same general accuracy with respect to such local effects will be obtained as is obtained with the longer waves.

A few examples are given below to illustrate the nature of these tests.

(i) Observations were made in a large field at a distance of about one mile from the Leafield transmitter. The field was approximately level and had an area of about 100 acres. Eighteen different positions were investigated in this field on a wavelength of 17 m. Eleven showed no error exceeding 1°, and individual readings could be taken to within ½°. Of the remaining seven for which the error was greater than this, one was within 10 yards of a cottage and had an error of 7°, and six were within 200 yards of a small village which lay between them and the transmitter. The errors increased steadily as this village was approached, reaching 2½° at a distance of 100 yards, while at closer range the minima became too flat to allow observations to be made. Although the field was within a mile of the transmitter, the intervening ground was by no means level. The waves in their passage had to pass over a deep fold in the hills which cut obliquely across their path. This feature, as the general freedom from error indicates, did not cause their course to deviate to any appreciable extent.

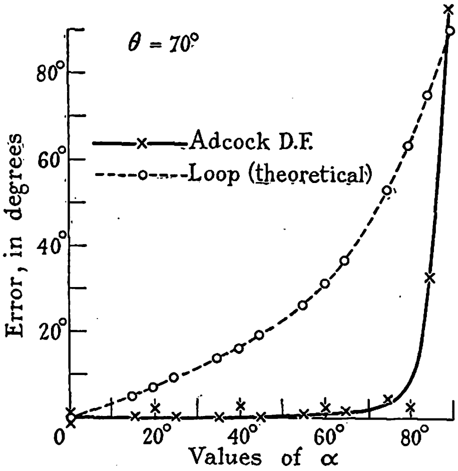


FIG. 22.—Tests on rotating Adcock direction-finder. Balanced aerials:—top half 5 ft., bottom half 4 ft. 10 in.

(ii) Observations were made on the error produced by a single tree 70 ft. high. At a distance of 10 ft. from the tree the maximum error was 40°; as the distance was increased this rapidly fell off until at 30 ft. it was 10° and at 100 ft. it was negligible.

(iii) Observations made near a stone boundary wall about 3 ft. high showed no appreciable error even when the distance away was only a few feet.

(*c*) *Ground-Ray Tests.*—The two types of apparatus (loop and Adcock pair) have been thoroughly tested on a wavelength of 24 m over a range of from 5 to 150 miles, i.e. up to the point where the ground ray disappears.

TABLE 3.—*Short-Wave Direction-Finding Observations on Adcock and Coil Portable Direction-Finding Apparatus.*
Transmitter at Chelmsford (5SW, $\lambda = 24$ m)

No.	Date	Time, G.M.T.	Place	Nature of site	Distance	True bearing	Error (mean of several observations)		Remarks
							Coil	Adcock	
					Miles				
1	5.6.28	Mid-day	Terling, Essex	Many local trees. Site otherwise good	6	223°	− 0·3°	− 0·3°	—
2	5.6.28	Evening	Bee's Farm, near Halstead	Bad. On grass space in centre of cross-roads	15	208°	+ 7°	+ 6°	—
3	6.6.28	Mid-day	2 miles N. of Sudbury on side of Sudbury–Melford road	Bad. D.F. only 60 yards from wires and very small field	24	205°	− 8°	− 9°	Marked fading
4	6.6.28	Evening	Thorpe Morieux, Suffolk	Good, open site in sloping field (5° to S.W.)	32	209°	+ 3·5°	+ 1·4°	Fading very strong, very difficult to take readings
5	7.6.28	Mid-day	Ixworth, Suffolk	By roadside after heavy rain. Bad site	43	202·5°	− 1·2°	− 2·5°	Fading very slight, but flat on coil and difficult to get bearing
6	7.6.28	Evening	New Buckenham, Norfolk	Very good site on large flat common	58	206·5°	—	—	"Night effect" too bad to take bearing
7	8.6.28	Mid-day	New Buckenham, Norfolk	Very good site on large flat common	58	206·5°	—	− 1·5°	Considerable fading
8	1.8.28	Mid-day	Wansford, Huntingdonshire	Good, open site 200 yards from North Road	73	148·5°	− 3·5°	− 3·5°	Signals rather faint and minimum flat and ill-defined
9	2.8.28	Mid-day	Waddington	Very good site on plateau	110	158°	− 3·0°	− 8°	Minimum very flat on both systems and all but impossible to obtain
10	2.8.28	Evening	Waddington	Very good site on plateau	110	158°	—	—	No minimum obtainable on either system
11	3.8.28	Mid-day	5 miles N. of Doncaster on Selby Road	Good site, though well-wooded district	150	152°	—	—	No minimum obtainable on either system

The plan of these tests was to limit the observations to one transmitting station only (Chelmsford 5SW, $\lambda = 24$ m), and to make these observations as nearly as possible simultaneously on both systems and at gradually increasing distances from the transmitter in approximately the same direction. The observations were made in a northerly and north-westerly direction from Chelmsford, the maximum and minimum distances from the transmitter being respectively 150 and 6½ miles. Observations were made at some sites at mid-day and at others in the evening about an hour before sunset, while again in some cases the same site was investigated in the morning and in the evening. At night it becomes difficult to take readings even at a distance of 30 miles, owing to fading effects. In the daytime 70 miles appears to be the limit, though at 110 miles it was possible to get a rough bearing. The results are shown in Table 3. The maximum fixed error observed, where observations were possible, was 9°. This was probably an error local to the site, which in this case was a bad one. On the whole, the results within the range of possible bearings stated are good and compare favourably with those obtained on longer waves under the same conditions.

It was noticeable in contrast to medium- and long-wave direction-finding experience that there were no "variable errors." When fading and the ordinary symptom known as "night effect" occurred, the changes were too rapid to enable bearings to be taken during a swing.

(*d*) *Long-Range Tests.*—To give some idea of the working of the apparatus at points beyond the "skip distance" a short series of observations were taken at Slough on the Nauen stations AGB. The loop receiver gave very large errors, the minimum shifting to all parts of the scale indifferently. At other times there was a faint indication that the very flat minimum oscillated about the true bearing. On the Adcock, however, the minimum, though shifting rapidly over a small arc, which would sometimes be as great as 10°, could always be found to average within 2° or 3° of the true bearing. The curves in Fig. 21 show the nature of the results obtained.

(4) CONCLUSIONS.

(i) The results obtained on the long-range tests (*d*), taken in conjunction with the local tests with the elevated transmitter (*a*) and those within the skip distance (*c*) (see Table 1 and Figs. 17 to 20), confirm the conclusions arrived at by Eckersley* from experiments of a somewhat similar nature. The variable errors and flatness of minima observed at distances exceeding 20 miles (and less than, say, 500 miles) are undoubtedly due to downcoming waves. The fact that at such ranges these effects were of equal extent on both loop and Adcock direction-finders is a clear indication that these downcoming waves are scattered or laterally deviated in the course of their reflection from above, for had the waves remained undeviated laterally the Adcock direction-finder would have shown less errors than the loop, as is clearly illustrated by the curves of Figs. 17 to 20.

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* *Loc. cit.*

(ii) With either of the instruments described, direction-finding is possible on a wavelength of 24 m up to a distance of 70 miles in the daytime and 30 miles at night (these results applying to summer season only). Up to a distance of 20 miles the bearings are sharp and accurate to within 2°, provided a good open site is found (say 100 yards clear of obstacles in all directions). At distances greater than 20 miles minima become flatter and flatter until they become too flat to read, on both types of direction-finder. At much greater distances, say more than 500 miles, the Adcock pair gives fair indications of bearings of errors not greater than 5°, while the loop direction-finder is practically useless on account of flatness of minima and extent of bearing variation.

(iii) The Adcock direction-finder, though not completely immune, is much less subject to errors due to downcoming waves (provided, of course, they are not scattered) than the loop apparatus, to an extent which is best expressed by the curves of Figs. 17 to 20, and it is for this reason more suited for use with aircraft or for long-distance working from ground stations. At close ranges to ground stations (say within 20 miles), where the downcoming radiation is weak, scattered or very steeply inclined, since there is nothing to choose in accuracy of results the loop direction-finder is to be preferred, being more compact, robust and portable.

This work was carried out as part of the programme of the Radio Research Board and is published by permission of the Department of Scientific and Industrial Research. The author wishes to acknowledge his indebtedness to the staff of the Radio Research Station at Slough and the assistance of many of his colleagues in the work. He would also like to thank Mr. Watson Watt for valuable suggestions relating to the presentation of the results. Much of the observational work was carried out by Mr. Chapman and Mr. Munro, and Mr. Hayman assisted in some of the experiments.

Discussion before the Wireless Section, 2nd April, 1930.

Mr. N. E. Davis: The author has obtained an excellent result in a difficult and patient research toward the elimination of "night effect" in radio direction-finding—a problem to which the research department of the Marconi Co. also continues to devote considerable time. The full practical realization of the Adcock principle for eliminating "night effect" depends almost entirely on providing a non-radiating link between the vertical aerials and the radiogoniometer. The problem is to devise a practical method of transferring energy from the vertical aerials to a receiver situated at ground-level, in such a manner that only the normally polarized components of the wave give directional indication. I should like to mention the method which we have developed for providing a solution of this problem, and the practical results so far obtained. The Marconi adaptation of the Adcock principle for indicating the incoming direction of short-wave radiation relies firstly upon effective screening of the horizontal members, and secondly upon nullification, so far as this is possible, of re-radiation from the screen to the active vertical aerials. The success obtained led us to believe that similar methods applied to the Adcock principle on the medium and longer wavelengths would probably provide a solution to the elimination of night errors in practical direction-finding. Owing to the increasing importance of producing reliable direction-finders as night navigation aids for aircraft, it was decided to make initial experiments on wavelengths of the order of 900 to 1 000 metres. For this experiment, four vertical aerials 70 ft. high were erected with a spacing of 100 yards. This represents a spacing of approximately $\frac{1}{10}$ wavelength. Each of the aerials was terminated in a screening box situated about 5 ft. above the ground and in the same vertical line as the aerial. A single conductor completely shielded in copper tubing and carried about 2 ft. above the ground constituted the horizontal lead-in arrangement from each aerial. This was led to a carefully shielded radiogoniometer in the hut. The ends and centre of the horizontal shields were earthed. Observations on this system over a period have shown that with this adaptation of the Adcock principle it is possible to guarantee an accuracy of 2° to 3° under the worst conditions of "night effect," on a wavelength of the order of 1 000 m. Our experimental apparatus as set up has a direction-finding range of the same order as that of the ordinary loop direction-finder, and it will fulfil commercial or service requirements. We are not yet certain what wave-range can be obtained on a given installation, when keeping within the above-mentioned limits of accuracy. The research department of the Marconi Co. thought that it might add to the interest of the meeting and to the discussion, as well as to the scope of the paper, if I were to show a few lantern slides of the arrangement of our experimental station of medium wavelength. [Mr. Davis here exhibited four slides illustrative of the Marconi Co.'s station.] Tests on wavelengths of the order of 450 to 500 m give every hope of an all-round direction-finding accuracy closely approaching that obtained on the longer wavelengths.

Mr. S. B. Smith: The medium-wave apparatus is of particular interest to most of us, as it is on these waves that radio navigation can be successfully carried out. I should like to ask the author his opinion regarding a suitable wave-range for his apparatus; no doubt commercially it would be ideal to operate the equipment on all usable wavelengths, but does a 2 : 1 wave-range *without rebalancing* represent what he considers to be practical? Eckersley's work on the short-wave Adcock system indicates that it is possible to obtain accurate indications though they may bear little relation to the geographical position of the transmitter, provided the feeder system connecting the aerials to the radiogoniometer is really efficiently screened, and it does seem that, if a solution on these lines can be obtained, balancing schemes, which always present practical operating difficulties, will not be required. The tuned Bellini-Tosi system can be made to give very accurate results in daytime, but the need for frequent and accurate rebalancing made the development of the so-called "aperiodic system" a real necessity. Recently one has read a good deal about directive beacon transmitters of various types, and of their utility as an aid to air navigation; it does seem to me that if night ranges greater than 100 miles overland are required, then the Adcock method in some form must be a natural development, and the present loop methods will become obsolete. The problem of producing a radio beacon free from night effect may become even more difficult than that of the direction-finder, since it appears likely that the equisignal beacon method of transmission will not prove to be free from night effect when applied to an Adcock aerial system, unless very careful symmetry be maintained between each aerial and the feeder system. In plotting the deviation curves on the Adcock and loop arrangements I notice that the author has omitted to record any observations on the Adcock aerials when quite large variations are present on the loop; why not give definite observations in such cases? It has been our custom in plotting swings greater than 90° to reverse the sign of the observations. The chain-coupled Adcock direction-finder shown in Fig. 12 suggests another method which in practice may be even more difficult to realize; this consists in coupling each aerial to a rectifier, radiating a local carrier from a central aerial, and passing a beat tone over four lines to a central hut. It should then be possible by this frequency change to construct a line of such constants that at the fundamental frequency it is *non*-radiating, while the changed frequency can be arranged to reproduce the desired results at the radiogoniometer, possibly at low frequencies. We tried this scheme on a wavelength of 15 000 m in 1923, but the test failed owing to the small receiving power of the aerial. The spacing between the aerials was only 1/200th of a wavelength. In comparing night variations on direction-finders spaced about 2 wavelengths apart it has been found that the deviations are far from synchronous, and although the variations do usually occur on both aerials a very small interval may pass before the variation will be reproduced on the second direction-finder.

Mr. C. E. Horton: The main results of the author's work are entirely in agreement with my own experience. With regard to the last sentence on page 1056, to the effect that the range of the installation with standard forms of amplifier was not noticeably different from that of the Bellini-Tosi system, I think it might legitimately be inferred from this that the Adcock is just as sensitive as the Bellini-Tosi direction-finder on medium wavelengths. A Bellini-Tosi system with square loops of 20-ft. side constitutes a satisfactory and sensitive receiver for wavelengths between 200 and 20 000 metres. Would an Adcock direction-finder be equally sensitive under the same conditions of space and wavelength range? I think that its sensitivity would be less, because the impedance of the aerial system of the Adcock apparatus on long waves compares unfavourably with that of the Bellini-Tosi equipment. The aerials used in the author's experiments are very large—80 ft. high and with 50-ft. spacing. A Bellini-Tosi system of corresponding size would give a large response. With a medium-wave Adcock system of the size of an ordinary frame coil it would be very difficult to get sufficient signal strength. With regard to residual errors in the author's system, it seems to me to be unfortunate that he did not use another system which has been employed in the Navy and which, while not theoretically faultless, gives very good results—possibly better than those in the paper. I refer to the method of eliminating all horizontal pick-up by using lead-sheathed cables. All horizontal leads take the form of paper-insulated cables several feet underground, as used by Mr. Eckersley in his short-wave work. For ground of ordinary conductivity this is a simple and satisfactory way of arranging Adcock aerials, and it would be of interest if the author were to continue his work by making a direct comparison between this method and his own. I am particularly interested in direction-finding in ships, where I found that the Adcock system was difficult both to install and to work. It is assumed in the theory that two aerials of equal height have equal e.m.f.'s induced in them, and serious errors will result if equal pick-up is not obtained on all the aerials. Two vertical aerials of exactly equal dimensions installed in a ship are generally found to differ perceptibly in receiving power, and it is only by careful adjustment, usually varying with the frequency, that exact equality of induced e.m.f.'s can be obtained. I refer chiefly to battleships, where the congestion of the metal work on the upper deck considerably affects reception. It is possible that equal difficulty is not experienced in merchant ships. On page 1068 the author refers to the necessity of a good open site (say 100 yards clear of obstacles in all directions). Such conditions are not found on a battleship, and remembering that an error of 2½° was obtained in a bearing owing to a village 100 yards distant, the effect of a funnel a few feet away and the difficulties associated with short-wave direction-finding in ships can be appreciated. Oddly enough, better results have been obtained on very short waves of the order of 12 m than on waves of the order of 30 or 40 m.

Mr. J. F. Herd: The difference in the behaviour of the closed-coil receiver and that of the Adcock in the presence of abnormally polarized downcoming waves is beautifully demonstrated by the small elevated transmitter (with which the author's curves of Figs. 17 to 20 were obtained). While the transmitter is giving normal polarization, the closed-coil receiver gives good and accurate minima. When the transmitter is tilted so as to give abnormal polarization the closed-coil receiver gives a minimum which is visibly inaccurate. This is particularly obvious if the coil is kept set at the minimum for the transmitter and the transmitter is then swung. Very considerable re-orientation of the coil is necessary to give even the inaccurate minimum. Repeating this experiment with the Adcock aerial, while the polarization is normal the directional indication is exactly similar to that obtained with the closed-coil receiver. When, however, the transmitter is tilted by the same amount as in the coil experiment, the minimum indication does not wander. This is again particularly obvious if the Adcock aerial is kept set at the transmitter minimum, and the transmitter then tilted, when no change of minimum is discernible. With reference to the medium-wave apparatus, it would be interesting to have a comparison between the results obtained by Dr.

Smith-Rose and the author when working in their original elevated hut, and those given by the present Adcock system (of Figs. 1 and 2) working at ground-level.

Dr. R. L. Smith-Rose: When Mr. Barfield and I wrote our paper* some three years ago we left the Adcock direction-finder literally in the air. The apparatus was suspended between the poles carrying the aerial system. The work of bringing the system down to earth, which the present author has carried out, may seem to be a simple operation so far as the hut is concerned, but the difficulties encountered in connection with the rest of the apparatus can only be fully appreciated by those who have had considerable experience of this class of research work. On looking through Mr. Adcock's patent recently I was surprised to find how completely its originator had appreciated the nature of the problem even so early as 1916. He has described in full a number of methods whereby the difficulties due to the downcoming horizontally polarized electric waves could be overcome. It appears, however, that his conception of this matter was rather too early for it to be fully appreciated by those responsible for the application of direction-finding to navigation. In the present paper the author has shown very clearly, in such diagrams as Figs. 17 and 18, the possibility of considerable errors, of 20° or more, being obtainable with the ordinary closed-loop direction-finder when used in making observations upon the transmissions from aircraft subtending an angle of elevation at the ground of the order of 10°. As the diagrams in the paper show, these errors can be reduced to about one-tenth of their magnitude by the use of the Adcock aerial system. I would suggest that it is important that the development of the apparatus in the direction of its practical application should be proceeded with as rapidly as possible, in order that it may be retained as an entirely British invention. I believe that no other country is at present using it for practical direction-finding, although the system is being used in America for studying the propagation of waves. In connection with the theoretical part of the first section of the paper given on pages 1059 to 1061, I should like to ask the author whether he has not taken into account twice some of the e.m.f.'s induced in the aerial circuit. It appears to me that the equation in col. 2 of page 1059 contains an expression of the current as derived from the electric force acting on the aerial system, plus the same quantity as derived from the magnetic force acting on the system. I would suggest that it is an axiom that, in dealing with electromagnetic waves and their effect upon aerials and loops, one may consider the effect of either the electric field or the magnetic field. By suitably manipulating the necessary equations one should obtain the same result from either method. For example, in the case of the induction of an e.m.f. in a closed loop by a stream of electromagnetic waves, one may take either the line integral of the electric force round the perimeter of the loop or the surface integral of the magnetic force intercepting the loop at right angles to its plane. Since the magnetic force is merely derived from the motion of the electric force the same result for the induced e.m.f. will be obtained for either case. I am aware that in certain cases, such as that of the reflection of waves from a conducting surface, it is possible to obtain a resultant magnetic component which is not equal to the resultant electric component in a certain direction, and the measurement of the ratio of the intensities of these components is used as the basis of the method of measuring the angle of incidence of waves upon a conducting surface. In this case, however, we are dealing with resultant fields in two directions, and a detailed consideration of the directions of the fields and of their motions will show that the conclusions stated above are not in any way invalidated. A portion of the analysis given on page 1060 is somewhat difficult to follow, apparently on account of one or two misprints and omissions in the nomenclature, which I have already pointed out privately to the author. I have always found the aerial system drawn in Fig. 9(*a*) a little difficult to follow, especially when one is attempting to visualize the conditions which are necessary for compensation of the e.m.f.'s induced in the horizontal portions. If, however, the aerial circuit is re-drawn as a simple impedance network, as indicated in Fig. A, it then immediately becomes apparent that in the presence of horizontal electric forces from the arriving waves the condition for obtaining low current through the field coil "a b" is that the reactance of the aerial must be equal to that of the earth connection beneath it, assuming that the four aerials and earth connections are identical in dimensions and configuration. This condition can be met either, as the author has stated, by introducing negative reactance into the earth lead or, alternatively, by introducing positive reactance into the aerial. Since in the case of the direction-finder it is desirable to maintain the natural wavelength of the aerial system well below that of the arriving waves, the alternative of introducing negative reactance into the earth lead is obviously the one to adopt. As the author has pointed out, a further condition to be met in order that a complete balance of the aerial system shall be obtained is that the current distribution in each aerial circuit shall be symmetrical about the centre point of the coil "a b." In col. 1 of page 1060 the author states that this condition is obtained at the same time as that of the equality of reactance by the use of balancing capacity in the earth lead. As the discussion of this condition is dismissed in a few lines and the conclusion is not quite obvious, I should like to ask the author whether he can elaborate this point a little and give a more detailed explanation. In con-

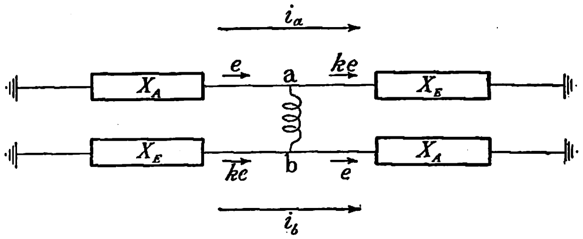

FIG. A.—Condition for zero current through "a b" is $X_A = X_E$.

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* "The Cause and Elimination of Night Errors in Radio Direction-Finding," *Journal I.E.E.*, 1926, vol. 64, p. 831.

sidering the possibilities of the future development of the Adcock system, I am not clear from the discussion given in the paper to what extent the systems indicated in Figs. 12 and 13 are superior to that of Fig. 11, which appears to me to offer the most hopeful promise of success in the future. The author admits on page 1062 that the arrangement shown in Fig. 11 is subject to only one type of error, viz. that due to the effect of the electric coupling between the horizontal conductors and the vertical aerial. I would suggest that there is also the possibility of the induction of an e.m.f. directly into the loop enclosed by the horizontal conductors. I think that both these errors could be reduced to zero by a suitable arrangement of the horizontal conductors between the two vertical aerials. In the second part of the paper the author has shown that with the aid of modern receiving amplifiers it is possible to use direction-finders of either the closed-loop type or the Adcock type on wavelengths from 12 to 60 m with similar success, as far as the actual instrument is concerned, to that obtainable on wavelengths of 300 to 1 000 m. The author has displayed considerable ingenuity in this short-wave direction-finder in arranging the coupling coil between the rotating aerial system and the secondary circuit with no mechanical connection between them. The latter portion of the paper describing the results of observations on short-wave transmissions is important not only in showing the limitations of any system of direction-finding on these wavelengths, but also in demonstrating the utility of the two types of direction-finder in studying the propagation of short waves.

Lieut.-Col. H. P. T. Lefroy: In communication by line, the " rotation " of the go-and-return conductors, to avoid effective radiation from, or absorption by, those conductors, is a well-known and very useful arrangement; the pitch of such mutual twisting of the two conductors about each other is relatively long, and the frequencies dealt with are of the acoustic order. In 1921 I investigated the effect of such mutual twisting for radio frequencies, and found that the shorter the pitch the more complete was the absence of radiation from, or absorption by, a pair of go-and-return conductors. The higher the frequency dealt with, the shorter should be the pitch. I tried twists up to 10 per inch, using silk-covered wires of suitable gauge. The effect of such intensive twisting is greatly to increase the mutual capacity and reduce the inductance of the pair; the effective resistance is also increased. When such a sharply-twisted pair, joined at one end, was wound to form the secondary of a radio-frequency transformer, no sound could be heard in a telephone fitted, in series with a rectifier, across the other end of the pair, when the coil was suitably coupled to a primary coil carrying fairly strong damped oscillations. It seems possible that all undesired " pick-up effect " might be eliminated, in the Adcock direction-finder for short waves, if such an intensively-twisted pair were fitted to act as the horizontal leads, with the receiving coil connected, between the centre points of the two wires forming the pair, by a small fixed condenser at each end of that coil.

Air-Commodore A. D. Warrington-Morris: I am glad that this paper on Adcock aerials has been read, because the subject has recently been arousing considerable interest from the points of view both of Service flying and of civil aviation. Three of the civil aviation companies—the French, German and Belgian—are starting night services to Croydon. We have three directional stations—at Croydon, Pulham and Lympne—which by day normally guide the movements of the international aircraft. They do it very satisfactorily, and in foggy weather their function is an important one. Now that night services are being started it is necessary to produce direction-finding apparatus which will be of use after dark. The results obtained with the Adcock aerial are strikingly good, but I am not clear as to what is meant by " standard deviation." The author states that it is obtained by taking the root-mean-square value of the variation of individual observations from their arithmetic mean: I should like to know how this compares with what we call the " average error " (plus or minus). The distance between the two vertical aerials shown in Fig. 1 is given as 50 ft. I understand that accuracy, as well as pick-up value, is affected by the distance apart of such vertical aerials, and I should like to ask the author whether it was purely with a view to economizing in space and the cost of masts, or whether it was due to the difficulty of balancing, that he only allowed 50 ft. between the two vertical aerials. In connection with this last difficulty, is it necessary to re-balance the system after a change of wavelength? I recently saw a demonstration at Chelmsford of a Marconi-Adcock arrangement in which four 70-ft. masts were employed, and the leads-in were thoroughly screened. This seemed to me to be a simple and efficient method of attaining the object in view, i.e. the elimination of the effect of the horizontal aerial. A number of bearings on Hilversum were taken at night simultaneously with this equipment and an ordinary Bellini system. Whereas the maximum error with the Adcock system was about 2°, the Bellini apparatus gave errors of 20° or more. With regard to the author's conclusions as to short-wave direction-finding, he deals a blow to the installation of short-wave apparatus in aircraft when he indicates that it will never be a practical proposition, on wavelengths of 12 to 60 m, to take direction-finding bearings of a transmitting station at ranges exceeding 20 miles. I should like to ask him whether there is any hope of success on rather longer waves of from 60 to 100 m, provided that the power of the transmitting set is considerably increased. A range of about 200 miles is required.

Mr. T. L. Eckersley: I am glad that the author has thoroughly tested-out the behaviour of the Adcock aerial under what may be called horizontal polarization conditions. Although my main interest at present lies with short waves, direction-finding results on the long-wave band which might affect this long-outstanding problem are of great interest to me. The author has produced at least one method of obtaining bearings free from night error. There are, I think, other systems capable of achieving this result, and it is merely a matter of practical handling to determine which is likely to be the best. Regarding the circuit shown by the author, in which horizontal lead-in is balanced by horizontal lead-out action and then balanced by a condenser to earth, I would mention that about 1917 I made a similar suggestion in a report to the War Office. It is easy, however, to make a suggestion: it is to the application of the suggestion to a practical system that the real credit is due. With regard to short waves, the author has done much of the work which I had left to future developments. I am glad to find that he affirms in a general way the results which I obtained earlier with rather a different type of Adcock apparatus, but one which appears to have functioned very similarly to the Adcock aerial which he himself has used. The short-wave frame apparatus with its screened loop seems to be a good arrangement as it almost entirely eliminates the vertical effect. By means of careful balancing, however, it is possible with a frame to get almost perfect minima on short waves if everything such as batteries, receiver, etc., is shielded. At present we are using a receiver in which the batteries are external with a short-wave direction-finder, and it is only with a 2-ft. frame that we find it possible to anchor the leads outside in such a way that the amount of energy received on battery leads, etc., is negligible compared with the amount received on the frame. Such an arrangement dispenses with the necessity of having batteries inside a portable box, and to a certain extent this makes it easier to work. With regard to the Adcock arrangement for short waves, this seems to be an alternative method of obtaining signals free from " night effect," and, as the author points out, it is rather difficult at first to see why the balance should not be perfect. I agree with him that this is not possible because of the fact that the lower limbs of the vertical part are not exactly symmetrical with the upper part. In connection with the long-distance test, I should like to ask whether the author made any measurements on distant stations, such as New York, so as to gain some idea of the accuracy obtainable on these. On our system I have noticed a swinging of the bearing of about 3° or 4° on long-distance stations, for example Canada and New York, and I am not sure whether to attribute it to a real wobble of the bearing or to horizontal polarization effect. I think that far better balancing than can be obtained either with the author's or my own system is necessary in order to make certain of this. The question would be important from the point of view of beam transmission should a wobble of 3° or 4° be shown to exist. I think that the author has confirmed the presence of scattering and, perhaps in response to this, one may say that there is little hope of getting reliable direction-finding results in the " skip distance." As a matter of fact, errors up to 90° may be obtained in the case of the beam transmitter, and one never knows where this may occur. So far as we know at present, it is impossible to be certain of the bearing within the " skip distance."

Mr. F. Adcock (*communicated*): In the course of the discussion on the paper a speaker referred to a direction-finder which appeared to be remarkably free from " night error." In that equipment the horizontal insulated leads were screened by placing them within metal tubes which were carefully sealed and earthed at several points. I am interested in this method of reducing or avoiding " night error," as at one time I experimented with a direction-finder in which the horizontal leads from the vertical aerials to the operator's hut consisted of insulated wires simply laid on the surface of the ground. With this improvised arrangement the errors in bearings taken on aircraft were about one-quarter as great as those procured by means of a closed-loop direction-finder. As it was impossible to make further experiments it remained doubtful how far the improvement in accuracy would be maintained for other wavelengths and for different conditions of the soil on which the direction-finder was erected. One would expect a reduction in " night error " when the horizontal leads of a direction-finder are placed near the ground-level, but the complete elimination of the error in all circumstances is unlikely by this method, owing to the poor conductivity of the soil. So long as the soil in the vicinity of the direction-finder is fairly uniform in conductivity the re-radiated energy takes the form of the usual reflected wave, which should not unduly disturb the bearings obtained by the installation. On the other hand, horizontal conductors situated near the direction-finder would distort the reflected wave. Expressed in another way, oscillations present in horizontal conductors or in the earthed screens surrounding horizontal conductors may, owing to re-radiation or to electric or magnetic coupling, give rise to undesired oscillations in the vertical aerials. Owing to the relatively poor conductivity of soil it is impossible to " anchor " the screening tubes by any ordinary system of earthing. For these reasons it appears that there is some risk of error in direction-finding installations where the horizontal leads are carried in long continuous screening tubes which are earthed at several points.

Mr. R. H. Barfield (*in reply*): I am interested to hear that Mr. Davis is adapting Eckersley's screened " U " Adcock to practical direction-finding, and to see that it is giving good results. Experiments which I have carried out since reading the paper show that for short waves (20 metres) the screen can have but a negligible effect on the performance of the system, whether earthed or insulated. The ordinary unscreened " U " Adcock is amenable to fairly simple calculation, and it appears that the horizontal pick-up may be of the same order as the vertical pick-up under some conditions. For this reason it was dismissed some time ago. Mr. Adcock gives a criticism of the "U" Adcock screened and unscreened, with which I am in substantial agreement. He gives a figure for the performance of the " U " Adcock which, though somewhat more favourable, is of the same order as that obtained by a calculation.

In reply to Mr. Smith, the wavelength range of the balanced Adcock system with a given balancing capacity has no upper limit other than that of amplifier sensitivity since, for waves long compared with that of the aerial, the impedances which have to be balanced are both purely capacitative and therefore change equally with frequency. The lower limit occurs when the working wavelength begins to approach that of the aerials. It should therefore be possible to work with very large wavelength ranges. For reasons connected with the residual effect referred to in the theoretical analysis, the balancing of the condenser is not critical, and the case of the tuned Bellini system is therefore not a parallel one. In a commercial design of the system they would probably take the form of fixed condensers in sealed weather-tight boxes and would never require any attention. The interruptions in the Adcock observations, referred to by Mr. Smith, were due to causes such as adjustment of apparatus, changing of batteries, etc.

In reply to Dr. Smith-Rose, in assuming a sine-law distribution for the current in an untuned aerial, I have taken it for granted that the relative value of the current at two points in an aerial would be independent of the frequency of the e.m.f., provided the aerial was oscillating as a whole and not in harmonics. The introduction of positive reactance into the aerial circuit is a possible way of balancing an Adcock system. I rather fancy, however, that a resistance balance would in this case be also necessary. I have no proof that balancing the impedances in the manner described in the paper causes symmetry of current distribution about the field coil, but I think it is a very reasonable hypothesis. It is difficult to see about what other point the distribution could be symmetrical than the point which divides the aerial into equal impedances. The type of error to which the system in Fig. 11 is subject is set out in paragraph (3) on page 1062. I cannot see that any arrangement of the leads in Fig. 11 could prevent the horizontal length as a whole acting as an antenna which is effectively coupled to the vertical members. The superiority of Figs. 12 and 13 is that this antenna is *broken into short lengths* which are individually too small to have any effect. I do not think I am guilty of using the same field twice over to derive the current in one circuit, as Dr. Smith-Rose suggests. The fact is, the circuits are not the same. Consider the aerial system in Fig. B, which is the combination of a loop and a vertical aerial, and is in many respects analogous to the arrangement questioned by Dr. Smith-Rose, as shown by Fig. C. The current in the limb CE is given by the sum of two currents,

$$I = \frac{Eh}{Z_A} + \frac{2\pi Ehd}{\lambda Z_L}$$

where Z_A = impedance of aerial circuit
and Z_L = impedance of loop circuit,

which is the same as

$$I = \frac{Eh}{Z_A} + \frac{\omega AH}{Z_L}$$

where A = area of the loop. Here we are taking both E and H into account without any redundancy.

Mr. Herd asks how the balanced Adcock compares with the elevated hut Adcock as regards immunity from night errors. No tests of the latter were made with controlled downcoming waves, and as the night tests were comparatively few in number the basis for comparison is scanty. I am inclined to think, however, that the elevated hut Adcock had a slightly better performance than the balanced system. Its characteristic curves would probably be similar to those obtained with the short-wave rotating Adcock of Figs. 19 and 20.

I agree with Mr. Horton that the sensitivity of the Adcock receiver is not as great as that of a closed-loop system of similar dimensions. This is particularly true on long wavelengths. For a system such as that shown in Fig. 10 the ratio of the current in the goniometer field coil to that in a closed loop is given by:—

$$\frac{I_{\text{Adcock}}}{I_{\text{Loop}}} = \frac{hs}{A} \cdot \frac{Z_{\text{Loop}}}{Z_{\text{Adcock}}}$$

Mr. Horton also refers to the screened "U" Adcock as being possibly superior to the balanced Adcock, as explained above. I do not think this is the case. Mr. Horton suggests that a careful comparison of the two systems should be made. I am at present carrying this out and hope to extend the work to a comparative study of the many other possible modifications of the Adcock system. I sympathize with Mr. Horton in the difficulties which he meets in attempting to install an Adcock direction-finder on a battleship.

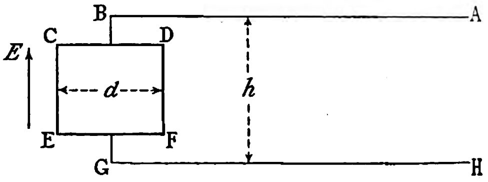

Fig. B.

Lieut.-Col. Lefroy's method of preventing pick-up on the horizontal leads by rotating them is sound in principle, but, on calculation, the amount of pick-up caused by the spacing of the wires is so small that rotation is in the nature of a refinement to which it would not be necessary to resort until the more important sources of error referred to in the paper have been eliminated.

In reply to Air-Commodore Warrington-Morris, the spacing of the vertical aerials certainly affects the pick-up value but not, I think, the accuracy during night effect, since the action of both vertical and horizontal fields is equally affected by any change in this dimension. The most important factor to be considered is the ratio of aerial height to wavelength, which should be made as great as possible. With the central mast arrangement an increase of spacing means a decrease in height; hence the spacing was kept as small as possible. As I have already pointed out in my reply to Mr. Smith, it is not necessary to re-balance on changing wavelength. I am interested to hear particulars of the performance of the Marconi Adcock system. As I have already said, I do not believe that horizontal pick-up can be eliminated or greatly reduced by screening. The "standard deviation" is not the same thing as "average error," but, as defined in Table 1, it is the root-mean-square. One reason why this value was used in preference to the other is that it gives a result free from permanent errors due to site, etc., in which we are not interested.

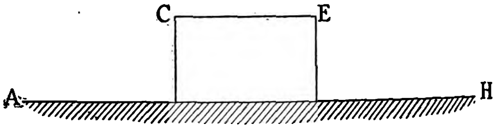

Fig. C.

In hearing from Mr. Eckersley that, in suggesting the possibility of balancing the Adcock system, I am forestalled by him by a matter of 13 years, I am rather flattered than discouraged and therefore gladly acknowledge his claim to priority. In developing the completely screened loop direction-finder I have always realized that the same result could be achieved by careful balancing. I think Mr. Eckersley will agree, however, that there is something attractively "fool-proof" about the screened loop which makes it superior for nearly all purposes. Though I should very much like to do so, I have not yet made any tests with the short-wave Adcock over very long ranges. The difficulty is to find time and staff for following up all the avenues opened by a given investigation, and, as Mr. Eckersley says, it will be well to wait until we have more perfect apparatus.

DISCUSSION ON

"THE HEAT PUMP—AN ECONOMICAL METHOD OF PRODUCING LOW-GRADE HEAT FROM ELECTRICITY."*

North-Eastern Centre, at Newcastle, 14th April, 1930.

Mr. T. Ritson: The title of the paper is rather misleading at a first glance, and the paper needs careful study before the author's meaning is fully grasped. It is only by the author's choice that electricity is used for this system; any other prime mover may be used as the operator, though the electric motor will probably be the most suitable in the majority of cases owing to its ease of control, absence of noise and other well-known advantages. In the application of the principle, available heat is transferred by the application of energy and not produced, so that I think the efficiency of transference (as defined in the paper) should not be compared directly with the efficiency of heat production by the direct conversion of energy. Perhaps it would be better to use some other term than "efficiency," because actually what is secured is a thermal advantage of heat transference. The system is very speculative in practice when one considers the amount of heat available for transference, but, given the correct combination of conditions, it should be a most economical method of using energy to obtain the desired result. I do not know how the space factor of the equipment compares with that of modern existing systems of heating, but if this is favourable and the possibility of obtaining a satisfactory heat source is secured, considerable progress should be made. The example of a swimming bath is given in the paper, and, speculatively, if the swimming bath were run in conjunction with a large refrigerating plant the combination of conditions might be satisfactory. There are many other such complementary instances of use, of which I will mention a smallholding, with a creamery or dairy requiring cold and forcing frames or greenhouses requiring heat; and a large hotel situated near the sea, with its vast store of heat.

Mr. T. Carter: In some ways the most significant sentence in the paper is that in which the author says that to the best of his knowledge no detailed experiments other than those carried out by him have ever been made on a refrigerator used primarily as a heat pump. The significance lies in the fact that the author has had the courage to prove the practicability of what was previously a purely theoretical proposal, and in so doing he has added one more to the already many uses of electricity in domestic or industrial applications. If he wishes, as he doubtless does, to familiarize electrical engineers with what to many of them may be a rather new idea, I suggest that in spite of his careful footnote on page 667 about the term "heating efficiency" it is not altogether easy to become accustomed to the thought of efficiencies greater than unity, greater, that is to say, than 100 per cent; and I think it would be better if he adopted another term, especially when in other parts of the paper he uses "efficiency" in the ordinarily understood sense. What the heat pump does, it seems to me, is largely to transfer existing heat from one place to another, adding to its temperature, more or less, on the way; and the less the temperature is raised, the greater is what the author calls the heating efficiency of the transfer. The heat transferred is a natural product, contained in a natural storehouse of atmosphere or ocean, and it appears from the formula for heating efficiency that a wind blowing from one place to another without change of temperature is carrying heat at an infinite efficiency, viewed from man's standpoint, since no artificial energy has to be put into the transfer at all. The ratio $T_2/(T_1 - T_2)$ is called the "coefficient of performance" of a refrigerating machine. The author uses the ratio $T_1/(T_1 - T_2)$, which in the ideal conditions is exactly equal to the coefficient of performance plus unity. Could he not use $T_2/(T_1 - T_2)$, and call it the coefficient of performance of the heat pump? Or, if he wants to use $T_1/(T_1 - T_2)$, could he not call it the "coefficient of operation"? But why cannot he use the same expression for efficiency, $(T_1 - T_2)/T_1$, as is used for the efficiency of the perfect heat engine, the heat pump being merely a heat engine working on a reversed cycle? If an electric motor happens to be used as a dynamo, does one describe its efficiency by a percentage greater than 100? By no means: the same kind of value serves both for motor and for dynamo, and so it might for heat engine and heat pump correspondingly. I have been trying to familiarize myself with the idea of the heat pump by using some analogies, imperfect, no doubt, as most analogies are, but still possibly helpful. I have thought of a 3-wire direct-current balancer, which transfers power from one side of a supply system to the other when the consumption is not equal on the two sides. A large load may be passing across the two sides in series, and the relative power of the balancer set may be very small, so that the efficiency of the whole operation is very nearly 100 per cent, considered on the ordinary lines of efficiency. This means that a small piece of additional apparatus is effecting a transfer or something within its capacity to deal with in such a way that it makes it serve some definite purpose in a very much larger system. So, too, the stoker in the boiler house does not produce the energy of the boiler fire, but merely puts the fuel where its inherent potential energy can combine with another and generate heat; and what has to be paid for is not the energy itself, which is a natural gift, but its release. I have thought, again, of a lake in a hollow on a hill-top, the water of which cannot be used to do any work unless a pump is installed to raise it up to the lip of the hollow, from which it can then flow down the hill-side. If the surface of the water is H_2 feet above sea-level, and the lip of the hollow H_1 feet above sea-level, the efficiency of the arrangement, calculated as the author calculates for the heat pump, is $H_1/(H_1 - H_2)$. Here, as in the heat pump, the body moved does not use its own energy for any part of the transfer from the useless to the useful place: a definite amount of power is used to make the inherent energy available in a particular way. I have thought, finally, of a postal order. If I hand 7d. to the post office, I can use one of the 7 pennies to make the other 6 carry their buying power to any place I choose. The penny is money with a purpose quite different from that of the 6 pennies. They are circulating coins, but it, like the energy of the electric motor in the heat pump, is absorbed in the machinery of the transfer, the feeding, clothing, sheltering, and entertaining of the post-office staff; and the author, I imagine, would agree that the efficiency of the transaction, calculated in his way, is 700 per cent. I should like to close with a quotation from Prof. J. A. Ewing's book, "The Steam-Engine and Other Heat-Engines," published in 1894, because it seems to me to express a principle of which we are only now beginning to realize the full importance. "Burning fuel to warm a room by a few degrees is a wasteful way to utilize heat, even if all the heat of combustion be conceived to pass into the air of the room. The high-temperature heat produced in the combustion of coal or gas could warm a much larger volume of air to the same extent if it were applied to drive an efficient heat-engine, which in its turn drove a reversed heat-engine or warming machine to pump up heat through a short range from the diffused store of heat which is contained in the atmosphere or in the ocean. This is because a heat-engine can be arranged to take advantage of the high temperature at which heat is produced in the burning of fuel, whereas any direct communication of this high-temperature heat to a comparatively cool body, such as the air of a room, is thermodynamically bad. It is interesting, and may some day be useful, to recognize that even the most economical of the usual methods employed to heat buildings, with all their advantages in respect of simplicity and absence of mechanism, are in the thermodynamic sense spendthrift modes of treating fuel." The author has left us in his debt by showing us in his paper one way of putting to practical use, instead of finding merely interesting, the process described 36 years ago in the words I have quoted.

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* Paper by Mr. T. G. N. Haldane (see page 666).

Mr. H. W. Clothier (*communicated*): Most of the speakers are concerned about the use of the term "efficiency" to describe the gain in heat energy claimed by the author for his system; but what matters chiefly is that the heat acquired from an external source with a comparatively small expenditure of motive power shall be put to a useful purpose in the efficient heating of a building. I agree with the author that the system which he describes should have the close attention of the electrical industry. I feel sure that this will lead to the working out of some practical applications; the use of electricity as a prime mover of the heat pump should be encouraged, if only on the off-chance that more electricity will be required for topping-up by means of immersion heaters. In a discussion * on the recent paper by Messrs. Monkhouse and Grant I gave comparative costs of heating a house by central heating from a coke boiler and by hot-water storage from an electric night-load. It would be of interest if the author could add to this comparison a statement of the corresponding cost of using the heat-pump system for the same purpose, on the assumption, let us say, that his suggestion of using sewage water as a source of low-grade heat could be put into practice. It may seem at first sight to be a rather far-fetched suggestion; but it is conceivable that it might lead to useful results in other situations where external water is available under similar conditions of temperature.

Mr. T. G. N. Haldane (*in reply*): I have been taken to task both by Mr. Ritson and Mr. Carter for the manner in which I have used the expression "heating efficiency" in connection with the heat pump. The main objection seems to be that my definition of the expression (which is carefully explained in the footnote on page 667) leads to efficiencies greater than 100 per cent. Now Mr. Ritson and Mr. Carter may very well object on principle to the suggestion that any machine can have an efficiency of over 100 per cent, and I would share their objection to my use of the expression "heating efficiency" if it were not for the fact that by universal custom and usage 100 per cent heating efficiency is said to be that which would be obtained if the whole of the heat of combustion of a given quantity of fuel or the whole of the heat equivalent of a given quantity of electrical energy were usefully employed for heating purposes. It is accordingly customary to refer to the efficiency of a coal- or coke-fired boiler as being a certain figure less than 100 per cent, depending on the fraction of the heat of combustion usefully employed, and the electric radiator is said to have a heating efficiency of 100 per cent because the whole of the heat equivalent of the electrical energy consumed is usefully employed for heating purposes. It may be unfortunate that the heating efficiencies of boilers and electric radiators are so measured, but neither Mr. Ritson nor Mr. Carter could have expected me to try to alter such universal practice. I had therefore little option but to accept the existing use of the definition "heating efficiency" and so give to the heat pump efficiencies running into several hundred per cent. As I remark in the footnote in the paper, this may be objectionable from a purely thermodynamic point of view, but I believe it is really descriptive of the practical operation of the heat-pump system. Mr. Carter goes so far as to draw a comparison between the expression "heating efficiency" and the efficiency of the transference of money by means of postal orders, and asks whether it would be reasonable to call the efficiency of a sixpenny postal order 700 per cent (I think he means 600 per cent) since by expending one penny we can transfer sixpence from one place to another. I would reply that if, previous to the invention of postal orders, we had been in the habit of spending sixpence in order to transfer sixpence and had called the efficiency of this process 100 per cent, then it would be reasonable to call the efficiency of the sixpenny postal order method 600 per cent.

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* See page 685.

I think Mr. Ritson and Mr. Carter feel that the heat pump is cheating because in their view it does not "create" heat as does a burning lump of coal or an electric radiator. To them the heat-pump process is only a transference of heat. It is essential, however, to bear in mind that the reversed-cycle heat engine is not merely transferring heat from one place to another, but in separating two quantities of heat is altering the temperatures and so actually creating something which was not there before. In other words, a given quantity of heat at one temperature is really an entirely different commodity from the same quantity of heat at another temperature. The process of the heat pump is to depress by an infinitesimal amount the temperature of the infinite quantity of heat of our surroundings, and so produce a limited quantity of heat at a temperature sufficiently high to be of use. Viewed in this way the heat pump is actually producing useful heat in very much the same way as the lump of coal produces useful heat when, in the process of combustion, its stored potential heat energy is converted into a useful form.

Mr. Carter's suggestion that the expression "coefficient of performance" or "coefficient of operation" should have been used in place of "efficiency" is open to the objection that it would almost inevitably have been confused with the coefficient of performance as used in refrigerating engineering, and moreover it would, in my opinion, have been far less descriptive of the actual operation of a heat pump.

The various analogies which Mr. Carter suggests are both ingenious and helpful, but, like all analogies, if they are pushed too far they break down. For instance, in Mr. Carter's analogy of a lake in a mountain hollow, the water of which has to be raised to the lip of the hollow by mechanical energy before it can fall to the valley below and so do useful work, he is comparing the quantity of water with the quantity of heat produced by a heat pump. Unfortunately these quantities are not comparable, one being a measure of mass and the other of energy. A more or less exact analogy can only be obtained if in place of heat we substitute the rather abstract conception of entropy and compare this with the quantity of water in the hydraulic analogy.

I am glad to find that Mr. Clothier is less critical of the expression "heating efficiency" and supports my contention that the use of the expression is justified, at least by works, if by nothing else. Mr. Clothier suggests that to the interesting figures of the annual cost of heating a dwelling-house, which he gives in the discussion on the paper by Messrs. Monkhouse and Grant, should be added a corresponding figure for heating by the heat pump. The heating of an ordinary dwelling-house is not at present a very favourable application of the heat pump, pending the development of cheaper small-size refrigerators, and an estimate of the cost is somewhat difficult owing to its dependence on the special circumstances of each particular case. Assuming, however, that sufficient radiator surface is available to operate the heating system at the comparatively low temperature suited to the heat pump, but that a large proportion of the heating is done during the day at day rates, I estimate that the annual cost of a heat-pump system would be slightly higher than that of the electric thermal-storage system, i.e. about £160, as compared with £150 10s. This makes no allowance for the advantage of abundant ice or cold storage, nor for the possibility of cooling the house in summer. I would refer Mr. Clothier to an interesting article by Monsieur Guarini which appeared in the issue of *Cold Storage* of the 17th April, 1930, dealing with small-scale heating by means of the heat pump.

DISCUSSION ON

"THE HEATING OF BUILDINGS ELECTRICALLY BY MEANS OF THERMAL STORAGE."*

WESTERN CENTRE, AT CHELTENHAM, 14TH APRIL, 1930.

Mr. W. J. Bache: Great difficulty is experienced in the satisfactory heating of a series of rooms such as the Cheltenham Town Hall by hot water. Conditions may vary every night in every room and constant complaints of overheating or underheating are the result. Electrical heating with thermostatic control would give much more satisfactory results.

Mr. H. R. Beasant: I doubt the utility of estimates of running costs based on such a low unit price, the price given by the author being exceptional and not generally available. Important advantages are to be gained by the use of electricity, e.g. convenience, ease of control, cleanliness and smaller space required for installation, and these in many cases justify the use of electricity at a higher unit charge. For premises where the period of use of different rooms varies considerably, the method of direct heating (e.g. by tubular heaters) appears to offer the better solution, especially where low night rates are not available. As an instance of this, a greenhouse where certain difficulties prevented the erection of a heating chamber and flue was heated electrically by tubular heaters controlled by a thermostat, to the satisfaction of the owner, although the price of energy was 1d. per unit.

Mr. J. M. Bowman: What will happen to the supply engineer if a multiplicity of thermal-storage connections is made to the distribution mains? For the smaller undertakings this would necessitate a complete re-laying of the distributing system and an increase in the capacity of the generating stations. Are any experiments being made with a view to providing an element which will give a maximum heating capacity at, say, half the present consumption of watts? I would refer to the rapid strides made in illumination, where the number of watts consumed per candle power has dropped very considerably—with a much greater efficiency as the result.

Mr. W. Burton: To fill up the valleys in the load curve has long been the ideal of the supply engineer, and this ideal can be achieved in another way, giving equally good results, if we encourage the use of 100 per cent load-factor supplies with, if necessary, certain restrictions during the peak hours of the winter months. The load curve will thus be raised to such an extent that the existing peaks will be small in comparison. This method is used in the London Underground Railway system, where the supply is always on except just at the peak hours. The ordinary supply undertaking load-curve is troublesome during a few months in the winter, and it would certainly pay to have the maximum demand reduced throughout the year. It is quite conceivable that if a large night load were encouraged it might ultimately result in the peaks appearing at the wrong places. We should aim at improving not only the power station load-factor but also the load factor on the system generally, so as to make the maximum use of cables, transformers, distributors, etc. If a 24-hour system could be adopted instead of a 12-hour system the maximum demand would be considerably less, for given heating requirements. It is interesting to note how the load factor may be improved by adding a constant 24-hour supply in the case of a load curve having the ratio of day to night load equal to 6 : 1; a constant addition of about 150 per cent of night load improves the load factor to 59 per cent. With a practicable arrangement for filling up the valleys the same additional amount at off-peak times improves the load factor to 61 per cent. It should be noted that there are practical difficulties in the way of filling up the valleys exactly, as this is dependent for the most part on time-switch operation. Reference is made to the use of water as a storage medium, and although it has the merit of cheapness the buildings have to be specially arranged and large radiator systems have to be fitted to make use of the heat. It is difficult to provide water piping round a big building, and when installed such a system is not nearly so flexible as direct electrical heating. It is much simpler to arrange for the wiring of a building, and the heaters themselves may be placed in the most convenient positions or they may be split up into a number of units so disposed about the room that uniformity of heating is obtained. Local automatic control is easy, and a predetermined room temperature can be obtained by the most inexperienced operator. There is no question of trial and error, as the thermostat needs only to be set to a given value. Since the electrical radiators are all at the same temperature the more remote rooms receive the same amount of heat as those near the supply, whereas it is a common occurrence to find that in the case of water-heated rooms those near the supply derive most of the benefit from it. Again, with electrical radiators the heating of the rooms is more rapid, as all the units attain their maximum temperature in a few minutes. The oil heating system is still on trial, and it may be that when the present difficulties of oil leakage, etc., have been surmounted this system will be used for heating buildings; at present it requires three transmissions of heat, viz. electrical energy to oil, oil to water, water to room. It is interesting to note that earth currents have not so far proved troublesome, and presumably this is due to the fact that the water in the electrode heaters forms combined delta and star loading, thus disposing of any triple-frequency currents. The author has made out a good case for thermal-storage electrical heating in the Newcastle Motor Depot, but it is probable that a more flexible arrangement would be obtained with electrical radiators. The following figures represent the capital and running costs of the heating supply to a large school holding 1 800 children. For heating by electricity, coke, gas, and oil the capital costs are £4 700, £6 300, £6 600, and £7 000, respectively; the corresponding running costs are £1 610, £1 250, £1 740, and £1 440 per annum, respectively. It will be seen that the capital costs of the electrical system are very much lower than those of the others, while the annual costs occupy a good position when the cleanliness and minimum of attention required are taken into account. This comparison makes no mention of the great savings in building charges which are possible by the electrical system. A heating system similar to that in the Newcastle Motor Depot, but of the direct tubular type, has been adopted for power-station heating with advantage. It would seem that for very large buildings the electrical storage system has a great field, but the direct heating system should receive serious consideration for smaller buildings.

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* Paper by Lieut.-Col. S. E. MONKHOUSE and Mr. L. C. GRANT (see page 657).

Mr. J. E. Gamage: As the question of the electric heating of greenhouses has been raised during the discussion the following information may be of interest. The first installation of this character was made in the North of England for a grower of orchids, who used large greenhouses for growing this and other tropical plants. He had previously had to depend upon hot-water pipes connected to a coke-fired boiler for the maintenance of a uniform temperature and the required degree of humidity. During the winter months many kinds of tropical plants die off quickly if they are subjected to a lower temperature than about 60° F., so that constant attention to the coke boiler was required to keep the temperature of the greenhouse at this figure. Firing late at night, early in the morning and several times during the day proved tiresome, especially as a lower temperature was sufficient in some of the greenhouses containing semi-tropical plants. The obvious remedy, therefore, was to supply the houses with separate heating installations, and a special waterproof type of tubular heater was designed for the purpose. The orchid house was equipped with 80 ft. of tubular heaters having a total loading of 16 kW, the heaters being connected directly to a 3-phase network. To preserve the proper saturation of the atmosphere the heaters are constantly covered with water, and accurate temperature control is effected by means of an adjustable air-thermostat working in conjunction with a 3-pole ironclad contactor. The chief features of the heaters are the load of 200 watts per foot length and the fact that they are designed as watertight elements capable of being constantly immersed in water. The advantages of this system are the maintenance of an equable temperature under easily controlled conditions, a cleanliness such as is impossible with coal-fired or coke-fired methods and, further, there are no products of combustion inimical to plants to vitiate the atmosphere. It would appear from the discussion that while the heating of large buildings by thermal-storage means is the only economical electrical method, for smaller buildings, particularly where the whole of the building is not necessarily always in use, direct heating by radiant heaters of tubular or other types is an economical proposition. As this is a day load it necessitates the provision of current at a higher price than night heating warrants, but this is compensated by the use of these heaters only at such times as the individual rooms are in use and the temperature conditions render it necessary.

Mr. W. Hill: I should like to ask the author for more details as to the connections on the boilers used in Newcastle, as such information would explain better the absence of leakage trouble. Is the boiler fitted with an earthed or shielded neutral or is it without a neutral? Previous speakers have made out an excellent case for direct electrical heating rather than thermal storage, and it occurs to me that a consumer can afford to pay three or four times as much for heating by the direct method as he can for heating by thermal storage. In the former case he will only have the heating on for 48 hours per week as against 24 hours per day for a 7-day week (i.e. 168 hours) if he chooses the latter alternative.

Mr. W. A. H. Parker: A previous speaker has advocated obtaining the 100 per cent load-factor consumer so as to avoid the necessity of obtaining off-peak loads to fill up the valleys. Whilst this high load factor is almost impossible, if we could improve the load conditions of the ordinary power consumer, who has a load factor of, say, 15 to 20 per cent, by inducing him to use the supply for thermal-storage purposes during periods of light load, it would enable the supply authority to sell at a reasonable price. It appears to me that good use could be made of the Wilkinson "change-circuit" system in this direction. I am pleased that the author has not fallen into the error made by those engineers who consider that as the plant is already in existence they can sell off-peak supplies at the bare cost of the coal consumed. I believe that there is a large field for thermal-storage supplies and they must bear their fair share of the total capital charges of the system. The unit charge of 0·3d. may appear small to us in this area, but I do not think that we need despair, as there is some demand for energy at about 0·5d. per unit. Electric heating offers something more than the ordinary heating system and, in my opinion, no other equipment can show such a close temperature-control—an advantage which the up-to-date consumer will appreciate. The slide showing the temperature record for one day was a revelation to me, and if the author could arrange for the record of the outside temperature to be placed on the same slide it would emphasize the constancy of temperature inherent in the system under discussion. The figures for the heat loss in lagging are interesting, and they compare favourably with those obtained by tests on the domestic hot-water storage tank. The author stated that one reason why the small immersion heater was adopted in the case of the L.C.C. offices was that it was feared that earth currents might be present with the electrode type. This difficulty, however, might have been avoided by installing a double-wound transformer, and it would be interesting to know whether there would have been any saving in the cost of the heaters which could have been set off against the cost of such transforming plant. The equipment adopted by the author appears to me to suffer from one disadvantage as compared with the tubular heating system in that it does not provide for individual automatic control—a very attractive feature where the rooms are not all used at once—and it may be that the capital cost of the water heating system, including radiator pipes, etc., is greater than that of an electric tubular heating plant. In a tubular heating system which has been installed locally the heaters have a total capacity of 45·82 kW and the capital cost is about £10 per kW. The cubic content of the offices is 76 930 cub. ft., giving a loading of 600 watts per cub. ft. Automatic control is arranged by the installation of several thermostats set at 65° F. and the annual consumption is approximately 80 000 units per annum or, say, 1 unit per cub. ft. per annum. The number of units consumed per day shows a considerable variation, especially during the cold snaps. The figures for the last five months—November, December, January, February and March—are 358, 352, 381, 550 and 450 units per day, respectively.

Mr. R. A. Parsons: A comparison between the unit system and the thermal-storage systems shows that the current consumptions of either are practically the same, whilst the number of watts consumed per cubic foot of space heated are identical. In either case there is a marked variation between the current consumption for a very cold winter and that for a mild one. Some information regarding the types of electrical heating systems most suitable for greenhouses of the residential size and for large glasshouses would be welcome.

Mr. P. J. Plevin: If the figure of 0·08 watt-hour per cub. ft. per deg. F. represents the consumption of electricity over the 8-hour storage period (this is not quite clear from the paper), the Banca Commerciale Italiana di Roma absorbed heat at an average rate of 0·034 B.Th.U. per hour per cub. ft. per deg. F. over the first winter's working. The corresponding figure for the Newcastle Motor Depot can only be obtained by assumption, because the mean temperature-difference between the inside and outside of the building during the 8-months' working period is not stated, but if this be taken as 10 deg. F. the average rate was 0·025 B.Th.U. per hour per cub. ft. per deg. F. in this case. Even the first-mentioned figure is well below values now commonly employed in computing the heat requirements of buildings, which seems to indicate that the facility and accuracy with which heat in the form of electricity can be measured (not only over short tests but over long periods of operation under varying conditions) may lead to a revision of present ideas on rates of heat consumption. The cost comparison in Appendix I seems to flatter the electrical alternative. If the calorific value of coke be taken as 11 500 B.Th.U. per lb. the efficiency of the coke-fired alternative works out at 32 per cent, a very poor figure. The efficiency of 50 per cent assumed in the table giving a comparison of the number of B.Th.U. purchasable for 1d. from coke, oil, gas and electricity is a much more reasonable one. Tests on coke-fired heating boilers indicate efficiencies of 70 per cent and over, but such figures cannot, of course, be expected under ordinary running conditions. If an efficiency of 50 per cent be taken instead of the 32 per cent assumed, the estimated coke consumption would be reduced from 90 tons to 57 tons, thus increasing from about £8 to £53 the cost difference in favour of the coke-fired alternative. Furthermore, is the price of 0·3d. per unit, taken as the basis of the electrical alternative in Appendix I, really an economic figure and can it be maintained? Power companies seem willing enough just now to supply current for electric storage purposes during light load periods at even lower prices, but what would happen should this load increase to such a degree that the day and night loads on the supply system became equal? Consumers taking supplies under similar conditions during the day could then not unreasonably demand equal terms. It is true that the improvement in load factor would cut down the standing charges and certain other components of generating and distributing cost per unit (the fuel-cost component of generating cost would not be greatly affected), but would this reduction make up for the loss in revenue which would result from a general reduction in tariff? Any electrical heating system is inherently wasteful because its efficiency is limited to that of the generating station which supplies it, and this efficiency—while generating stations continue to reject to cooling water 60 per cent of the heat which they produce—must remain a low one. Nevertheless, despite objections from the economic standpoint, the electrical storage system seems to offer advantages where heating installations in city buildings are concerned, not the least of these being the freedom from the dirt and nuisance of fuel handling, storage and combustion which it affords in crowded areas. A definite cash value cannot be assigned to amenities such as these, but they may, in such cases, go far to outweigh the heavier cost of electrical heating.

Mr. J. W. Spark: From the supply engineer's point of view the first considerations are the load factor and diversity which this class of load will bring. I find from the paper that the load factor is only 28 per cent and although the diversity is very desirable it does not in the least help to remove the valley in the summer load-curve, since for the four summer months the system is out of commission. I am not satisfied, therefore, that the flat rate of 0·3d. per unit, advocated in the paper, is justified. From the user's point of view, the system carries with it all the advantages and disadvantages of hot-water central heating, which, I submit, is not comparable in point of efficacy with a low-temperature tubular electric heating system where the heating units are placed where they will be most effective. In the Cheltenham Town Hall, for instance, which has a flat glass roof, a heating system employing hot-water radiators at practically floor-level would not be satisfactory. A hot-water radiator sets up rapid convection and produces a deposit of burnt dust which is detrimental to decorations; there is a consequent increase in the cost for re-decorating, which is not the case with tubular electric heating. In the system advocated by the author the automatic heat control is operated at one point, so that the temperature in the whole of the building will be varied irrespective of the requirements of the different rooms. With a hot-water system, owing to the comparatively high thermal capacity of the transmitting medium, the changes in temperature are bound to be sluggish and they will not follow the variations of the outside temperature in the satisfactory manner characteristic of tubular heating, where simple thermostats are installed in various parts of the building. Whatever the merits of the system may be, the examples given in the paper apply to large new buildings in large centres, whereas existing buildings of more modest size have usually to be dealt with. Whilst I have no experience of an electrically heated building of any size, I have dealt effectively with the Banqueting Room at the Guildhall, Bath, where other systems have failed. The room to which I refer is a beautiful example of the Georgian period with delicate decorations and pictures of considerable value. The cubic capacity is 93 642 cub. ft. Tubular heaters have been installed round the skirting and round the cornice of the room, coloured to harmonize with the decorations, and in order to retain the original two fireplaces "Magicoal" fires have been fitted. The total load is 26·4 kW for the tubular heaters and a 3-kW bar has been fitted in each fireplace; these latter are really more for psychological effect than for actual heating. Thermostat control is used, so that any predetermined temperature is maintained. For the first 12 months interesting and surprising figures were obtained. The room was in use 58 times during the year, so that the heating had to be started up with cold walls each time. The total hours of actual occupation were 185 and the consumption was 3 904 units, so that at the rate of 1d. per unit—the figure which I am able to justify—the total cost was £16 5s. 4d., or an average of 5s. 7d. each time the room was occupied. I submit that no other system of heating can produce such results. One outstanding difficulty which I have experienced in introducing electric heating of buildings is the obstruction of even well-known architects, who, I suppose, have had no experience with electric heating. I have twice had my proposals turned down at this source recently without being given any figures to show whether or not they compared with the alternative schemes. I am interested to learn that with the boilers described, using electrodes connected directly to the e.h.t. 3-phase system, there is no circulating-current trouble.

Mr. L. W. Barnard: Electric heating should be very useful in schools and churches. Old churches are invariably lofty buildings and it is necessary to distribute heat to the upper part as well as to supply a little heat low down. Electric heating is ideal for this purpose.

Lieut.-Col. S. E. Monkhouse and **Mr. L. C. Grant** (*in reply*): Mr. Beasant appears to regard 0·3d. per unit as an exceptionally low figure; he will find this price and lower ones available in many parts of the country, for instance in London, Manchester, Birmingham and on the North-East Coast. There does not appear at present to be any sign of the thermal-storage load exceeding the available capacity of the plant and mains.

In reply to Mr. Burton, the radiator capacity required with electrical thermal storage is not greater than with other forms of central heating. The temperature of the radiating units is frequently controlled individually by a modification of the ordinary screw-down control valve. Mr. Burton's figures for heating the school seem to be rather high, as regards both the capital and running charges. His coke system appears to have an efficiency of 10 per cent. We are aware that coke-fired systems are not particularly efficient, but it has been noted that an efficiency of 30 to 40 per cent can be obtained. Mr. Burton appears to have the impression that electrical thermal-storage is suitable only for very large buildings, but installations from 50 000 to 2 500 000 cubic feet are in use, and the electrical thermal-storage system has been equally successful with all.

In reply to Mr. Hill, the majority of electrode boilers have a definite internal neutral point, which is usually connected to the boiler shell. In his comparison of electrical thermal storage and direct heating, he has apparently forgotten (*a*) that the electrical thermal-storage system can be shut down at a moment's notice, and (*b*) that a direct heating system switched on for, say, 48 hours in a building which is occupied for 48 hours per week would be inadequate unless a considerable amount of extra heating capacity were provided for the first few hours.

In reply to Mr. Parker, the outside temperature-range during the week shown on the slide was from 25° F. to 45° F., during which the internal temperature was maintained at 63° F. with a variation of ± 1 degree. It has been pointed out that the electrical thermal-storage system can be arranged for individual automatic control. Mr. Parker should compare his figure of £10 per kW (capital cost) for the tubular system, with the figures which we have given for electrical thermal storage, namely £3 to £5 per kW.

If Mr. Plevin compares his efficiency figures for coke-fired boilers with those given by others who have taken part in the discussion, he will find that the latter figures are considerably lower than those mentioned in the paper. Perhaps he has omitted to include stand-by losses.

We do not follow Mr. Spark's argument, and we see no reason why, with an electrical thermal-storage system, radiating units should not be placed just where they are required. Moreover, we have emphasized the fact that, with an electrical thermal-storage system, the radiating system can with monetary advantage be built to run at a lower temperature than with other heating systems, thereby eliminating the dust and dirt troubles. Of the three methods, namely, electrical thermal storage, the ordinary hot-water system and tubular electrical heating, the first runs at the lowest temperature and the third at the highest temperature, and the third would thus set up the most rapid air currents. With regard to his figure of 5s. 7d. for heating electrically the Banqueting Room at the Guildhall, Bath, with electrical thermal storage the cost would be rather below 2s. The electrical thermal-storage system is not sluggish in action. At a cost of about 30s. per room, automatic control gear can be installed which will enable the temperature to be controlled directly, or the heating to be completely shut off.

DISCUSSION ON
"WATER PENETRATION EFFECTS IN LEAD-SHEATHED POWER CABLES."*

Dr. N. A. Allen (*communicated*): The author is to be congratulated on giving prominence to an important fact which has long been realized by power-cable engineers, namely, that the 24-hour immersion in water previous to conducting pressure and insulation tests on power cables serves little, if any, useful purpose, except perhaps in the case of 660-volt cables. A series of tests which we carried out seven or eight years ago in the testing laboratories of Standard Telephones and Cables, Ltd., illustrated this very clearly. A short length of 7/14 S.W.G. concentric 660-volt cable (insulation thickness 0·080 in.) was placed under water, with the ends clear, and a $\frac{1}{8}$-in. diameter hole was cut through the lead. Insulation-resistance, electrification, capacity and a.c. pressure tests were carried out at intervals of a few hours until water had penetrated to such an extent as to cause breakdown. Fig. A shows that the reduction of insulation resistance within 24 hours was in this case sufficient to condemn the cable, but the cable did not actually break down until the immersion period had reached 103 hours. It was also established, by cutting out the faulty section, that the water penetration was local, since the insulation resistance of the remainder was normal. The conclusion reached in this experiment was that the water test might enable faulty sheathing to be detected, but since faults which might exist would not be $\frac{1}{8}$-in. diameter holes, but pinholes so small as not to be detected by careful ocular inspection, the value of applying the test was thought to be somewhat doubtful. In any case, since defects rarely exist, and since low-tension cables are generally armoured, it is considered much more satisfactory not to expose the lead-covered cable to water at all, but to pass the cable direct from the lead press through a bath of hot compound of an impervious and elastic nature, thus sealing effectively any minute holes which might exist in isolated cases. Such a layer of compound adhering to the lead sheath forms an excellent basis for the various layers of armouring afterwards applied, and materially assists in increasing the efficiency of the protective coverings as an anti-corrosion medium. Another series of tests was also conducted with a length of 3-core, 0·007 sq. in., 6 600-volt cable, in an identical manner. In this case the insulation resistance was still at a satisfactory level after 475 hours, at the end of which period breakdown took place at 18 000 volts (a.c.) during one of the periodic pressure tests. This is illustrated in Fig. B. The conclusion reached in the second experiment was that the 24-hour immersion in water previous

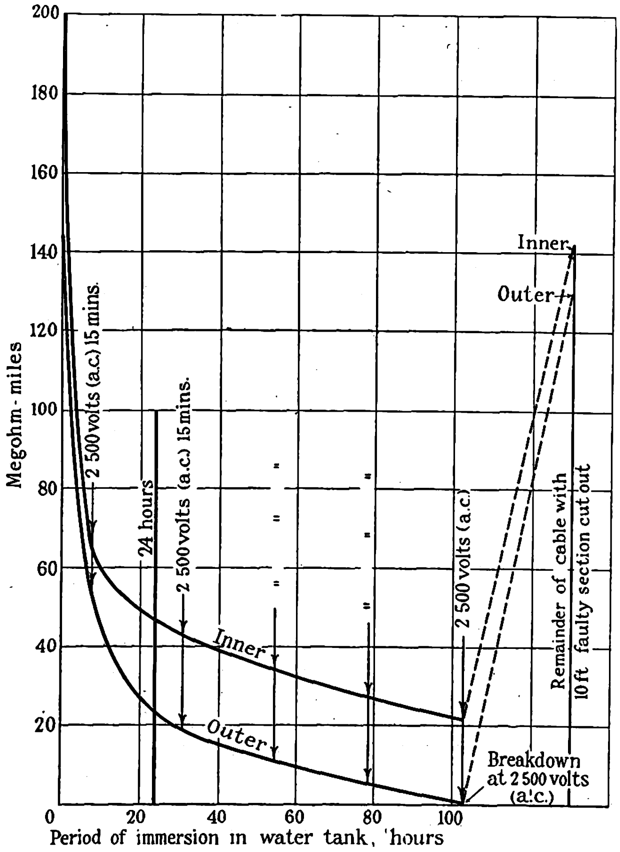

FIG. A.—Immersion test on 7/14 S.W.G. concentric cable with $\frac{1}{8}$-in. diam. hole in lead sheath.

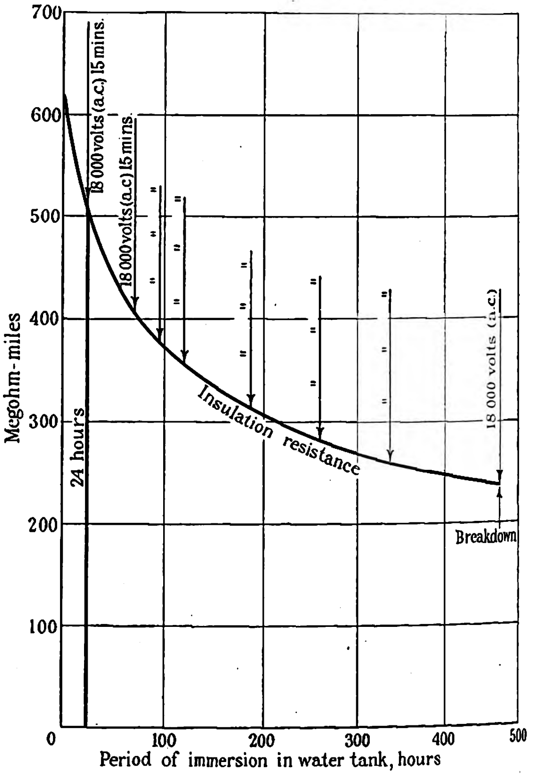

FIG. B.—Immersion test on 0·007 sq. in., 3-core, 6 600-volt cable with $\frac{1}{8}$-in. diam. hole in lead sheath.

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* Paper by Mr. E. A. BEAVIS (see page 434).

to carrying out standard tests is of no assistance in detecting lead-sheath faults on high-tension power cables.

Mr. F. Farmer (*communicated*): I have conducted a series of tests for three years with a view to determining the time required for water to penetrate sufficiently far into the insulation of a cable to cause a breakdown. In these tests, however, arrangements were made to simulate as nearly as possible operating conditions where a cable lies, say, in a wet duct and is subjected to a breathing action consequent upon regular cycles. The cable sample under test was 15 ft. long, 8 ft. of which was submerged to a depth of 4 inches in a trough filled with water taken from a typical city manhole (simulating a flooded duct), and three holes $\frac{3}{16}$ in. diameter were made through the lead sheath in such a position that they lay on top of the cable in the trough. The ends of the cable were suitably terminated in order to be connected to the high-voltage side of a bank of transformers. Low-voltage current to the capacity of the cable (1 500 amperes per sq. in.) was circulated through the conductors and this was switched on in the morning and off in the evening, the potential meanwhile remaining on continuously. The type of cable was 2/0 A.W.G. (about 0·1 sq. in.), three round conductors, paper-insulated, $\frac{9}{32}$-in. paper on the conductors with a $\frac{7}{32}$-in. paper belt and a $\frac{1}{8}$-in. lead sheath over all. The cable was rated at 24 kV. The set was shut down momentarily once per week for insulation-resistance and temperature measurements to be made, the insulation-resistance readings being taken with a 1 000-V or 2 500-V megger. One conductor failed to the sheath after a total immersion of 368 days. The insulation resistance to earth and to each of the other two conductors ranged from 10 000 megohms to 1 000 ohms, the former reading being the highest of the range of readings (10 000 to 4 000) during the main period of the test, and the latter reading being observed at the close of the experiment. This was the insulation resistance to earth of the faulty conductor. Dissection of the faulty cable showed that the water had penetrated the belt, spreading over a 4-in. diameter area immediately under the lead and decreasing in extent towards the fillers. After soaking the filler in the immediate vicinity of the fault, the tapes of the faulty conductor were next attacked. Fifty of the 64 tapes (5 mils thick) were affected, presumably before electrical failure took place. Thus, under normal operating conditions, a period of over one year was required to penetrate $\frac{7}{32}$ in. of comparatively loosely wrapped belt paper and about $\frac{9}{32}$ in. of tightly wrapped conductor paper, all well-impregnated. Similar tests are being run with both a joint filled with black asphaltic compound and a length of shielded conductor cable. After a period exceeding 2 years the joint is still operating, while 2 years have now elapsed since the second cable was installed. During the whole of this time regular load cycles have been impressed on both cable and joint. The insulation-resistance readings are up to the present as high as when the tests were first started, and show no indication of the extent of the penetration of water into the insulation. American practice has for some years omitted the " tank " test as unnecessary, and operation reports show the omission to have been warranted.

Mr. T. L. Horn (*communicated*): In the year 1914 some paper-insulated lead-sheathed cables were manufactured for the undertaking with which I am connected. They had to stand a test pressure of 50 kV, and at my instigation they were not tanked. Up to the present time these cables have given no trouble. Following my experience, for the past 6 years none of the e.h.t. cable for the same undertaking has been either run through a water bath or put in a tank, and, although the cable has lain in water in many places, no trouble has been experienced. For many years it has been my opinion that the tanking of e.h.t. cables is likely to lead to more trouble than it prevents, and experience has so far confirmed this view.

Mr. E. A. Beavis (*in reply*): The results given by Dr. Allen are of interest as they represent tests carried out on different types of cable, and bring additional evidence to bear out the conclusions put forward in the paper. With regard to the experiment on the low-tension sample shown in Fig. A, the water appears to have penetrated the insulating material rather quickly as the insulation of the inner conductor has become affected almost as soon as that of the outer, and from the results given by the curve the sample is undoubtedly condemned before the standard immersion period has expired. The question as to whether such a fault occurring in practice in a drum length of cable would become so definitely apparent on the initial test after the 24-hours' tanking is somewhat uncertain. To some extent it would depend upon the general order of uniformity obtained for the insulation resistance of low-tension cable and in particular upon the range of values concerned with other drums of the same batch. When these are subject to wide variations the increased difficulty of detecting a fault of this nature is apparent.

Mr. Farmer's remarks afford a practical idea of the time taken for faults of this nature in high-tension cables to show up under operating conditions. It would appear that the continual heating and cooling of the insulation, consequent upon the loading cycles, has had little effect in aggravating the defect, judging by the period taken for breakdown to occur. The megger test is of course only a rough-and-ready measurement of the insulation resistance and will not give any indication of the nature of the electrification characteristics of the cable. It is possible that with a delicate galvanometer and a steady battery some indication of faulty insulation may show itself in the case of these experiments, either as unsteadiness or as a faulty charging-current curve, particularly if reverse currents be employed. This matter is, however, somewhat removed from the question of the standard specified test, but the experimental evidence contributed shows conclusively once more the inadequacy of the water-immersion procedure.

Mr. Horn's remarks hardly need comment. He is to be congratulated on an early policy of waiving the matter of tanking for e.h.t. cables, and has possibly been saved much worry and anxiety by this foresight. It is quite time that serious attention should be given to this subject, and the present standard specifications revised at least on the question of tanking, thereby relieving to some extent the individual responsibility undertaken in this respect by many consulting engineers and inspectors.

DISCUSSION ON

"ALTERNATING-CURRENT TESTS ON HIGH-SPEED TELEGRAPH CABLES."*

Mr. A. L. Meyers (*communicated*): On page 453 the corrections for tests on long coils are given in terms of the corrected constants instead of the test values; hence the second-order terms are erroneous. The author should have expanded the inverse function arc tanh *Pl* in place of the direct function. In connection with the damp-surface error in leakance testing, it is my experience that errors of much more than 10 per cent may arise from this cause. In fact, the example given indicates an error of over 50 per cent. The chief disadvantages of the Wein bridge shown in Fig. 6 disappear at audio frequencies if the Wagner earth is eliminated. Not only is double balancing dispensed with, but an earthed tank may be used. The correct connections for the screens are surely as given at (*d*) in Fig. 7; the capacity of *R* to its screen may be compensated for by an equal air condenser across the unknown arm. Turning from testing to telegraphy, the arguments on page 449 [section (2) (*b*)] appear to imply that frequencies above the reversal or "dot" frequency *f* are not essential to signal formation. Milnor † states that frequencies as high as 1·5 *f* are desirable for recorder and 1·65 *f* for relay reception. It is also necessary to question the remark at the commencement of section (2) (*c*)—that distortion on modern continuously-loaded telegraph cables is less than on unloaded cables.‡ I feel that the author does not fully appreciate the information to be gained from the departure curves in Fig. 26. These curves furnish a more delicate determination of the presence and position of irregularities § than the frequency plot of impedances in Fig. 28. Thus he cannot from the latter detect the disturbance from the resistance termination of the sea earth; but it is clearly visible at 0·015 and 0·044 sec. in the former, and gives a velocity of propagation (for an impulse of 60 volts) of 7 000 nautical miles per sec. The main irregularity found in the cable is confirmed at 0·017 sec. by Fig. 26, but its position is found to be about 60 instead of 47 nautical miles from the end. The smoothness of the cable curve at 0·030 sec. makes the existence of a reflection at 90 nautical miles very doubtful. The position of the irregularity suspected in the sea earth is verified at 0·009 sec. The author does not state that the attenuation results plotted in Figs. 34 and 36 are values obtained at Bamfield when transmitting from Fanning. Table A compares the attenuations given in the paper, for sinusoidal alternating current, with those measured by the present writer at Fanning, transmitting southwards, at the R.M.S. sending voltage stated. The differences of the tests in the two directions are attributed to unsymmetrical reflections; if these occur at quasi-infinite distances their effect on the attenuation is eliminated to a first approximation in the mean. Hence the last column should be used in estimating the cable constants. Comparing these figures with those in the paper, it will be seen that the deduced constants require approximately the following corrections: inductance 1 per cent less, capacity 1 per cent greater, sea-return resistance less at the higher frequencies (0·235, 0·31, 0·37 ohm per nautical mile at 30, 40, 50 cycles per sec., respectively). The slope of the sea-return resistance curve now decreases instead of increasing with frequency, and is theoretically more satisfactory. The following suggestion for the cause of the difference between the head-end loss for sinusoidal and for square-topped sending voltage, shown in Fig. 34 and Table 7, is due to Mr. D. E. Clarkson. On re-plotting the experimental results on a basis of maximum instead of R.M.S. voltage, the two sets of results are in good agreement. This indicates that the apparent discrepancy is not to be attributed to suppression of hysteresis loss by harmonics, but to the phenomenon of hysteresis being dependent on maximum values of flux density. No mention is made of the effect of the earth's magnetic field on the high-permeability

TABLE A.

Frequency, cycles/sec.	Northwards		Southwards		Mean of both directions			
	$V_s = 0$	$V_s = 60$	$V_s = 0$	$V_s = 60$	$V_s = 0$	$V_s = 60$	H.E.L.*	$a_0 \times 10^3$
5	6·18	6·62	6·30	6·62	6·24	6·62	0·38	1·80
12·5	6·80	7·55	6·92	7·43	6·86	7·49	0·63	1·98
20	7·39	8·20	7·47	8·12	7·43	8·16	0·73	2·14
30	8·23	9·08	8·29	9·06	8·26	9·07	0·81	2·38
40	9·25	10·16	9·17	10·10	9·21	10·13	0·92	2·655
50	10·30	11·32	9·98	11·14	10·14	11·23	1·09	2·925

* Head-end loss for $V_s = 60$ volts R.M.S.

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* Paper by Dr. E. W. SMITH (see page 447).

† J. W. MILNOR: *Transactions of the American I.E.E.*, 1922, vol. 41, p. 27. His theoretical conclusions are confirmed in practice; see A. M. CURTIS: *Bell System Technical Journal*, 1927, vol. 6, p. 432.

‡ Cf. O. E. BUCKLEY: *Transactions of the American I.E.E.*, 1925, vol. 44, p. 888, and *Bell System Technical Journal*, 1928, vol. 7, p. 238.

§ Similar curves were used for this purpose as an aid to duplexing the Bay Roberts–Horta (1928) cable; see L. S. COGGESHALL: *Journal of the American I.E.E.*, 1930, vol. 49, p. 219.

mumetal loading, either in factory tests or as estimated for the cable *in situ*. Published figures on this point would be of considerable interest. The difference between the realized (19 or 20 per cent) and the anticipated (15 per cent) drop in inductance on laying may perhaps be due to this cause. The aspect of the paper to which I attach most importance is its insistence on the need for accurate tests on loaded cables to determine their performance and estimate their constants. In combination with factory tests this leads to the possibility of the accurate prediction of the performance of future cables. When designing to meet a guaranteed attenuation, a margin of safety has of course to be allowed. Largely as a result of the accurate work outlined by the author, the margin required has been reduced to about 8 per cent of the total attenuation. A further outcome is the isolation of a small loss—the after-effect—hitherto overlooked on loaded conductors. The discrepancy of 3 to 5 per cent obtained in the resistance of three loaded Atlantic cables * may be due to neglect of after-effect resistance. It appears that the least accurate factor determined by tests on laid loaded cables is that of the sea-return resistance. It is true that, assuming ideal conditions, the sea-return impedance can be calculated,† but it is doubtful how far these conditions are realized in practice. Application of the same principles of testing to unloaded cables would accurately determine the resistance in question, and the need for such tests to compare with calculation is evident.

Dr. E. W. Smith (*in reply*): Among the many significant points raised by Mr. Meyers the most important are those connected with reflections, the evidence of which are the departure and impedance/frequency curves, and the different results of the attenuation tests in the two directions. The departure curves referred to, taken with a sending current decreasing from 110 to 80 mA, are not, however, comparable with the impedance/frequency curve for a current of 1 mA. The resistance termination of the sea earth, being designed to simulate the seaward portion of the cable for interference currents of small magnitude, will naturally give marked reflection for larger currents, and (as noted on page 465) the location of irregularities in general changes with testing current. The additional attenuation tests given by Mr. Meyers are of interest. Given the average inductance near one terminal of the cable higher than that near the other, I should expect, at the higher-inductance end, higher head-end loss and higher received voltage. These conditions do not consistently hold at either terminal, but the differences between the tests are capable of partial explanation when corrected for differences in the impedances under test conditions at the two terminals. With regard to the difference between head-end loss for sinusoidal and for square-topped sending voltage, the theory supported by Mr. Meyers is verified by the experimental results at 50 and 33·5 cycles per sec., but not by those at 20 cycles. From such tests on other cables as are available, I consider the theory of hysteresis suppression by harmonics to be more tenable. With regard to testing, in using the Wien bridge I have found screen-connection scheme (*a*) of Fig. 7 preferable to (*d*), as the correction is usually negligible in the former case only. The elimination of the Wagner earth from the bridge impairs its accuracy, and the disadvantages (ii) and (iii) given on page 452 remain. The effect of the earth's magnetic field on the permeability of the loading is small when the loading is in the form of wire. A specimen orientated magnetic North-South retains about 98·5 per cent of the inductance obtained when the effects of the earth's field are eliminated by screening. The chief cause of distortion is the variation of attenuation with frequency, but while frequencies higher than the reversal frequency f are certainly necessary for good signal formation, the attenuation at f cycles has been found to be the chief factor in design. For an unloaded cable the ratio of the attenuation at $1\cdot5f$ cycles to that at f cycles is approximately $\sqrt{1\cdot5} = 1\cdot22$. Although this ratio is less than 1·22 for the Bamfield–Fanning II Cable, it is certainly greater in the case of other continuously-loaded cables.

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* J. J. Gilbert: *Electrician*, 1927, vol. 99, p. 251.

† J. R. Carson and J. J. Gilbert: *Journal of the Franklin Institute*, 1921, vol. 192, p. 705.

INSTITUTION NOTES.

Council for the Year 1930–1931.

The scrutineers appointed at the Ordinary Meeting held on the 1st May, 1930, have reported to the President that the result of the ballot to fill the vacancies which will occur on the Council on the 30th September next is as follows:—

President: C. C. Paterson, O.B.E.
Vice-President: R. K. Morcom, C.B.E., M.A.
Hon. Treasurer: E. Leete.
Ordinary Members of Council: (Members) F. W. Crawter, A. Ellis, E. W. Hill, R. P. Sloan, C.B.E., V. Watlington, M.B.E.; (Associate Member) R. Grierson; (Associate) J. F. W. Hooper.

The Council for the year 1930–1931 will therefore be constituted as follows:—

President.

C. C. Paterson, O.B.E.

The Past-Presidents.

Colonel R. E. Crompton, C.B.
James Swinburne, F.R.S.
Sir R. T. Glazebrook, K.C.B., D.Sc., F.R.S.
W. M. Mordey.
Sir John Snell, G.B.E.
Charles P. Sparks, C.B.E.
Roger T. Smith.
Ll. B. Atkinson.
J. S. Highfield.
F. Gill, O.B.E.
A. Russell, M.A., D.Sc., LL.D., F.R.S.
W. B. Woodhouse.
R. A. Chattock.
W. H. Eccles, D.Sc., F.R.S.
Sir Archibald Page.
Lieut.-Col. K. Edgcumbe, T.D., R.E.T.(Ret.).
Col. Sir Thomas F. Purves, O.B.E.

Vice-Presidents.

P. V. Hunter, C.B.E.
R. K. Morcom, C.B.E., M.A.
A. H. Railing, D.Eng.
B. Welbourn.

Honorary Treasurer.

E. Leete.

Ordinary Members of Council.

A. R. Cooper.
F. W. Crawter.
A. Ellis.
R. Grierson.
T. G. N. Haldane, M.A.
S. Harcombe, M.A., B.Sc.
E. W. Hill.
J. F. W. Hooper.
J. M. Kennedy.
Sir Philip Nash, K.C.M.G., C.B.
F. W. Purse.
E. E. Sharp.
E. H. Shaughnessy, O.B.E.
R. P. Sloan.
Lieut.-Col. W. A. Vignoles, D.S.O.
V. Watlington, M.B.E.
R. S. Whipple.
Prof. E. Wilson.

And the Chairman and immediate Past-Chairman of each Local Centre.

Graduateship Examination Results: May, 1930.

*Passed.**

Ainge, F. J. (Weeford).
Altham, T. F. (Hersham).
Armstead, H. C. H. (London).
Bailey, W. N. (Birmingham).
Baker, C. H. (Monkseaton).
Barrett, E. D. (Chelmsford).
Bell, R. (London).
Berry, J. B. (Kelty).
Billson, F. W. (Wolverhampton).
Birch, H. (Sutton, Surrey).
Bower, C. W. (Sheffield).
Boyce, J. S. (Plymouth).
Brassington, F. (Arnold).
Brook, C. B. (Huddersfield).
Brown, G. V. (Glasgow).
Buckley, S. E. (London).
Buffery, G. H. (Portland).
Burford, G. G. (London).
Caldwell, J. (Newtown Stewart).
Candler, J. E. (London).
Cattan, G. (Palestine).
Chapple, S. H. (London).
Charlton, T. C. (London).
Chittenden, P. A. (London).
Christie, R. F. (Manchester).
Clough, A. W. (Manchester).
Cole, F. J. (London).
Collier, A. S. (Manchester).
Colquhoun, J. B. (Glasgow).
Craster, T. Y. (Alnwick).
Crew, W. S. (Sunderland).
Davies, W. T. (South Farnborough).
Dixon, A. (Glasgow).
Donaldson, A. (Preston).
Dudley, H. (Countesthorpe).
Eagling, O. A. (Norwich).
Easton, H. (Manchester).
Edwards, H. G. (London).
Edwards, N. H. (London).
Faithfull, E. W. (Seaton).
Fowkes, F. K. (Codnor).
Gallop, C. C. (Newcastle-on-Tyne).
Geach, E. A. (Chichester).
Goddard, M. W. (London).
Gould, B. W. (Bletchley).
Gray, C. A. (Manchester).
Greenall, G. D. (Nottingham).
Hacking, A. (Nottingham).
Hallett, L. W. (London).
Hancock, C. G. (Hull).
Harknett, S. G. (Chelmsford).
Hawksley, E. (Mansfield Woodhouse).
Hawley, P. A. (Stafford).
Henderson, S. T. (Manchester).
Heslop, J. P. (Birmingham).
Hewitt, T. H. (Leigh, Lancs.)
Hime, M. W. (Rugby).
Hinchingbrooke, The Viscount (London).
Hodkinson, J. C. (Manchester).
Jeffrey, L. F. (Birmingham).
Johnson, R. A. (Doncaster).
Keene, R. N. (London).
Kelso, A. (Rosyth).
Knights, G. (Manchester).
Laing, D. P. McN. (Glasgow).
Lash, A. R. (Caernarvon).
Lawson, C. J. V. (London).
Lever, V. (Oldham).
Lightbown, J. (Blackburn).
Linley, F. (Manchester).
Lumby, F. (Manchester).
Maltby, J. H. (Harrow).
Mayer, V. (Manchester).
Midforth, J. D. (Dundee).
Milligan, J. W. C. (London).
Milne, W. H. (Preston).

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* This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

Passed—continued.

Mitchell, H. L. (Holmfirth).
Morley, J. E. (Chatham).
Mullane, A. J. (Cardiff).
Newing, A. (Bradford).
Newsam, C. A. (Blackpool).
Palmer, E. H. K. (Harrow).
Parsons, A. G. (Dudley).
Philp, H. (Glasgow).
Pilkington, G. D. (London).
Pilsbury, R. C. (London).
Pinhorn, R. V. F. (London).
Powell, A. N. (Birkenhead).
Price, A. J. (Blackpool).
Price, B. T. L. (Newport, Mon.).
Rawson, J. E. (Todmorden).
Rowe, P. F. (Dublin).
Sainsbury, E. G. (Birkenhead).
Sands, P. C. (Nottingham).
Saunders, A. E. (Southampton).
Sclar, D. (London).
Smith, A. G. (Leeds).
Smith, H. D. R. (Chislehurst).
Smith, R. (Eastwood, Notts.).
Smith, S. C. (London).
Soulsby, G. E. W. (Dipton).
Stonehill, D. H. (Palestine).
Sutcliffe, W. D. (Manchester).
Swash, K. N. (Chester).
Taylor, J. R. (Hull).
Thornhill, W. (Manchester).
Todd, W. G. (Great Yarmouth).
Tull, A. W. (Portsmouth).
Tyack, F. G. (London).
Underhill, C. (London).
Vickers, S. (Carnforth).
Watkin, T. I. (St. Helens).
Whittaker, D. (Ipswich).
Whittingham, W. T. (Bradford).
Woodward, G. L. (Bush Hill Park).
Woolman, J. A. (Birkenhead).

Passed Part I only.

Atkins, C. J. (London).
Badham, W. (Cardiff).
Brown, L. R. (Portobello).
Chowdhury, M. K. (London).
Clark, R. E. (Southsea).
Cooke, C. H. C. (Westcliff-on-Sea).
Galle, G. A. (London).
Horsington, L. R. (Lee-on-Solent).
Jones, H. H. (London).
Kinross, R. I. (London).
Manning, C. C. (Preston).
Messenger, A. R. (Andover).
Pathak, C. C. (London).
Pearce, F. B. P. (Bexley Heath).
Penny, A. G. (London).
Pratt, J. H. (Edinburgh).
Pridding, J. A. (Barry, Glam.).
Sharpe, H. A. (Manchester).
Slee, W. J. G. (Lancaster).
Tancred, B. J. P. (Liverpool).
Thomas, E. C. (Southampton).

Passed Part II only.

Highfield, J. W. (Birmingham).
James, G. A. (London).
Kerridge, K. E. (Hull).
Kuriyan, K. T. (London).
Lindsey, G. T. (Romford).
Ralphs, L. C. (Tipton).
Tatton, E. (Stockport).

Further results, relating to candidates who sat for the Examination abroad, will be published later.

The Benevolent Fund.

The Committee of Management of the Benevolent Fund desire to draw the attention of the members to the last page of the cover of this issue of the *Journal*, on which will be found particulars of certain publications, etc., offered for sale on behalf of the Fund.

Informal Meetings.

120th Informal Meeting (13th January, 1930).

Chairman: Mr. C. F. Mounsdon.

Subject of Discussion: " Efficiency " (introduced by Mr. A. Morgan).

Speakers: Messrs. J. R. Bedford, J. H. C. Brooking, E. Kilburn Scott, S. B. Jackson, N. Prentice, R. Grigg, S. W. Melsom, J. A. H. Lloyd, C. F. Mounsdon.

121st Informal Meeting (27th January, 1930).

Chairman: Mr. W. A. Ritchie.

Subject of Discussion: " High-Tension Distribution" (introduced by Mr. G. V. Twiss).

Speakers: Messrs. J. R. Bedford, R. S. Odd, A. F. Harmer, J. H. C. Brooking, N. Prentice, C. Wade, D. H. Stewart, A. G. Hilling, C. F. Mounsdon, R. C. Anderson, J. F. Shipley, E. Kilburn Scott, S. B. Jackson, G. H. Holding, W. Lang, F. B. Allcock, C. W. Prescott, H. D. Barlow.

122nd Informal Meeting (3rd February, 1930).

Chairman: Mr. A. Morgan.

Subject of Discussion: " Maintenance of Telephone Plant " (introduced by Mr. H. G. S. Peck).

Speakers: Messrs. E. S. Ritter, D. H. Stewart, J. R. Bedford, C. W. Prescott, W. H. Grinsted, W. Wheeler, C. S. Kieran, E. J. Reed, P. J. Ridd, A. Morgan, R. Grigg, J. F. Perrin.

123rd Informal Meeting (17th February, 1930).

Chairman: Mr. E. S. Ritter.

Subject of Discussion: " The Nickel-Iron Battery and its Uses " (introduced by Messrs. M. E. Fox and W. E. Warrilow) and " The Lead Battery and its Uses " (introduced by Mr. E. C. McKinnon).

Speakers: Messrs. A. J. Bousfield, A. C. Hardy, S. B. Jackson, W. A. Erlebach, F. R. Perris, J. F. Perrin, G. L. Drury, A. F. Evans, S. A. Stevens, H. V. Schofield, G. L. Rose, J. R. Bedford, P. F. Grove, —— Sutton, W. S. Sholl.

124th Informal Meeting (3rd March, 1930).

Chairman: Mr. H. T. Young.

Subject of Discussion: " Push-button Control " (introduced by Mr. J. J. Fisher).

Speakers: Messrs. J. R. Bedford, A. Morgan, J. Eck, J. F. Shipley, T. S. Martin, W. A. Erlebach, S. B. Jackson, A. N. D. Kerr, T. N. Lockett.

125th Informal Meeting (17th March, 1930).

Chairman: Mr. M. Whitgift.

Subject of Discussion: " High-Tension Substation Control Gear " (introduced by Mr. A. F. Harmer).

Speakers: Messrs. A. Morgan, S. B. Jackson, C. O. Milton, J. P. S. Pillans, C. F. Mounsdon, W. E. Bradshaw, J. F. Shipley, G. H. Holding, W. L. Wreford, W. R. Hackworth, J. R. Bedford, A. T. Scott, H. Lloyd Williams, R. Leach, P. A. Jackson, W. Wilson, S. W. Melsom, F. O. Harber.

126th Informal Meeting (31st March, 1930).

Chairman: Mr. J. R. Bedford.

Subject of Discussion: "Loud-speakers" (introduced by Captain P. P. Eckersley).

Speakers: Messrs. A. G. Warren, A. J. Gill, J. F. Herd, H. J. Neill, E. J. Reed, W. Day, F. A. Cobb, H. R. Clarke, E. S. Ritter, — Whitehead, E. C. S. Megaw, F. R. Brindle, A. B. Howe, P. Voigt.

Elections and Transfers of Members.

At the Annual General Meeting held on the 15th May, 1930, the following elections and transfers were effected:—

Elections.

Associate Members.

Bull, Reginald Alfred, B.Sc.(Eng.).
Boles, Geoffrey Coleridge, Commander R.N.(Ret.).
Bradock, Gordon Higson.
Carr, Cuthbert James, Lieut.-Comdr. R.N.
Clark-Nichols, Edward Christopher.
Clyne, Thomas Maurice.
Cross, William Herbert.
Gilbert, Thomas Charles.
Goddard, Leonard Douglas, Captain R.S.
Haynes, William, Lieut.-Commander R.N.
Hopkirk, Kenneth Robert, B.A.
Horne, Leonard Ralph, B.Eng.
Hunt, Keith Flashman, B.Sc.
Lendrum, Harold Leslie, Lieut. R.E.
McGill, Ernest William.
Mathieson, Thomas Barclay.
Pevzner, Levy.
Reynolds, Raymond Douglas.
Sparrow, Albert Victor.

Associates.

Barnicoat, William James.
Binns, Joseph.
Bond, John Alfred.
Hart, Edwin Caithness.
Hine, William Charles.
Naudain, Willis A.
Newberry, William Edward.
Plummer, Alec Frederic.
Powell, Dick.
Pring, Francis Ernest.
Sherriff, George William.
Warren, William.

Graduates.

Berkeley, Julius John C.
Bridges, James.
Costello, James, B.E.
Evans, Arthur Frederick E.
Grieveson, John Alan, B.A.
Hebard, Hugh Charles, B.A.
Hunter, Ian Wilson, B.Sc.
Mathewson, Eric Walter, B.E.
Philip, Mathew, B.A.
Ruff, Harold Robert, B.Sc.(Eng.).
Simpson, Geoffrey Elliott, B.Sc.
Womersley, Donald Charles.

Students.

Alexander, John Montague.
Anderson, Murice Hector.
Ashford, James Leslie.
Barge, Rupert Maurice.
Chapman, Kenneth George.
Clarence, Walter Anthony.
Conly, Patrick.
de Necker, Jan Daniel J.
Digyani, Jai Krishen.
Donnelly, John Francis.
Dumra, Harichand Motiram.
Ellis, Robert Henry.
Hearn, John.
Hughes, Stanley Owen.
Hutchinson, Samuel Watson.
Jessel, Geoffrey.
Kapur, Roshan Lall.
Ladell, John Ernest C.
Larkin, Alfred Spencer.
Laycock, Leonard Spencer.
Leighton, Gerald Crocker.
Oldhams, Arthur Stanley.
Partridge, Wilfrid Howard.
Paul, Robert Hoisington, B.A., B.Sc.
Pickup, Harry.
Rao, Karavadi Gopala.
Savage, Francis Montague.
Sengupta, Amulya Nath.
Singh, Harbans.
Smith, Clifford.
Smith, George Ernest.
Smith, Robert Frederick.
Stevenson, Ian Douglas.
Thorn, Arthur Eldred.
Turtle, Albert Edgar.
Ward, Leslie Ernest.
Whitaker, Frank.
Wilcox, Thomas Webster.
Wolff-Schoemaker, John Prosper.

Transfers.

Associate Member to Member.

Besly, James Campbell.
Blackmore, Robert.
Fletcher, George Herbert.
Gil, Joseph Valderrame.
Glasse, Alfred Onslow.
Hoseason, Donald Bright.
Landau, Szymon I.
McColgan, Albert John.
McHaffie, Hugh Gunn.
Margary, Thomas Alfred G.
Smith, Clarence Herbert.
Waters, John Henry.

Associate to Associate Member.

Leary, John Francis.
Rennie, William.

Graduate to Associate Member.

Benson, Robert Hamilton.
Black, Richard Henry.
Damp, John William.
Devereux, Reginald William, B.Sc.(Eng.).
Fry, Eric Charlton.
Hodgson, Arthur Geldart.
Horwood, Hyman.
Hunter, Charles Moore.
McMahon, Alfred Joseph, B.Eng.
Martin, Reginald Ian.
Newman, Samuel Emil.
Palfrey, Harry James D.
Pedrick, Sydney.
Smith, William Francis, B.Sc.(Eng.).
Sowter, George Alfred V., B.Sc.(Eng.).
Swinney, John.
Vickers, Harold Edwin.
White, William George, B.Sc.(Eng.).
Whitney, Herbert Edwin.

Student to Associate Member.

Mathews, Henry Mends.
Rowe, Charles.
Southin, Charles Frederick.
Whitcher, Athol Eric Jaime, B.Sc.(Eng.).

THE BREAKING PERFORMANCE OF HIGH-POWER SWITCHGEAR AND OF A NEW FORM OF QUENCHED-ARC SWITCH.

By L. C. GRANT, Member.

[*Paper first received* 14*th April*, 1928, *and in final form* 21*st November*, 1929; *read before* THE INSTITUTION 23*rd January*, *before the* EAST MIDLAND SUB-CENTRE 21*st January*, *before the* NORTH-EASTERN CENTRE 27*th January*, *before the* TEES-SIDE SUB-CENTRE 5*th February*, *before the* NORTH MIDLAND CENTRE 25*th February*, *before the* WEST WALES (SWANSEA) SUB-CENTRE 28*th February*, *and before the* WESTERN CENTRE 10*th March*, 1930.]

SUMMARY.

The difficulty of breaking the high short-circuit powers of large modern systems has an important bearing on the security of electrical distribution. The oil switch, as usually constructed, is in some ways a fortuitous device and, as will be shown in this paper, the very act of breaking a circuit under oil, and thus bringing a high-temperature arc into contact with the oil, results in pressures being set up which are not necessarily dependent upon the actual circuit power being broken. Briefly, it can be shown that even with fixed prebreaking conditions the formation of the arc and the oil pressure set up within the tank will vary. Moreover, such factors as the effect of phase angle, the influence of the layout of the system and, in another sense, the speed of breaking and the effect of oil head, have important effects upon the process of circuit rupture. The author has carried out an investigation in an attempt to assess the effect of these and other factors and to determine whether material improvement is possible without radical changes in design.

The author's investigation has led him to conclude that the fundamental limit of breaking capacity, that is the short-circuit power which can be broken time after time by a given switch without breakdown, is for the largest examples of present designs of oil switches rather below 1 million kVA and that the present breaking-capacity rating of oil circuit-breakers is correct only if a certain factor of reliability is taken into account. For high-power breakers this factor expressed as a percentage appears to be about 96·5 per cent, and indicates that such circuit breakers can be relied upon in 96·5 operations out of 100, or, in other words, that there is a 3·5 per cent chance of breakdown. In order to eliminate this element of breakdown the breaking-capacity rating should be divided by a factor which the author's tests indicate to be 2·5. Moreover, the limitation of the short-circuit current by means of reactors may be responsible for troubles not hitherto identified with such a cause.

A circuit breaker embodying entirely new principles has been evolved and tested under short-circuit conditions. Its performance is superior to that of the usual oil switch, and a unit of a given size and weight is capable of breaking many times the power broken by an oil switch of similar dimensions, while its performance appears to be wholly consistent.

Throughout the paper, tests are quoted and illustrated by oscillograph records wherever possible, but it is, of course, quite impossible, while keeping the dimensions of the paper within reasonable bounds, to give anything more than a skeleton selection of the tests carried out. A few details of the tests and equipment used may, however, be of interest.

The majority of the tests were carried out on a 6 000-volt, 6 000-kVA, 40-cycle alternator. Other tests were carried out at 11 000 volts with a 10 000-kVA, 25-cycle alternator, and at 6 000 volts with a 25 000-kVA alternator.

The power used in the tests varied between 500 kVA and 270 000 kVA. In all, some 800 tests were carried out, in most of which such factors as periodicity, kVA and power factor were kept reasonably constant. Factors which could not be so readily controlled were investigated by carrying out groups of rapidly repeated tests from which a selection was made in such a way that the results bore directly upon the point being investigated. This may appear to be rather a roundabout method, but it was found that groups of tests could be usefully co-ordinated and, for instance, results rejected from one group used in another. In addition to this group of 800 tests, at least an equal number was available which, although not directly forming a part of the work described in this paper, were sometimes used for comparison.

The switching apparatus consisted of several model switches; 4 of these were of an experimental character, while the remainder, 5 in number, were of commercial or semi-commercial form. Compared with power-system conditions, the majority of the tests were carried out on a reduced scale, the switchgear being reduced in size so that it could be overstressed if necessary with the power available. With a 50 000-kVA source of power, the switch models were regarded as being $\frac{1}{64}$th of their commercial cubical content, with the object of obtaining a switch with a commercial maximum rupturing capacity of about 50 000 kVA, and comparing its performance with a full-scale switch on 1 500 000 kVA. Such a full-size switch, as the author has already suggested, would be about the largest commercially available, and thus one which would be likely to be used in practice on a short-circuit power of 1 500 000 kVA. With a larger source of testing power a correspondingly larger switch was employed. The largest used (excluding the quenched-arc switches) could break a maximum power of about 200 000 kVA.

In no group of tests were fewer than 5 repeated tests carried out under similar conditions—a relatively small number, perhaps, for many conditions—but when there arose good reason to believe that closer investigation was necessary, as many as 25 repeated tests were sometimes made. The work described in this paper has been carried out—at intervals —during a period of about 8 years.

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Speed of break.
Oil volume and air cushion.
Effect of power broken.
Symmetry of current.
Phase angle and power factor.

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  The security of a system in terms of liability to circuit-breaker failure.
  Calculation of breaking capacity.

(6) Cause of distress variation.
(7) New designs of switching apparatus.

  Arc stability.
  The arrangement and action of the quenched-arc switch.
  Performance.
  Comparative performance.
  Effect on security of system and power-supply economics.

Bibliography.
Appendix.—The limitation of short-circuit current.

(1) INTRODUCTION.

The term "nominal short-circuit power" is used throughout this paper to indicate the product of the short-circuit current and the open-circuit voltage. With a quick-acting switch the first complete cycle of current could be taken as this short-circuit current, but in a slow or deliberately delayed switch it would perhaps be fairer to take the cycle immediately before the commencement of movement of the switch. In this paper the first cycle of current has been taken.

The tests recently carried out by Sporn and St. Clair * and other investigators show the difficulty of designing a circuit breaker capable of dealing with high short-circuit powers. Inductance coils and high-reactance generators have been used to limit the short-circuit power. Such limitation is of great value in ensuring the security of busbars and other parts under short-circuit conditions, but, unless a proper value of reactance is selected, alterations in the phase angle which outbalance the current reduction may be produced. (Similar effects could be produced if ohmic resistance were used for the limitation of short-circuit current, but, of course, the permanent insertion of resistance has, for obvious reasons, not been applied.) Oil switches employing resistance steps have, however, been used to some extent, and it will be seen later that such switches may offend in this respect. Between the ill effects of the high short-circuit current and the possible increase in phase-angle difficulties when current limitation is resorted to, it appears in practice to be difficult to produce in large power systems switching conditions which are certain under all circumstances, or, in other words, to ensure that 100 per cent security is obtained with the switchgear under all breaking conditions. If the author's tests be accepted, it can be said that when dealing with short-circuit powers greater than about 800 000 kVA the 100 per cent security of the oil circuit-breakers is impaired to some extent, and it is the assessment of this reduction in security which has been one of the objects of the present investigation. This matter is dealt with in detail in Section (5).

Irrespective of the different values of short-circuit current which may be obtained from time to time, there is a very remarkable variation in the distress set up even when an oil switch is made to break the same amount of power on successive occasions. Thus an oil switch operating at its maximum rated breaking capacity will, because of this variation in distress, operate a certain number of times successfully, but under continued testing would also be subject to a certain percentage of failures.

Spurck, Hilliard, Sporn, St. Clair and Slepian, the British Electrical and Allied Industries Research Association and others* have recently carried out investigations of the problems of circuit rupture. One of the results has been to show that the process of circuit rupture is very complicated. In the present investigation it has been found that, with circuit breakers of existing form, consistent breaking performance and mechanical stress could not be obtained.

It has become very important both to users and to designers to have more exact knowledge of the effect of circuit conditions on the breaking performance, and, as it is possible for the switchgear to be subject to stresses which are very difficult to cope with commercially, it is necessary to have more knowledge of the nature of these stresses and of the frequency of their occurrence. The formulation of a method of assessing the security of a power system will thus be possible. To determine these factors it becomes necessary (1) to investigate, either experimentally or otherwise, the nature of the stress which can be set up in an oil switch, (2) to find the best value for design factors such as speed of break and air cushion, (3) to determine the effect of the external or circuit conditions, and (4) from a consideration of operating data to determine the frequency of operation of switchgear under working conditions, and the range of magnitude of the power involved in such operation.

The paper deals also with a recently evolved circuit breaker, which has been called the "quenched-arc switch," by means of which high powers can be broken safely and in which it would appear that complete control of the action is possible. Its operation is consistent and reliable and is a marked improvement over that of the ordinary type. This apparatus is of simple construction and of relatively small size as compared with the conventional form of oil switch.

(2) NATURE OF SWITCH DISTRESS AND THE DIFFICULTY OF GAUGING IT.

Preliminary.—One of the greatest difficulties is the initial one of defining distress. Pressure is set up inside an oil-switch container when it operates, but this pressure takes various forms. Impulses of high magnitude are obtained but are not necessarily dangerous. On the other hand, sustained pressures of much lower values may be very dangerous, and the two effects are perplexingly mingled in practice. The reliable measurement of such pressures is difficult and the results are of doubtful interpretation, even where obtainable. The ejection of oil and flame during the breaking process is a secondary effect due chiefly to faulty construction, and can be remedied by baffling any openings between the inside of the tank and the external atmosphere. The top plate and tank should be stiff, well machined and well bolted together, while venting arrangements, insulator orifices and similar parts should be so constructed that ejection of oil or flame is not possible. Such measures, however, do not limit the mechanical distress due to the internal pressure; on the contrary, they may sometimes increase it.

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* See Bibliography.

* See Bibliography.

Further difficulty is experienced from another complication. It is frequently assumed that an oil switch arranged to break a definite amount of power a number of times will, on each occasion, produce the same symptoms of distress. Actually, the distress varies within wide limits.

It is sometimes stated that distress is proportional, either completely or in part, to arc kVA, arc energy or arc kW-seconds (to quote the various terms used to denote the product of the current and the voltage across the arc during the arcing period and the time of arcing). The author uses the term " break energy " to denote the same factor. The justification of this term is that it implies all the energy released at the break, whereas " arc energy " and " arc kVA " imply only the energy produced by the arc—an important distinction, since a considerable proportion of the break energy can be absorbed by the contacts. An oscillograph record of the voltage across an oil switch during the opening process includes, amongst other things, true arc voltage (or the voltage across the gaseous part of the circuit) and the voltage employed in overcoming the resistance of the circuit in the vicinity of the contacts. The former is available for action on the oil and produces a gas pressure, but the latter produces heat energy which may be disposed of without producing pressure effects. For instance, large contacts exert a heat-absorbing effect, with a corresponding reduction in the amount of energy available for heating and cracking the oil.

It may be mentioned here that heavy contacts have proved to be of great advantage in oil switches and, other things being equal, the switch with the heavier contacts will give the better breaking performance. The larger the heat capacity of the contacts, the lower is the surface temperature reached and, therefore, the less will be the volatilization of the contacts and the generation of oil gas. Fig. 1 illustrates very well the severe burning which takes place with contacts of insufficient heat capacity.

The variation in distress for a given short-circuit current is very remarkable. Tests were carried out in which, as far as practicable, all variable factors were kept constant. The resultant break energy varied enormously but, what was much more remarkable, the distress varied in a totally different manner and independently of the break energy.

A series of tests was carried out on a somewhat reduced scale with a maximum available short-circuit power of about 80 000 kVA, and other tests employing a maximum power of 160 000 kVA and 250 000 kVA. Switches of various designs were built. These were so proportioned that, with the power available, they would be subjected to approximately the same relative conditions as would high-power switchgear on a large modern system. These switches could be fitted with heavy and light tanks, but most of the quantitative results were carried out with a heavy tank fitted with a special device for indicating distress.

It is difficult to find a reliable method of indicating distress. Several devices employing plungers and diaphragms were tried and some appeared for a time to give fairly consistent results. Prolonged testing of these showed that there were serious inconsistencies, which led to their abandonment. A fundamental shortcoming of such arrangements appears to be that the moving portion employed as a medium for passing on the pressure indicates to some extent its own characteristics, rather than real pressure or stress on the oil switch. The indications given by apparatus of this character will depend on such factors as the amplitude and duration of the pressure wave or wave train.

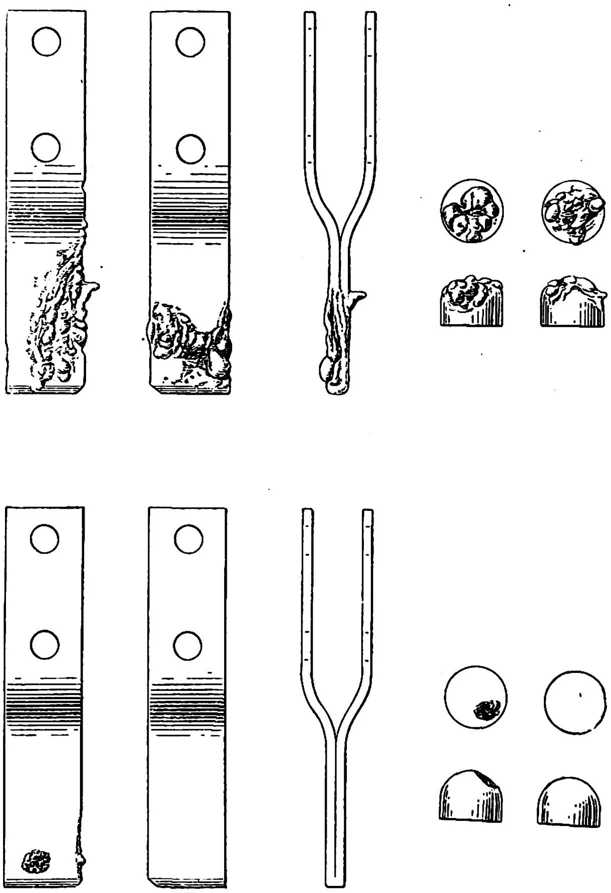

FIG. 1.—Burning of contacts of insufficient heat capacity.
This figure also illustrates the effect of phase angle.

For some time it seemed almost as though the only reliable way to measure distress was the somewhat heroic method of bulging or bursting tanks, but a more economical method was developed and preliminary tests were made to determine a suitable size. The pressure set up in the oil acts directly on a renewable disc fitted into the tank wall, without intervening plungers and their corresponding disturbing results. The relative deformations corresponding to the maximum safe stresses on heavy and light tank switches respectively were experimentally determined. The figures given in the paper are believed to be fairly accurate over the lower and middle ranges; the maximum figures are perhaps rather too low, so that the figures relating to maximum distress may be correspondingly low. Any such errors would tend to strengthen the author's contentions. Other apparatus found to be useful in the tests included an automatic cinematograph camera and a high-speed camera capable of taking a short series of pictures at the rate of 2 000 per sec.

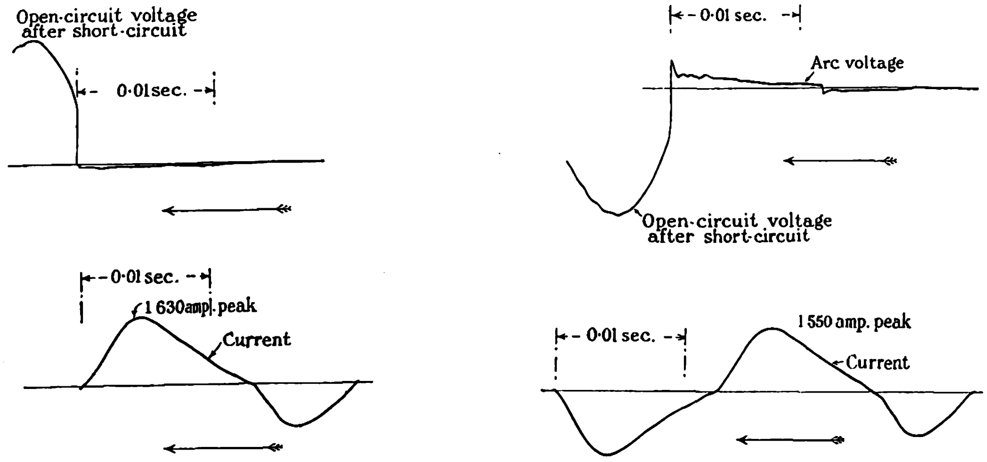

Fig. 2. Fig. 3.

Oscillograms of two tests wherein voltage, frequency and current were held simultaneously constant.

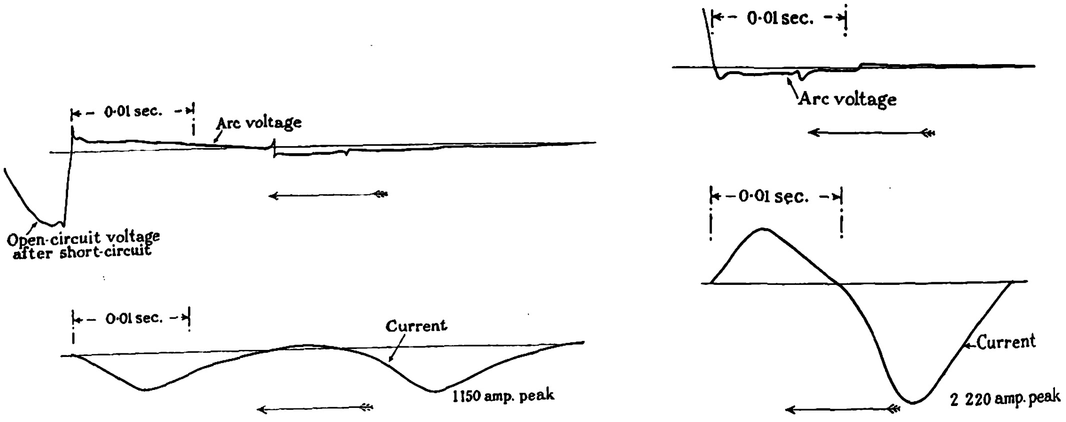

Fig. 4. Fig. 5.

Two oscillograms with break energy similar, but distress different.

The work subsequently carried out is now described, and it is prefaced by a short section submitted to show the influence of various factors on break energy and to indicate how far the latter is from being even an approximate measure of the distress.

(3) UNRELIABILITY OF BREAK ENERGY AS A MEASURE OF DISTRESS.

Voltage, Frequency and Current Constant; Break Energy Varied.—Figs. 2 and 3 show oscillograph records of two tests taken from a group wherein the voltage, frequency and current are of the same order. Particulars of three tests are given in Table 2. It will be noted that the break energy is not proportional to the variation of voltage, frequency and current, thus showing that break energy is not directly influenced by any of these factors.

Table 2.

Voltage	kVA	Current wave-form	Break energy
volts			kW-sec.
5 500	6 150	Symmetrical	4·64
5 500	5 180	Symmetrical	0·775 (Fig. 2)
5 500	4 870	Symmetrical	7·35 (Fig. 3)

Break Energy Similar, Distress Dissimilar.—Figs. 4 and 5 show two records wherein the break energy is substantially the same but the distress is different. These results are shown in tabular form in Table 3. This comparison shows that distress does not vary with break energy, as has frequently been assumed.

Break Energy Dissimilar, Distress Similar.—Figs. 6 and 7 and Table 4 show two records wherein the distress is substantially the same but wherein the break energy is not the same. In one test it is twice that obtained in the other.

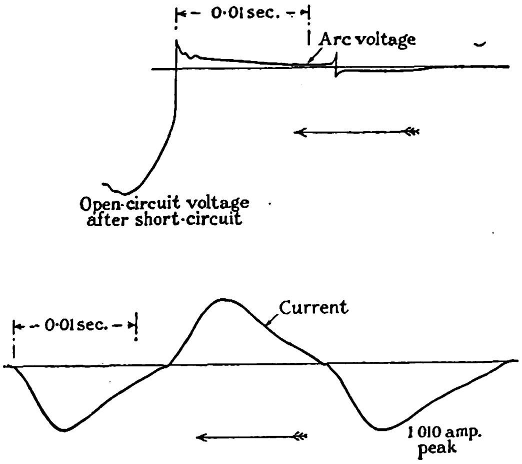

FIG. 6.

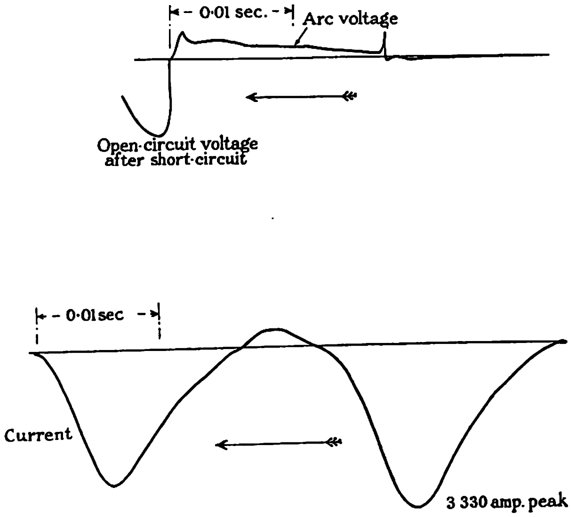

FIG. 7.

Two records with break energy dissimilar, but distress similar.

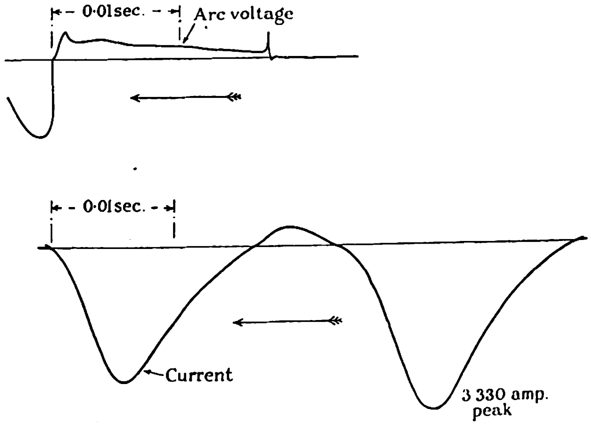

FIG. 8.

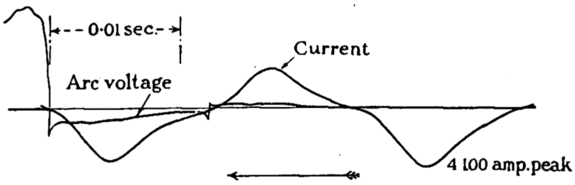

FIG. 9.

Two oscillograms showing similar pre-arcing conditions and similar break energy and wave-form but dissimilar distress.

Break Energy, Arc Characteristics and Wave-form Similar, Distress Dissimilar.—Figs. 8 and 9 show not only similar pre-arcing conditions but similar break energy and similar wave-form during the arcing period, yet the distress in the two tests is dissimilar (see Table 5). Thus, in addition to the broad comparison, this result disposes of the assertion sometimes made that variations of arcing voltage wave-form are responsible for the variations of distress.

It is considered to be unnecessary to quote any further tests to illustrate the foregoing, although many more are available. The existence of the extreme conditions alone would appear to indicate that the unreliability of break energy as an indication of distress has been proved.

TABLE 3.

Voltage	kVA	Break energy	Distress as gauged by deformation
		kW-sec.	
5 500	3 720	5·15	2·3 (Fig. 4)
5 500	6 150	4·64	1·3 (Fig. 5)

TABLE 4.

Voltage	Break energy	Distress as gauged by deformation
volts	kW-sec.	
5 500	9·2	2·6 (Fig. 6)
5 500	17·35	2·6 (Fig. 7)

In these tests and in similar ones which were carried out and in which the same inconsistency was displayed, the phase angle and other electrical conditions were similar in comparative groups. In addition, all the tests were carried out on similar switching apparatus to ensure that no possible source of error should creep in.

The results can be epitomized in the following. A given voltage, current amplitude or symmetry, wave-form, break energy or arc-voltage characteristic will produce switch distress of varying magnitude, the variation being of a considerable order. This does not imply that distress or even break energy is entirely independent of such factors. There would, of course, be greater average distress and break energy with 500 000 kVA than with 50 000 kVA.

Table 5.

Voltage	kVA	Break energy	Distress as gauged by deformation
volts		kW-sec.	
5 500	9 250	17·35	2·6 (Fig. 8)
5 500	11 000	19·8	5·1 (Fig. 9)

(4) Investigation of Existing Switching Conditions.

Preliminary.—This section deals with the work which was carried out to determine the effect on oil-switch performance of circuit conditions such as voltage, current and phase angle, and of that separate group of factors which form an inherent part of switch design, such as oil head, class of enclosure and speed of break. This work was necessary to determine the best working conditions and to assess the risk.

The same type of switch was employed in all comparable tests carried out and described in this section. The switches were usually of such dimensions that with the power available they could be subjected to considerable stress; in many of the tests they were worked at what was believed to be the maximum breaking capacity, without any factor of safety.

In view of the widely varying nature of the phenomena involved, each test was repeated many times.

Comparison of Single-break and Multi-break Switches of Normal Design.—The advantage of breaking a circuit at more than one point is well recognized, and considerable investigations have been carried out by Messrs. Brown, Boveri and Co., the American General Electric Co. and others, to determine the precise nature of the advantage. Curves have been published connecting the number of breaks in series with break energy, and other factors intended to represent distress, but, while the results show correctly the trend of the relationship of the factors, the standards used are open to criticism and such curves are probably no more than a rough guide. A series of fixed relationships has been obtained by the author, but it is recognized that accurate relationship must vary somewhat with each design and possibly also with variations in circuit conditions. The degree of variation, however, is not great.

The comparisons given herein deal with the most common commercial instances, namely a single break compared with two breaks, and a single break compared with four breaks. Tests at 3 300 volts carried out on a single-break switch are compared with similar tests carried out on an otherwise similar 2-break switch. Further tests are given at 5 500 volts on a single-break switch and are compared with tests at 5 500 volts on a 4-break switch. All tests were carried out on similar switches.

Single Break versus Double Break.—The single-break tests were carried out at 3 300 volts with the generator on dead short-circuit and an unsymmetrical current wave. The phase angle was 85°, and six units of distress were registered. The unit of distress used herein is based on the deformation of the renewable section of the switch tank. The oscillograph record of this test is shown in Fig. 10.

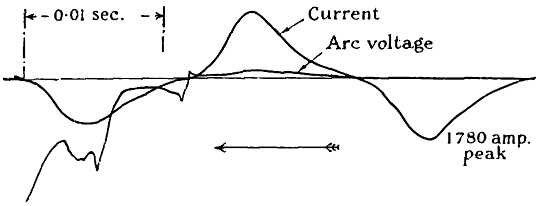

Fig. 10.

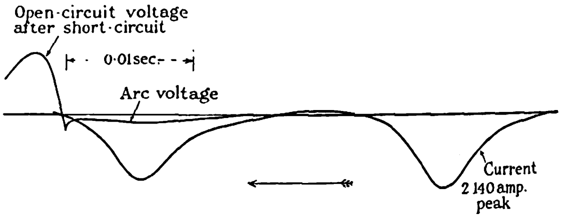

Fig. 11.

Single break versus two breaks on 3 000-volt short-circuit.

The 2-break tests were carried out, as in the single-break tests at 3 300 volts, with the machine on dead short-circuit, the current wave unsymmetrical and the phase angle 85° (see Fig. 11).

Single Break versus Four Breaks.—The single-break tests at 5 500 volts were on dead short-circuit at a phase angle of 84° with the current wave symmetrical (see Fig. 12). In this particular test the switch flashed over

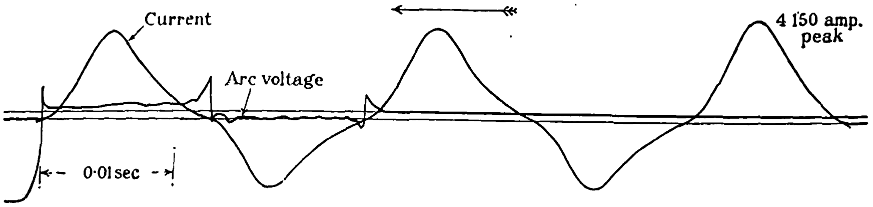

Fig. 12.—Single break versus four breaks on 5 500-volt short-circuit.

to earth internally and had to be cleared by other means.

The 4-break tests were carried out under similar conditions at 5 500 volts. In the first test illustrated the phase angle was 84° and the current wave symmetrical. The oscillograph record is shown in Fig. 13.

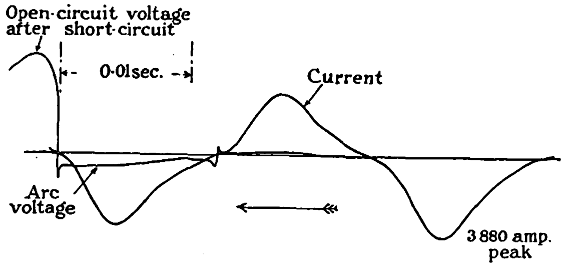

FIG. 13.—Single break versus four breaks on 5 500-volt short-circuit.

In the next tests the phase angle was again about 84° and the current wave totally symmetrical.

TABLE 6.

Single-, Double- and Four-Break Tests.

Type of break	Voltage (nominal)	R.M.S. current	Break energy	Distress
	volts	amps.	kW-sec.	
Single	3 300	1 050	9·83	6 (Fig. 10)
Single	3 300	1 750	4·63	6
Two	3 300	1 150	1·82	4 (Fig. 11)
Two	3 300	1 730	3·2	4
Two	3 300	2 080	6·15	3
Single*	5 500	2 040	15·4	10 (Fig. 12)
Single	5 500	2 040	18·2	9
Single	5 500	2 043	46·2	10
Four	5 500	1 960	16·75	6 (Fig. 13)
Four	5 500	1 950	15·3	4
Four	5 500	2 020	19·8	6

* Internal flash-over in this test.

It is not suggested that these results provide a precise comparison of breaking capacities, but rather that they provide evidence to enable a sufficiently close estimate of the relative performance to be made.

Conclusions.—In the comparison of single-break, 2-break, and 4-break tests, it can be accepted with fair accuracy that the breaking capacity gauged on the actual distress produced is in the ratio 100 : 62 : 50 for single, double, and 4-break switches respectively. Between four breaks and six breaks there appears to be less than 10 per cent improvement, but only a few tests were carried out and the results are not very definite.

Speed of Break, and Distress.—From the results of the tests carried out, the author reached the definite conclusion that, within limits, the speed of breaking has comparatively little effect on the distress. There is a range of speed which gives satisfactory operation, whilst operation becomes progressively more dangerous both above and below this band. The question of speed of break, however, is a more complicated matter than might appear at first sight, as it is involved with many other factors to an extent which makes it difficult to treat it adequately without becoming diffuse. Wilkins and Crellin have recently made some interesting observations * on the speeds attained on breakers installed in the United States, but the author is not entirely in agreement with them.

Very low breaking speeds produce excessive distress, but at about 10 ft. per sec. in the 3 000 V/20 000 V range the distress curve usually commences to flatten. The advantage of higher speeds is largely dependent upon the reactance of the system to which the switch is connected. It will readily be appreciated that if a switch were to open at an extremely rapid rate there would be danger of an induced voltage-rise owing to the current being forced down more rapidly than the rate which corresponds to the normal decrement for the inductance/resistance ratio of the circuit. This immediately introduces the very broad question of the working voltage of the system, since the impedance of, say, a 6 000-volt system will be greater than that of a 440-volt system and correspondingly less than that of, say, a 132 000-volt system. For instance, a 6 000-volt system is characteristically a distribution system; in a given instance which was investigated the short-circuit impedance was found to be 0·12 ohm. A voltage of 132 000 is essentially a transmission voltage; in a given instance the short-circuit impedance was found to be 150 ohms. Furthermore, the ratio of inductance to resistance is probably greater in the higher-voltage system. Therefore, to avoid voltage-rise, the interrupting speed should, if anything, be lower for the higher voltage, whereas the contrary is the usual practice. The high-voltage system, however, is capable of withstanding rather a higher opening speed than would be thus indicated, because the resistance of an arc for a given power is greater than on the low-voltage system, owing to the smaller current at the higher voltage. (The resistance of an arc, of course, decreases as the current increases.) The two factors are unlikely to balance one another and, furthermore, their respective numerical values are not in fixed ratio. Therefore the breaking speed should be fixed with due reference to both these factors.

The actual average linear speed of the main contacts, however, is, in the author's opinion, of small importance compared with the maximum speed of these contacts and with the effect produced by arcing contacts or other special devices which may introduce a very high momentary increase in speed with consequent disturbance of the arc. Certain contact arrangements tend to break circuit more rapidly than others, and the use of snap or other high-speed contacts is in fact more common at high than at low voltages, so that, apart from the simple question of cross-bar or main contact speed, special features of design may cause effects similar to those produced by a high average cross-bar speed. For instance, Fig. 14 shows an oscillograph record of a comparatively slow-moving oil switch which was fitted with snap contacts. All goes well until the snap contacts are released, when the voltage suddenly rises, producing not only increased energy at the break but actual re-establishment of the arc just at the moment when it is extinguished. Fig. 15 shows a record of a similar effect produced by a powerful magnetic loop formed by the arrangement of the internal connections, while Fig. 16 is another example produced by the action of explosion pots. These effects have been noticed at various voltages and seem liable to occur, irrespective of the circuit conditions, thus indicating the great influence which contact design has on this important problem. Therefore high-speed spring contacts, explosion pots (which have a similar effect in accelerating the speed of break), magnetic blow-out and anything which may tend to produce sudden speed-changes should be adopted only after careful consideration. It may be of some significance that one of the first troubles to develop in the past in explosion-pot switches has been insulation or mechanical breakdown of the pots, while the author is aware of several instances of flash-over and insulation breakdown on magnetic blow-out (air) breakers which could be attributed only to incorrect design of the blow-out field.

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* See Bibliography.

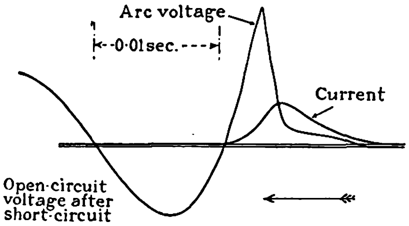

FIG. 14.—Oscillogram of voltage-rise obtained on oil switch with snap contacts.

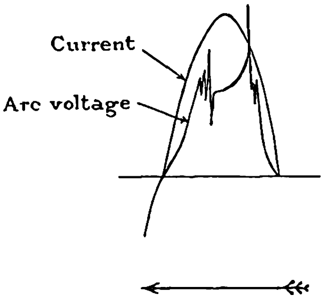

FIG. 15.—Oscillogram of voltage-rise obtained with magnetic blow-out.

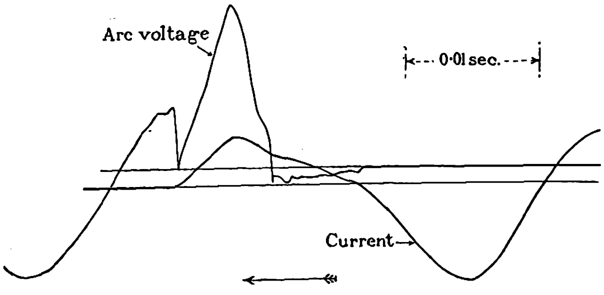

FIG. 16.—Oscillogram of voltage-rise obtained on oil switch with explosion pot.

Ratio of Air Cushion to Oil Head.—When the contacts of an oil switch separate, an arc is drawn which immediately commences to heat and crack the oil in its vicinity. A pressure is set up by the displacement of the oil by the growing arc, but a greater pressure results from the gas formed by the action of the arc on the oil. The gas bubble continues to grow, even after the arc is extinguished. The final size of the bubble depends upon the ratio of air cushion to oil volume, because the expanding gas bubble reaches a state of equilibrium only when the air cushion is compressed to an appropriate reactionary pressure; therefore, the larger the air cushion the larger will be the gas bubble and the lower the resultant pressure. It might be concluded, therefore, that it is necessary only to increase the air cushion to a large enough extent to reduce the gas pressure to a safe value, but a limit is reached when the gas bubble, which is of a conducting character, tends to bridge the contacts or form a path to earth and so introduce the danger of an internal short-circuit. During the early stages of growth the gas bubble does not move far from the point of formation—it may elongate from its originally roughly spherical form to a pear shape. At this stage the gas bubble somewhat resembles the core of a peach with the oil forming the flesh of the fruit and accordingly pressed into contact with the skin or container on all sides, including the top, the air cushion having nearly disappeared through compression and absorption, as illustrated in Fig. 17.

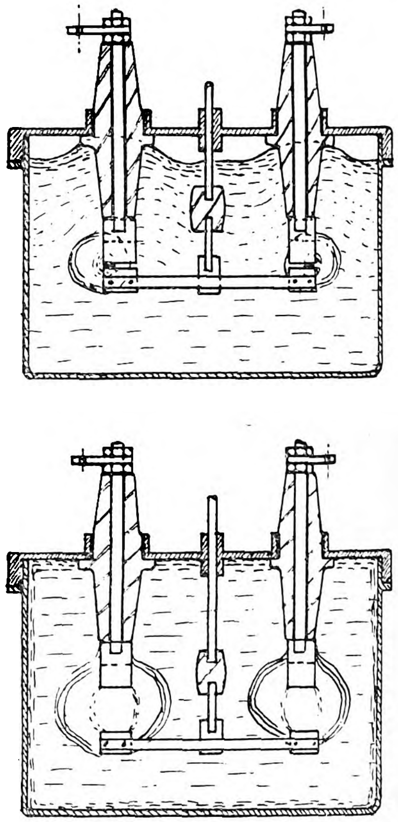

FIG. 17.—Disposition of oil during arcing period.

It might be helpful to consider an actual instance of what occurs in practice. An oil switch undergoing test had a tank measuring 20 in. × 20 in. × 20 in. with an air cushion of 10 per cent of the total tank volume. On a 150 000-kVA short-circuit the gas bubble, during an arcing time of 0·06 sec., was found to expand to approximately 11 inches in diameter and it set up a pressure of about 160 lb. per sq. in.; thus the air cushion would be reduced in the ratio of the two pressures, i.e. to 15/(160 + 15) = 0·086 of its original volume. The diameter of the gas bubble at the volume taken in the example is already about as large as is consistent with safety, so that an increase or decrease of the air cushion results respectively in either a larger gas bubble or a higher pressure. Furthermore, if the gas bubble be allowed to grow to a larger size, or if the oil head be not great enough, the gas bubble may break through to the surface in an incandescent state, so introducing the danger of a surface flash-over.

Safety is obtainable over a fairly wide range without sharply defined limits; the one extreme, that of no air cushion whatever, is dangerous, while operation with a large air cushion again becomes dangerous. Tests on commercial and experimental switches without any air cushion showed that successive operation under short-circuit conditions resulted in oil being forcibly ejected, even through bolted flanges, until a reasonably safe air cushion was obtained. Hermetically sealing the container with no air cushion will produce bulging or bursting of the tank and top plate. In general, tests indicate that, over the range of tank sizes in general use, the air-cushion volume should be at least 5 per cent, but not more than 15 per cent, of that of the tank.

Variation of Distress with Power Broken.—The term "power broken" is used herein as meaning the product of the open-circuit voltage and the R.M.S. value of the short-circuit current (during the first cycle). It will be shown that the average distress on a given switch varies roughly with the power broken, as might be expected. Repeated tests under similar conditions, it is true, do not give the same results, but the average of groups of repeated tests gives distress values which do vary roughly with the power broken. Two groups of tests are given as a partial illustration of this.

Tests.—The figures given in Table 7 and Fig. 18 were obtained in tests carried out at 5 500 volts at a phase angle of about 85°.

Symmetry of Current, and Distress.—When an alternator is short-circuited, the currents in the three phases assume varying degrees of asymmetry, depending upon the point of the voltage wave at which the short-circuit commences. The unsymmetrical condition persists for a few cycles to a progressively decreasing extent, and it is sometimes assumed that this condition is responsible for the distress variation when breaking the circuit. Results have been obtained, however, which show that such an assumption is largely untenable. There is certainly a small variation in average distress between the symmetrical and unsymmetrical conditions, but there is no doubt that this variation is relatively small and it is hardly of such magnitude as to render it worth while to modify the design of switching apparatus to provide for it, while relatively greater causes of variation remain unchecked and quite unprovided for. In a 3-phase single-tank switch the compensatory effect of the three phases is such that the degree of symmetry can usually be neglected as a factor in total distress production. It is in the 3-tank design only that any consideration of the effect of the degrees of symmetry may possibly be warranted. It has been the author's experience that the greatest result of current asymmetry is the effect it produces on subsequent phenomena such as arc growth, arc formation and arc fluctuations, rather than the smaller variations in distress produced by the current value *per se*.

TABLE 7.

Voltage	kVA broken	Distress as gauged by deformation
volts		
5 500	5 180	0·9
5 500	6 150	1·3
5 500	6 350	2·5
5 500	6 960	1·8
5 500	10 500	4·4
5 500	11 000	3·5
5 500	11 000	5·1
5 500	10 500	5·2
5 500	10 260	1·5

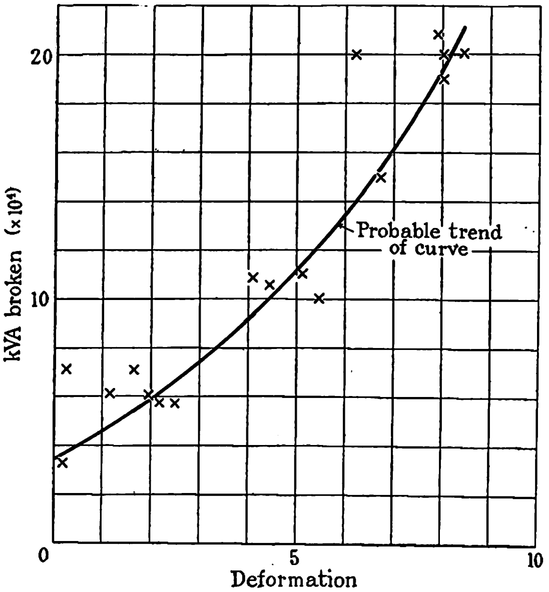

FIG. 18.—Curve showing relation between kVA broken and deformation (see also Table 7).

Table 8 shows a few selected tests from which it will be seen that the symmetrical and unsymmetrical conditions are almost swamped by other variable factors.

Phase Angle and Distress.—Consideration of the question of phase angle is allied with other matters, e.g. the influence of the arc phase-angle. The arc during the circuit-breaking process acts as an ohmic resistance which commences at a low value when the arc is short and the current heavy, so that the effect on the total phase angle is small. As the arc is lengthened, the resistance increases, but, as the current is now small, the relatively large effect on the phase angle is of small importance. In the subsequent paragraphs, therefore, arc phase-angle has been ignored, although its effect is, of course, contributory to the test-results given and all further references are to circuit phase-angle. A considerable number of tests were carried out in order to find the critical zones, and the figures given below were selected to represent roughly the maximum and minimum angles met with in practice, the third figure being approximately in the centre of the range and selected to correspond to maximum distress as shown by test.

TABLE 8.

Symmetry	Voltage (nominal)	Current	Break energy	Deformation
	volts	amps.	kW-sec.	
Sym. ..	5 500	1 250	3·1	3
Sym. ..	5 500	1 200	4·96	1·8
Sym. ..	5 500	1 150	2·2	1·3
Unsym...	5 500	700	5·15	2·3
Unsym...	5 500	800	5·0	2·3
Unsym...	5 500	767	0·5	0·1
Unsym...	5 500	750	7·1	3
Unsym...	5 500	650	4·9	2

At a phase angle of about 36°, current symmetrical, a group of tests produced deformations between 2·3 and 3·0. The general performance in these tests was fair; there was a fair amount of noise, oil throwing and gas. Fig. 19 is a characteristic oscillograph record of one of these tests. Between 54° and 57° phase angle, corresponding to 0·6 power factor, current again totally symmetrical, the deformation varied between 2·6 and 4·4. The general performance was poor. Fig. 20 is a typical oscillograph record. At 85° phase angle, with the current totally symmetrical and other conditions unchanged, the deformation varied from 0·1 to 3·3. Fig. 21 is an oscillograph record characteristic of these tests. (See also Fig. 1, which shows burning of contacts when switching a similar load at 60° and 36°.)

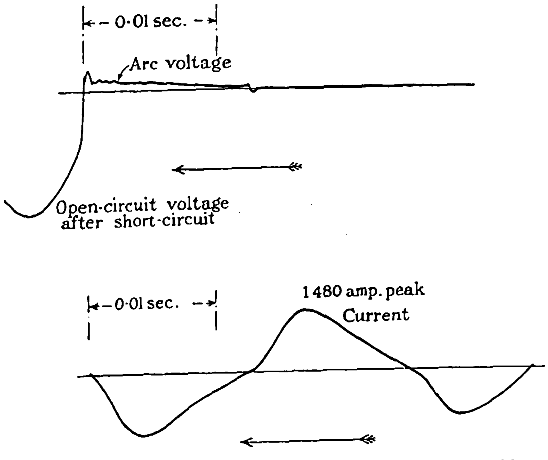

FIG. 19.—Reactance tests at a phase angle of 36°.

Conclusions.—These results are shown graphically in Fig. 22.

A phase angle of 36° is the smallest ever likely to be met with under short-circuit conditions; it is unlikely that this value will be reached except under extreme conditions. In practice, such a small phase angle indicates that the current cannot attain great proportions, as a considerable amount of resistance would necessarily have to be in circuit to change the low phase angle of the generating plant, alone, to the higher value. Therefore 36° is considered to be the extreme limit. At such a phase angle the author's tests show that the average distress is about two-thirds of that in the 55° zone, while the maximum distress is also about two-thirds. A phase angle in the 55° zone would be likely to be produced on a short-circuit at a short distance from the power source. At this phase angle the greatest average distress is produced,

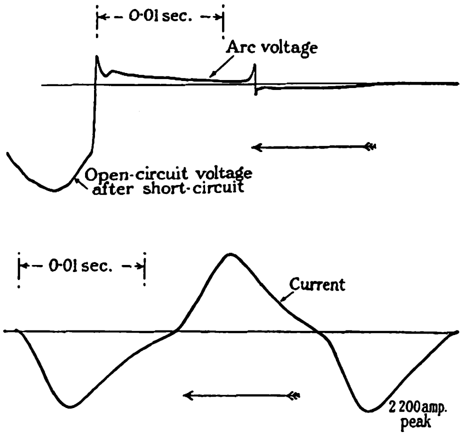

FIG. 20.—Reactance tests at a phase angle of 55°.

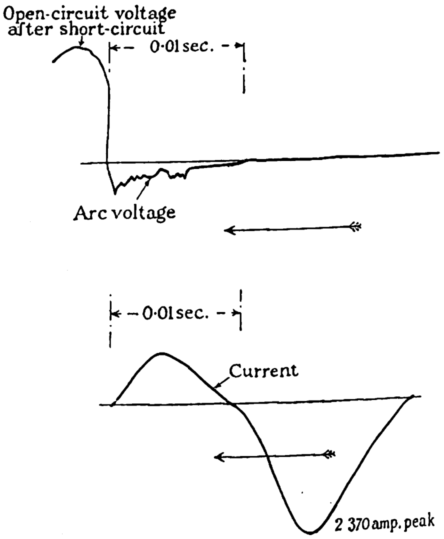

FIG. 21.—Reactance tests at a phase angle of 85°.

the actual range of distress being 2·6 to 4·4, while the range of variability is smallest at this value. At a phase angle of 85° the range of distress is 0·1 to 3·5, thus producing a low average and consequently indicating a lower frequency of occurrence of the maximum distress as compared with that at 56°, but the maximum is high at both 55° and 85°. Thus the switchgear is likely to be subject to about the same maximum distress, but the chances of such distress being produced are smaller. Therefore the switchgear user has to decide whether the apparatus is required to stand up under all circumstances, in view of the decreased expenditure or whether the lower frequency of distress occurrence can be taken advantage of and faced as a legitimate commercial risk.

The Effect of Resistance and Inductance.—The resistance of the cables or overhead lines has usually the most influence on the phase angle. Where the transmission-line resistance has not to be considered (as in the case of a busbar short-circuit), the addition of current-limiting reactors would reduce the current on short-circuit without affecting the phase angle to any material extent, as on a dead short-circuit of this character the phase angle is very large without the reactors, and the addition of the reactors makes but little difference. Therefore, the initially large generator phase-angle is not greatly augmented by the inductive effect of the reactors, so that the effect of the small phase-angle variation would usually be negligible.

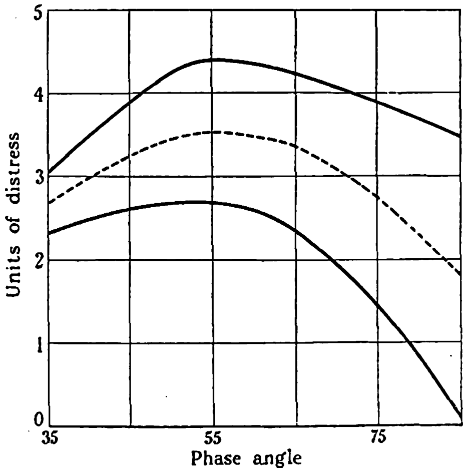

FIG. 22.—Curves showing mean distress for a group of tests at various phase angles.

Relatively heavy feeder short-circuits may be divided into near-by faults, within a radius of a few hundred yards from the power station, and those of greater radius up to about 2 miles; with a near-by fault the phase angle is already of the order of 55° to 60°, so that the addition of reactors would probably be helpful.

Beyond this area, as the radius increases, the phase angle would normally decrease owing to the resistance of the transmission system; the addition of reactors then has a progressively greater effect in bringing the phase angle back into the region of maximum distress. On a 6-kV system within a radius of about 2 miles from the power station a considerable proportion of large substations are normally placed, and their capital cost is largely dependent upon the class of switchgear installed. It is, therefore, in such circuits that reactance has frequently been provided, either at the substation or at the power station, usually with the intention of reducing switchgear costs. In the production of switchgear stresses, the current reduction may in some such situations have been more than offset by the increase in the phase angle.

In a transmission system consisting chiefly of radial feeders not interconnected, the phase angle would change into the middle zone at a shorter distance from the power source. For instance, at the end of a 1-mile length of 0·1 sq. in. cable, the conditions may be roughly equivalent to those obtained at a radius of about 2 miles on an interconnected network. The phase angle on short-circuit would in both instances be of the order of 45°, and the addition of current-limiting reactance with too great a proportion of inductance would increase the phase angle to the 55° zone.

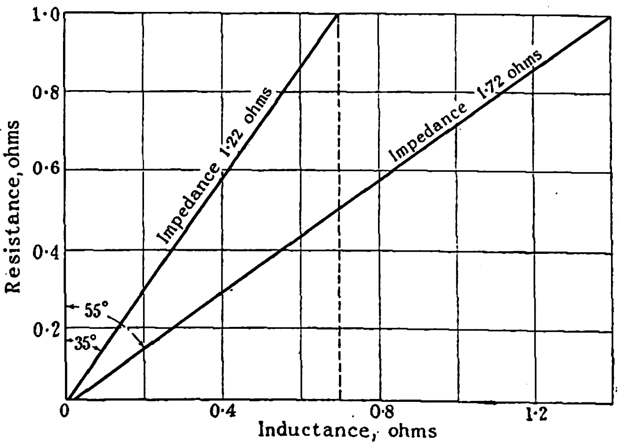

FIG. 23.—Vectorial relationships of current and voltage on increasing inductance by 100 per cent.

The curves in Fig. 22 show that the distress can increase approximately 46 per cent for a given current by the simple increase of the phase angle from 36° to 56°. The phase-angle conditions corresponding to these values are shown vectorially in Fig. 23, which also shows that to bring about a current reduction of 29 per cent on a given circuit composed of 1 ohm resistance and 0·7 ohm inductance, it is necessary to double the inductive component, thus making it 1·4 ohms, with a corresponding phase angle of 55°. At 36° the total impedance corresponds to 1·22 ohms and at 56° to 1·72 ohms, an increase in impedance of approximately 40 per cent, which results in a current reduction of 29 per cent.

The phase-angle variation during this change, after making allowance for the current reduction, thus causes an increase in distress of about 15 per cent in the instance considered.

Fig. 24 shows how the reactance of an alternator alters at various overloads and indicates that this variation may also contribute to alterations in the current phase angle.

Transmission-line transformers at a power source may bring about switching conditions of the same sort.

Two instances of this happening in practice are as follows:—In one, a 2 000-kVA transformer bank was connected to a 6 000-kVA, 6 000-volt alternator, with the result that, on short-circuit, the distress on the 6 000-volt generator switch was considerably greater than with the transformer not in circuit. The other instance happened with a 6 000-kVA step-up transformer bank, where the switchgear operated satisfactorily when dealing with a given load fed direct at 6 000 volts, but ejected oil when breaking a load of similar magnitude consisting of a step-up transformer bank.

Phase-angle variations have an important bearing on the use of step-switches employing resistance on the intermediate step or steps, for such a switch on a large-phase-angle short-circuit is liable to pull the phase angle into the 60° zone. Two commercial switches of this type were tested and, somewhat to the astonishment of the manufacturers concerned, the switching performance was considerably improved by the removal of the resistances. This does not mean that resistance step-switches are to be wholly condemned, but is intended to show that the haphazard introduction of resistance may be the reverse of helpful.

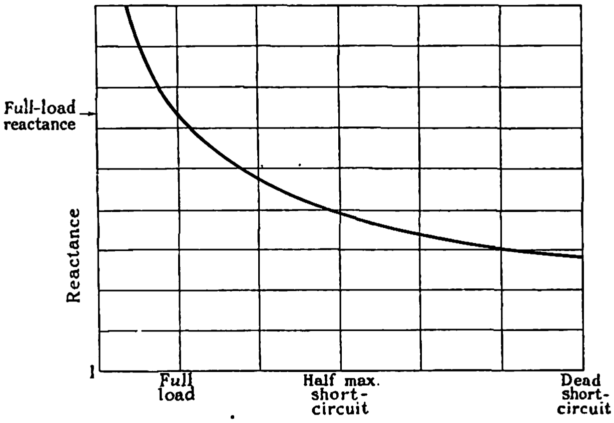

FIG. 24.—Alternator reactance at various overloads.

(5) CONCLUSIONS TO BE DRAWN FROM THESE TESTS.

Variability of Circuit-breaker Performance.—Switchgear designs tend to reach a stage of equilibrium owing to the experience gained from successive breakdowns on the one hand and the restraining demands of economics on the other, with the result that present-day apparatus appears to have gradually evolved to a condition suitable for average distress conditions.

This would indicate that the present commercial breaking-capacity ratings are similarly average ratings and, as such, are liable to a percentage of breakdowns of varying degree. The relative proportions of safe operations and unsafe operations depend upon the ratio of stress produced under the average and the maximum conditions. Having found this ratio, the maximum safe breaking capacity under all conditions can be determined. Using the ratio given below, i.e. 2·5 : 1, and assuming the largest commercial breaking capacity at present economically possible to be 2 million kVA, the true breaking capacity (i.e. that which will ensure 100 per cent service) will be 800 000 kVA.

Switchgear can generally be considered as falling into two groups. The first group includes the heavy-tank switch, usually of the ironclad form, which is so much used in this country and which is capable of withstanding a sustained pressure of 150 lb. per sq. in. and upwards, and the largest of which will, in the author's opinion, give satisfactory service on a short-circuit power of 800 000 kVA. The second group, although intended for the same duty as the heavy type, is of the light-tank design, largely adopted abroad and perhaps to a smaller extent in this country. Comparative tests indicate that the lighter type is likely to fail at about one-third the stress which the first group can withstand, both as regards the maximum power for which such switches can commercially be built and also with respect to the comparative performance of a given pair of switches from the two classes, assuming, of course, that switches of similar overall dimensions and nominal rating be compared. It has therefore been assumed that 300 000 kVA is the maximum power for which such switches can be relied upon under all conditions. These conclusions are roughly confirmed by an examination of records of switch failures under extreme working conditions and by comparative tests on smaller switches of both the light and the heavy pattern. The maximum safe rupturing capacity is assumed to be rather below the point at which permanent distortion of the container would be set up. This limit was decided upon by deformation experiments upon oil containers manufactured specially for various test-switches, and it was noticed that it was possible for failure (distortion) to occur at something less than half the commercial rating, or, more precisely, at two-fifths of this rating.

In the first (or heavy switchgear) group the ratio of maximum to average distress in all the tests carried out, of which those described in this paper are a representative selection, is approximately 2·5 : 1, whilst the ratio of maximum to minimum distress is 77 : 1.

If the previous paragraphs be accepted, this 800 000-kVA rating corresponds to the manufacturers' rating for a circuit breaker of 800 000 × 2·5, i.e. 2 000 000 kVA, since designs are based on average experience. Actually, a short-circuit breaking capacity of at least 2 000 000 kVA is required if service free from chance of breakdown is to be obtained, so that such a breaker would have a rating corresponding to 2·5 times that of the present-day 2 000 000-kVA breaker, or 5 000 000 kVA, and would be very costly.

An adequate source of testing power will soon become a *sine qua non* in the production of reliable circuit breakers. The possession of such a plant would enable circuit breakers to be tested at their rated breaking capacity, and would greatly assist in the evolution of designs without having to wait for operation experience, with its attendant risks to both user and manufacturer.

Mechanical Strength.—Arising out of the necessity for great mechanical strength, a comparison of rectangular and round tanks discloses the fact that, for a given volume and thickness of material, the round-tank switch is usually capable of withstanding 50 to 100 per cent greater hydraulic pressure than the square-tank type.

This is confirmed by an examination of manufacturers' test figures. It would thus appear that round tanks should be used wherever the space available and other factors permit this to be done.

There seems to be a tendency on the part of manufacturers to attribute quite low test pressures to tanks which should be capable of withstanding considerably higher pressures. For instance, one manufacturer tests to 50 lb. per sq. in. on a tank little greater than 1 cub. ft. in volume and constructed of stiffened $\frac{5}{16}$-in. steel. Such a pressure is very low for a tank of this class of construction, and one is left wondering whether it indicates lack of faith in the workmanship put into the welding and riveting, or whether there is some weak spot which, by comparatively minor modifications, could be improved sufficiently to make the whole apparatus of consistent strength. There is no doubt that a considerable increase in pressure could be applied to a tank of these dimensions if it were soundly constructed, and without adding materially to the cost, and, as it seems clear that breaking capacity is proportional to some function of the pressure-withstanding capability of the switch tank, it seems but logical to ask for a test pressure which indicates that the materials from which the tank is constructed are being reasonably well utilized.

TABLE 9.

Switch No.	Breaking capacity	Test pressure	Vol. of tank
	kVA	lb. per sq. in.	cub. ft.
1	75 000	150	3·0
2	100 000	150	3·3
3	150 000	200	4·4
4	250 000	200	7·1
5	350 000	250	12·7
6	500 000	350	16·1
7	750 000	350	30·5
8	1 000 000	500	56·2
9	1 500 000	800	88·0

In a given range of switches the rated breaking capacities and corresponding test pressures shown in Table 9 have been standardized, while Fig. 25 includes a number of other switches.

After making due allowance for size of tank or enclosure and after certain adjustments to some of the designs, the test pressure and mechanical strength in the above range of switches were found to be, in general, proportional to breaking capacity and, as it is found convenient in the manufacture of all except super-voltage high-power switches to increase both size and strength as the rated breaking capacity is increased (rather than to keep, say, size constant and to increase strength to a greater and disproportionate amount, or vice versa), it is evident that the breaking capacity is to some extent proportional to the product of tank volume and mechanical strength as indicated by test pressure.

If, in conjunction with the foregoing, the requirements of breaking speed and other factors are duly observed, it should be possible to specify breaking capacities with a fair degree of confidence.

Breaking-capacity Formula.—It will perhaps be agreed that any attempt to devise a breaking-capacity formula from a theoretical standpoint is doomed to failure because of the variability of the arcing phenomena. It seems, furthermore, somewhat futile to attempt to tie into a formula such factors as speed of break and air cushion, which, in a given design, must either be right or wrong, and, if wrong, should be remediable with little difficulty.

The factors which mainly determine the breaking capacity are volume and strength of oil container, and number of breaks in series per pole. That the number of breaks has a definite influence on the breaking performance is shown on pages 1094 and 1095. Using the 2-break switch as a standard it has been found possible to correlate strength, volume and breaking capacity in a formula based on practice and on test data. The work done in compiling figures similar to those in Table 9 has had a considerable bearing on the results.

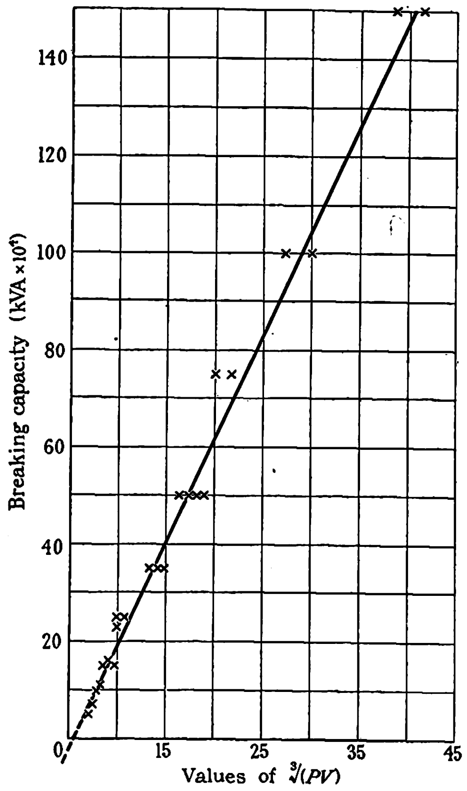

FIG. 25.—Curve showing connection between breaking capacity and the value of $\sqrt[3]{(PV)}$ of oil switches by various manufacturers.

The breaking capacity has been found to be not directly proportional to the strength and volume but proportional to the cube root of the product of these factors. It was found to be possible to plot breaking capacity to the cube root of this product down to quite low values; but values below about 50 000 kVA have had to be excluded by the introduction of a minus factor into the equation. At the other end of the scale the formula applies to switches up to about 100-cub. ft. tank capacity and, if care has been taken to ensure that switches lying off the line conform in the same manner as the range shown in Table 9, it will be found that the formula

Breaking capacity (average or commercial)

$$= 4\cdot26\left\{\sqrt[3]{(PV)} - 5\cdot7\right\} \times 10^4$$

applies consistently and that, given any two of the three factors, breaking capacity, test pressure and volume, the third can be found. The breaking capacity thus found is that corresponding to the average rating referred to on page 1100. To obtain the 100 per cent breaking capacity under all conditions it is necessary to divide the result by 2·5. In other words, the first result is the breaking capacity of a switch which under the usual load and running conditions on a large system (see pages 1101 and 1102) would break the power indicated by the formula in 96·75 per cent of the total times of operation. The second result, introducing the constant 2·5, gives the safe breaking capacity under all conditions, and is thus:—

Breaking capacity (true or 100 per cent value)

$$= 4\cdot26\left\{\sqrt[3]{(PV)} - 5\cdot7\right\} \times 10^4 \times \frac{1}{2\cdot5}$$

The results so obtained give the breaking capacity of a switch having two breaks per pole. With four breaks per pole the commercial breaking capacity would be greater by the fraction $\frac{5}{4}$, so that the formula would become $4\cdot26\left\{\sqrt[3]{(PV)} - 5\cdot7\right\} \times 10^4 \times \frac{5}{4}$, and the true breaking capacity would be

$$4\cdot26\left\{\sqrt[3]{(PV)} - 5\cdot7\right\} \times 10^4 \times \frac{5}{4} \times \frac{1}{2\cdot5}$$

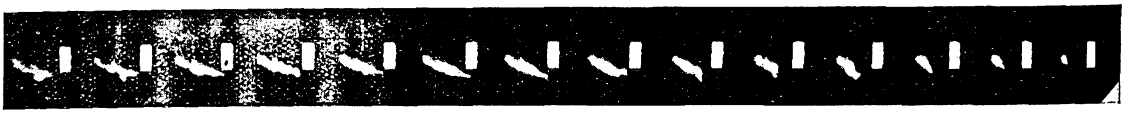

FIG. 26.—Photograph showing 6 000-volt 100-ampere arc, under fixed circuit conditions, fluctuating and breaking up.

Approximate distance between two arc roots under worst conditions = 30 in.
Approximate distance between two arc roots under best conditions = 2 in.

When considering extra-high-voltage high-power circuit breakers, voltage clearances necessitate a large tank volume and in consequence it is usually found that the mechanical strength is rather below the standard upon which the formula is based, and that the ratio of volume to strength is greater than in the former class of apparatus. Although the formula has been found correct in all instances where it has been so far applied, irrespective of the volume/strength ratios, in the large-volume range of switchgear it should be used with caution.

Existing Switching Conditions Analysed.—Existing switching conditions should apparently be regarded from the point of view of engineering risk, since it would appear that the short-circuit powers which now have to be dealt with cannot be broken with certainty by any existing oil switch. The question is: What is the maximum risk and what risk can or should be undertaken? To answer this involves an analysis of faults, first in the power station itself where the maximum short-circuit power occurs, and secondly on the distribution or transmission system where the short-circuit power does not attain such a high value. In such an analysis on three different power systems taken together, it was found that the annual total number of faults was 170. Of these, 11 were major faults; that is to say, they were either power station short-circuits or were in a part of the system where the short-circuit power could reach a greater value than the maximum certain rupturing capacity of the largest switching unit installed. Therefore, the switchgear would be called upon to operate under conditions exceeding its rating in 11 out of 170 times, or 6·5 per cent of the total.

It will, of course, be appreciated that on smaller systems where, especially during the slack hours, a maximum short-circuit kVA of less than 800 000 is available, the above percentage must be correspondingly reduced.

Still dealing with the larger type of power system, it is now possible to correlate these figures with the test figures showing the rates of variability in distress produced under various circuit conditions. The actual numbers of tests in the two groups (over-stress and maximum safe stress) were found for all practical purposes to be equal; therefore, taking 800 000 kVA as the greatest breaking capacity obtainable and the over-stressed condition as happening in 50 per cent of the total times of operation, the chances against the switchgear having to deal with more power than that equivalent to its true maximum breaking capacity become the product of the percentage already obtained and the ratio of over-stressed tests to total tests, i.e. 1 : 2, thus giving 3·25 per cent of the total. In other words, a high-power heavy-construction oil switch under the usual operating conditions in a power system having a short-circuit capacity greater than 800 000 kVA, but not much greater than this, will give a 96·75 per cent service.

(6) CAUSE OF DISTRESS VARIATION.

Switch Oil and its Effects.—The fortuitous variations in distress to which attention has been drawn in this paper undoubtedly depend on effects inherent in the electric arc and on the behaviour of the switch oil under its influence. The author considers that only a very crude smothering process takes place in an oil switch on breaking, and that the resultant action on the oil is complicated and largely uncontrollable. The function of the oil has become somewhat obscured in the evolutionary process. Oil was originally used in switchgear because it was found that, without it, the arc and the arc gases spread and burnt surrounding apparatus, but there seems little doubt that there has never been a true condition of arcing in the oil, and that actually the arc has been a gaseous one wherein the arc is surrounded by a gas skin which intervenes between it and the oil.

Oil has the advantage of reducing the hot zone of the arc gases, but unfortunately it localizes the pressure effects and, as a result of gasification of the oil, produces much higher pressures than those which can be caused by the arc alone. Prof. Thornton's work on this subject is of fundamental importance.

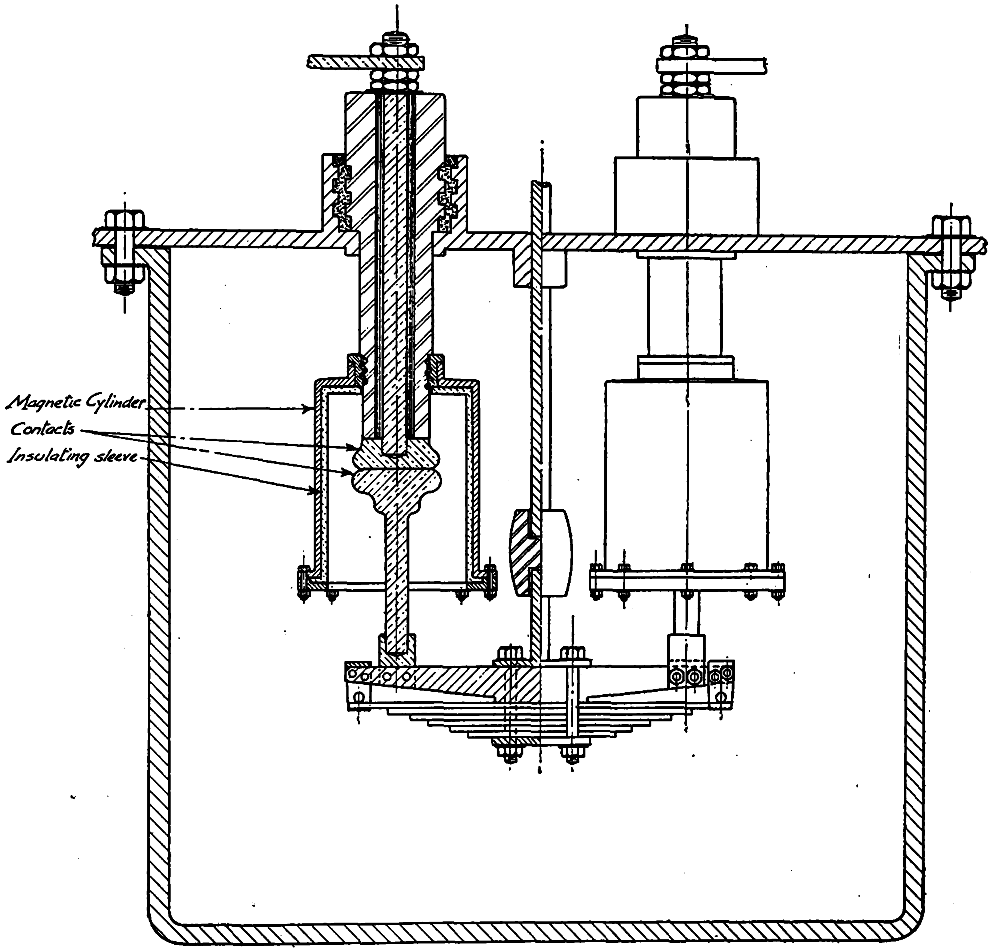
Magnetic Cylinder
Contacts
Insulating sleeve

FIG. 27.—Single-phase oil switch with stabilized arc.

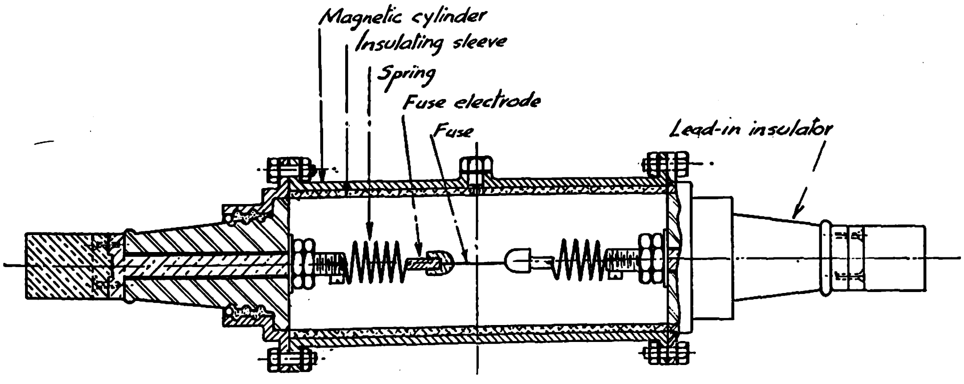
Magnetic cylinder
Insulating sleeve
Spring
Fuse electrode
Fuse
Lead-in insulator

FIG. 28.—Single-phase oil-immersed fusible cut-out with stabilized arc.

Arc Form and Ion Mobility.—Contributing to the complication are the variations in the arc, which is extremely unstable and takes infinite forms (see Fig. 26). It varies in the path it takes, in the length of the path, in its shape and in many other ways, and its thermal effects must vary in a similar erratic manner. A considerable amount of work on the theory of the arc has been carried out by Prof. Compton. One of the things he has demonstrated is that with an electric arc in oil the ion mobility is so small that the ions remain in sufficient concentration to re-strike the arc after the voltage has fallen to zero or has reversed. Slepian demonstrated that a 20 000-ampere arc, when moved rapidly across its source, could be maintained without any sign of the copper melting; there were only the merest traces of oxidation even with the greatest current used. Herr Solt (*Zeitschrift für Physik*) describes further experiments using smaller currents than Slepian. A somewhat similar effect seems to be embodied in the British Electrical and Allied Industries Research Association's British Patent No. 242318/25.

(7) New Designs of Switching Apparatus.

Preliminary.—In 1912 the author carried out tests which were probably similar to those of Slepian and Solt, and succeeded in obtaining improved results. In a paper* read before this Institution in 1926 a partial reference was made to the results of these tests in a brief description of a fusible cut-out with a stabilized arc which had given very consistent and favourable results. This, however, was really a side issue to the 1912 work which is embodied in the new switch described on page 1105.

Stabilized Arc.—In the stabilized-arc device as made, the cut-out is surrounded by a magnetic field which assists the tendency of the arc to keep in a straight line in the shortest path between the electrodes. Since that date, further tests have been carried out both on cut-outs and on switches designed in this way; oil immersion was used in most of the tests, but is not essential. Fig. 27 shows the arrangement of a single-phase switch of this form which was constructed for test purposes and which embodies a simple way of obtaining the required field, while Fig. 28 shows a convenient form of oil fuse embodying the same principle. The two oscillograph records in Fig. 29 show a comparison between the new form of switch and an oil switch of the usual form when breaking a 5 500-volt short-circuit. The comparison shows that in the ordinary oil switch the arc is unstable, whilst in the new arrangement the arc is stable and the voltage wave-form is smooth and flat, and the distress is substantially less than in the ordinary oil switch under corresponding circuit conditions. The flat wave-form of the stable-arc switch is very striking, as there is not even the normal double-peak wave-form which is generally associated with the electric arc.

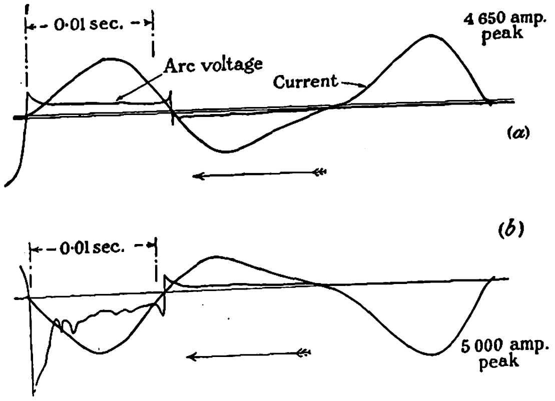

Fig. 29.—Oscillograms of stabilized and ordinary oil-switch wave-forms.

(a) Oil switch fitted with arc stabilizers.
(b) Oil switch without arc stabilizers.

The advantage of this stabilizing principle is generally similar when applied to multi-break switches. So long as the number of breaks is the same, the comparison between the operation of the ordinary type and the stabilized type shows to the advantage of the latter for any number of breaks. Mechanical and electrical forms of stabilization give somewhat similar results. Fig. 29 is a typical example of the results obtained. In a short-circuit at 5 500 volts with a phase angle of 85°, 49·2 kW-sec. of arc energy and 9 units of deformation were obtained on a non-stabilized switch. With the same switch fitted with stabilizers, and on a similar short-circuit at 85°, 29·2 kW-sec. of arc energy was registered and only 3 units of deformation. The switch employed had 4 breaks per phase.

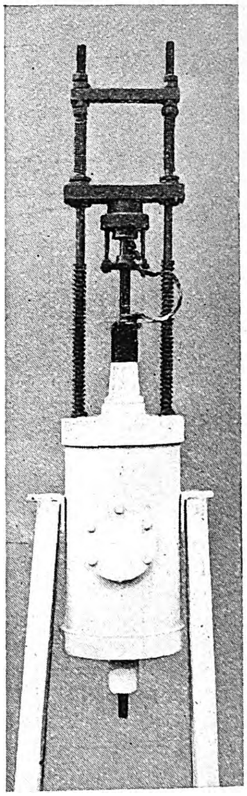

Fig. 30.—Single-pole quenched-arc circuit breaker in the "open" position.

Prolonged testing, however, showed that it was not possible to obtain the complete consistency of performance which was required.

This type of switch, although successful in stabilizing the arc, made no attempt to control the heat production and further tests were therefore carried out, from which was evolved the quenched-arc switch, which combines the features of arc stabilization and heat control.

A New "Quenched Arc" Switch.

Preliminary.—The evolution of good switching apparatus depends upon the observance of a number of factors, some of which have been dealt with in this paper. It has been shown that arc stability produces greater consistency of distress symptoms than is possible with an oil switch of ordinary form. The new step is to reduce the amount of energy appearing at the arc under given circuit conditions. This reduction can take two forms, one, of magnitude, by reduction of the voltage which appears across the arc, and the other, of time, by reduction of the arcing period. The first can be achieved in practice with an arc of low resistance per unit of cross-sectional area, and the second by rapid abstraction of the heat of the arc and consequent reduction of ion generation, upon which depends the ability of the arc to continue. The control of ion production is really at the root of the matter, but the majority of the existing designs of circuit breakers, although excellent in other respects, bear but little evidence of this principle having been recognized. Much good work in other directions has thereby been stultified.

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* *Journal I.E.E.*, 1926, vol. 64, p. 920.

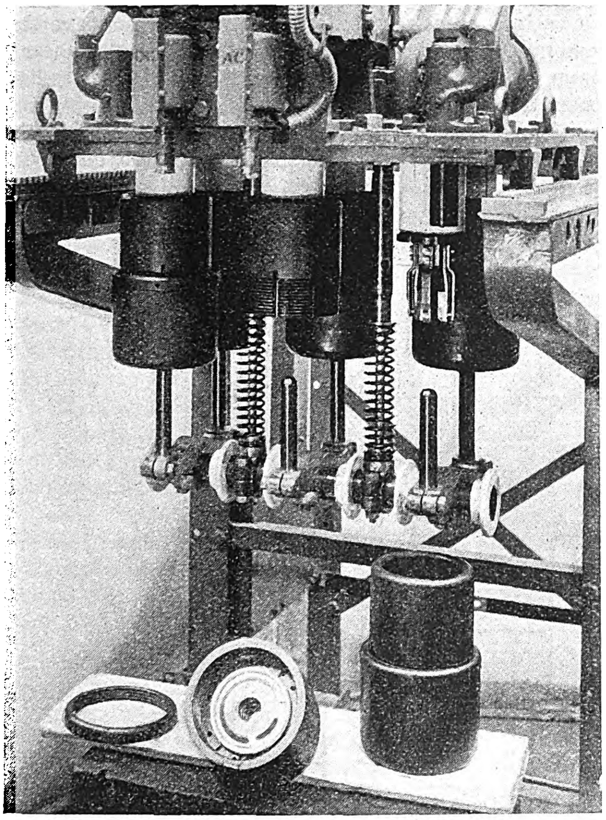

FIG. 31.—An 11 000-volt 350-ampere quenched-arc circuit breaker with two arcing contacts removed.

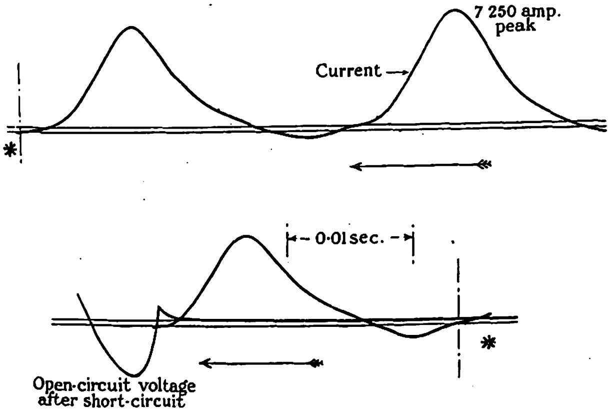

FIG. 32.—Oscillogram of quenched-arc switch clearing dead short-circuit on 6 000-kVA alternator.

The quenched-arc switch is designed to embody the above principles. The energy dissipated at the contacts is reduced to a low value and abstracted in the form of low-grade heat, thus preventing it being passed to the surrounding air, gas or oil, in any other form than that of low-grade heat.

Construction.—The switch * is arranged with a central orifice with lateral discoid openings between heavy metal plates between which a powerful quenching action is set up. This portion of the switch can be under oil, thus preventing the formation of gaseous conducting paths, but a large head of oil is unnecessary, a large air cushion being frequently beneficial. The arc is opened by withdrawing a central contact rod from a circuit contact under the oil; the rod then passes the discs (or other surfaces) successively, the arc being forced by magnetic and thermal action into the radial extinguishing openings. The extinguishing process takes place at a comparatively small radial distance from the central rod when medium amounts of power are being handled, while with greater amounts of power the path of

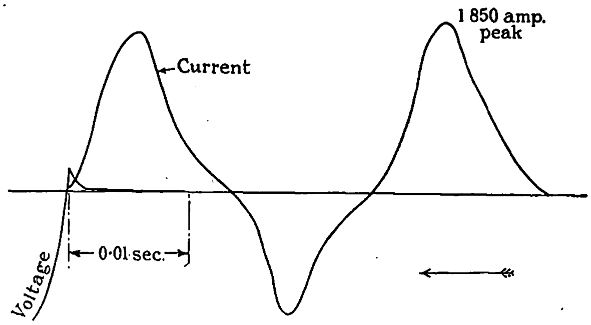

FIG. 33.—Test on quenched-arc switch at 3 000 volts, 900 amperes.

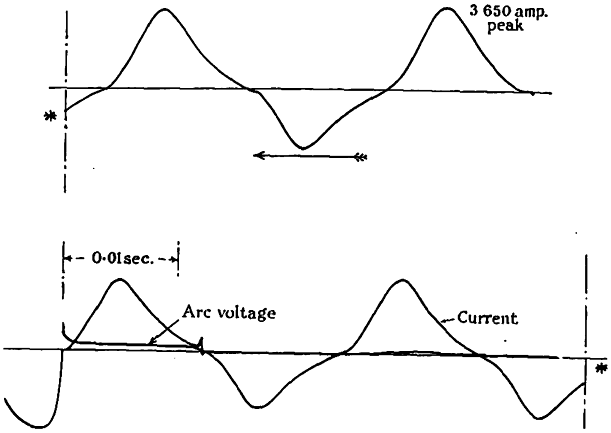

FIG. 34.—Test on quenched-arc switch at 5 240 volts, 2 020 amperes.

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* British Patent No. 29714/1927.

travel becomes longer and broader, finally emerging into an annular extinguishing chamber near the outer edge of the discs where the heaviest power can be quietly broken. Arc stability is produced mainly by the metal discs which constitute guiding contacts, and partly also by the concentric iron container.

When passing through the radial openings the arc is formed into a series of annular sections which are kept constantly in motion, expanding radially under conditions of gas pressure and temperature which produce a low arc voltage and assist in the rapid extinction process. These are the factors which determine the fundamental voltage basis for a given design of switch. The correct pressure and temperatures are automatically provided under all conditions of breaking, and the moving parts are simple and strong. There are no valves, pipes or delicate parts, and the construction can be more robust, both mechanically and electrically, than the oil switch of conventional form. The current-carrying and arcing conductors are heavy and the insulation clearances considerable. Although strong construction is an inherent feature of the design, this ranks only as an additional safeguard, as in practice the pressure set up during the breaking process is negligible.

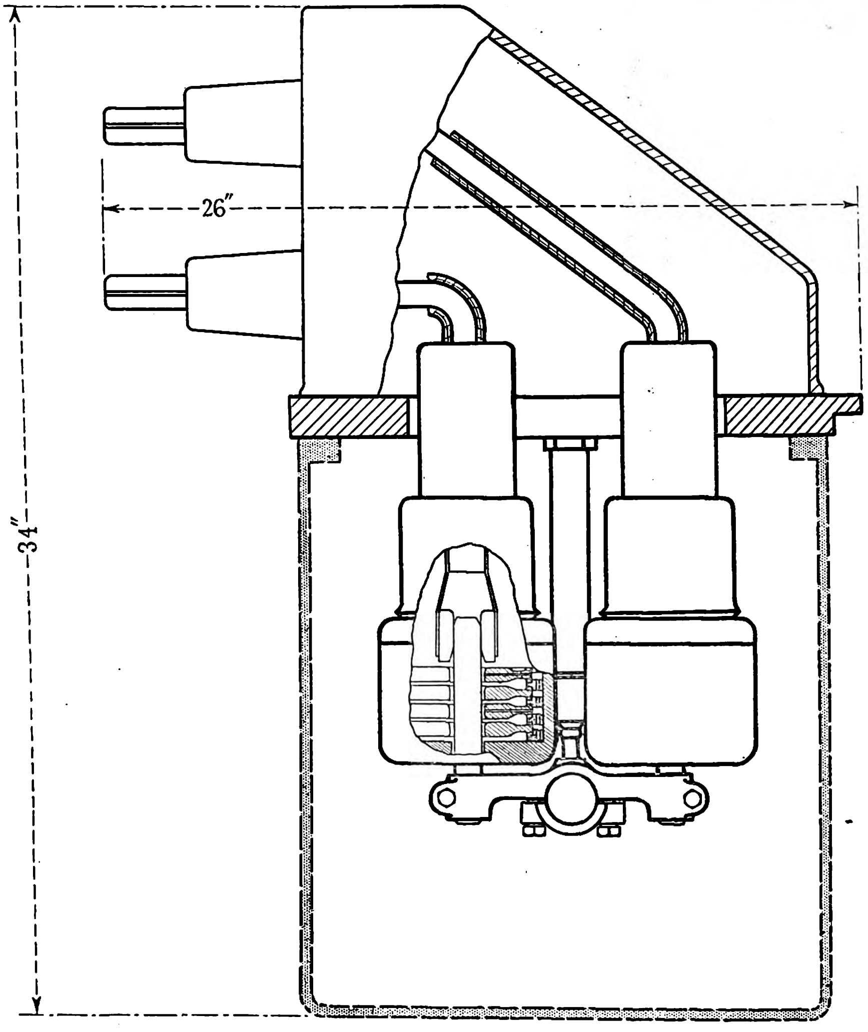

Fig. 35.—Quenched-arc circuit breaker for 1 million kVA (true rating).

Arrangements of baffles, metal and other cooling discs and similar arrangements have been previously proposed on various occasions, but these arrangements have been generally more or less haphazard and do not appear to have followed a logical scheme. Such of these as have been tested have not shown any radical improvement in performance distinguishable from existing forms of switchgear, and sometimes they are actually dangerous.

Fig. 30 shows a single-pole quenched-arc circuit breaker in the "open" position. The pressure disc can be seen in front of the container, the total length of the latter being 9 in. and its overall diameter 5 in. Fig. 31 is a view of an 11 000-volt 350-ampere quenched-arc circuit breaker with two of the arcing contacts removed to show the construction. The contacts can be changed in a few seconds. In the development of the quenched-arc breaker, special care has to be taken to depart as little as possible from well-tried constructional forms; and Fig. 31 shows a breaker of this pattern built into a standard ironclad draw-out pedestal.

B.E.S.A. clearances and tolerances have been observed throughout.

Object of the Oil.—Oil is introduced with the object of reducing insulation clearances. This is important, since a switch operating in a gaseous medium must necessarily have considerable clearances to prevent the arc and arc gases forming a conducting path; the oil enables the clearances between live parts and earth to be cut down to about 25 per cent of those necessary in an air design. During operation, the oil is forced automatically from the arcing area, but not from the region where it is required to maintain the insulation. When the arc is extinguished, the oil passes back into and scavenges the cells.

Performance.—A switch measuring 6 inches in diameter by 6 inches long, and weighing less than 28 lb., interrupted on numerous occasions 50 000 kVA at 6 000 volts without any external sign of its operation. There were none of the symptoms usually obtained with an oil switch, such as noise and gas, oil or flame, and, most important of all, no measurable pressure was set up in the container. Another switch unit, 6 inches in diameter and 3 inches long, interrupted the same amount of power, again without any distress. Attempts to measure the duty on the container by the deformation method used for the other tests described in this paper gave no indication of pressure.

TABLE 10.

Voltage	kVA	Size of unit	Performance
volts		in. in.	
6 000	50 000	6 × 6	Not near limit
6 000	50 000	6 × 3	No sign of distress
5 500	8 250	6 × 4	No sign of distress
3 100	2 800	6 × 4	No sign of distress
4 520	7 200	6 × 4	No sign of distress
5 240	10 600	6 × 4	No sign of distress
11 000	230 000	6 × 4 (6 units, 3-phase, 2 per phase)	Operated quietly. No distress

Test-records.—Fig. 32 is an oscillograph record taken during a test on a switch of this pattern when clearing a dead short-circuit on a 6 000-kVA alternator. The voltage was 5 500 (R.M.S.) across phases, and the switching element was subject to the full line voltage, i.e. $\sqrt{3}$ times that to which it would be subject in service; its maximum rupturing capacity was not nearly reached in this test. The switch measured 6 in. in diameter by 10 in. long and the container enclosed 1 500 cm^3 of ordinary switch oil. The clearance to earth between the switching element and the earthed container was about 1 in. The resultant short-circuits at 85° phase angle were cleared quickly and silently.

Examination of the oscillograph record rarely shows any perceptible voltage during the arcing period, the arc being extinguished very rapidly and without any sign of instability. As no appreciable voltage is set up across the switch, there can obviously be no material amount of power expended in it and consequently no generation of pressure inside it. Actually, of course, there must be some voltage, but it is a small percentage of that which would be set up across the contacts of an ordinary oil switch under similar circuit conditions. Prolonged arcing is effectively and safely prevented, and secondary effects on the oil are found by observation to be reduced to a negligibly low value.

In one of several series of tests, a group of 12 short-circuits at 5 500 volts was applied at intervals of 30 seconds. The switch was not opened out, and received no attention whatever between tests—the same oil being used throughout—and it operated perfectly in all these tests. No arc voltage was indicated and no deformation of the pressure-indicating apparatus was recorded.

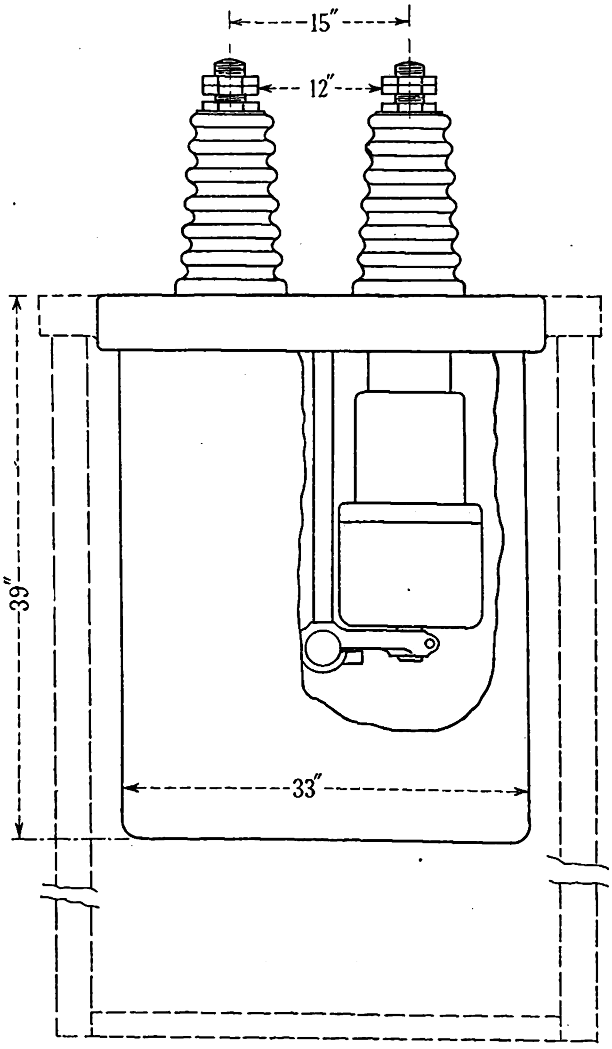

FIG. 36.—Quenched-arc circuit breaker for 2 million kVA (true rating) and 33 000 volts.

A number of tests were carried out at reduced power (examples being 4 520 volts, 1 590 amperes; and 3 750 volts, 1 475 amperes) to investigate the working of the switch at reduced current and voltage. One test, at 3 000 volts, 900 amperes, is illustrated in Fig. 33.

Fig. 34 shows a test at 5 240 volts, 2 020 amperes, equivalent to 10 600 kVA. This test is representative of a number carried out in steps between the low and the high values. A few tests under different conditions are given in tabular form in Table 10. Fig. 35 shows the commercial form of an ironclad oil-immersed circuit breaker of the quenched-arc type, with a breaking capacity of about 1 million kVA (true, not commercial, rating). Fig. 36 shows an enclosed 2 million kVA, 33 kV breaker. The highest power so far broken by a quenched-arc breaker in any test is 230 000 kVA: the breaker used for these tests is shown in Figs. 31 and 35. In all approximately 100 full-scale short-circuit tests have been carried out. By "full scale" is meant short-circuits involving 50 000 kVA and over.

It is interesting to consider what the development of this switch may mean for high powers. The present limitation of the oil switch is mechanical and it is this factor which is responsible for the economic difficulty in the way of further developments. The new device has apparently no such limitations. When breaking a 50 000-kVA short-circuit it has been proved that a unit measuring about 6 in. × 6 in. can meet all demands with perfect ease. To do this with an oil switch embodying the various important features discussed in this paper, i.e. massive mechanical construction, multi-break, correct speed of break, correct air cushion, etc., would necessitate a unit much greater in size than the new switch. There would, moreover, be this important difference: when the ordinary oil switch was breaking under short-circuit conditions considerable mechanical stress would result, whereas the quenched-arc switch of smaller size would break the same power with no appreciable mechanical stress. It would appear that there is no great difficulty in designing a circuit breaker of the quenched-arc type to deal with 2 or 3 million kVA, on the 100 per cent service basis.

The author is very grateful to all those who have helped him to carry out the work on which this paper is based. He is especially sensible of the assistance accorded by Messrs. C. A. Parsons & Co., the Newcastle-upon-Tyne Electric Supply Co., Mr. H. W. Clothier and Messrs. A. Reyrolle & Co., the British Electrical and Allied Industries Research Association, Prof. W. M. Thornton, Mr. Vernon Hope, Mr. R. W. Gregory, Mr. H. B. Poynder and Mr. D. Adam.

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APPENDIX.

Limitation of Short-Circuit Current.

It would seem probable from this paper that the 100 per cent rupturing capacity of any oil switch commercially available is about 800 000 kVA. It has been stated that to reduce the short-circuit power of a large system to a value of this order may introduce power-factor conditions which, even taking into account the reduced current, could produce greater oil-switch distress at the lower current owing to the power factor passing into the heavy 55° to 60° zone.

In view of this the author has carried out a few experiments with the object of improving the conditions by other means. This Appendix has been included as a résumé of the results of these tests and to deal with other possibilities of achieving the same object, namely the reduction of short-circuit current without the introduction of detrimental effects.

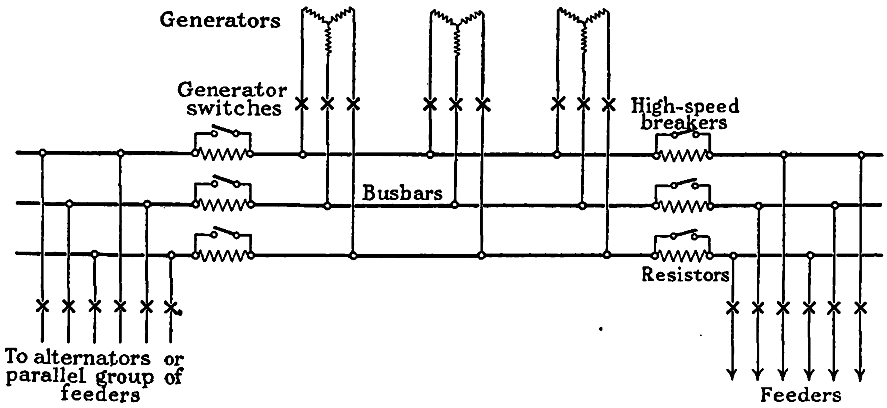

Fig. 37.—Busbar lay-out, showing oil circuit-breakers backed by high-speed breakers.

The new switch described in the paper appears to be one solution of the problem of breaking high short-circuit powers satisfactorily and, as this has been dealt with fairly fully in the body of the paper, nothing further need be said about it here. Other methods of tackling the problem all appear to take the form of current limitation, and to the author there seem to be two possibilities in this direction, (1) to limit the short-circuit current by means of resistance or high-inductance coils which, under load conditions, are cut out of the circuit and which under short-circuit conditions are sufficiently high to keep the phase angle out of the 50°–60° zone; and (2) to regulate the short-circuit current by manipulation of the excitation of the generating plant.

Current Limitation by means of Resistance (or Inductance).—Even if the effect of reactance were quite above suspicion and its influence on switchgear performance purely beneficial, there would yet remain the disadvantages attendant upon its being connected in the circuit at all times, chief amongst these being the permanent voltage-drop set up and the somewhat reduced security with such apparatus. With resistors in the place of inductance coils it becomes essential to devise a means of keeping them out of circuit until actually required.

A considerable amount of development has been carried out during the last few years on high-speed circuit breakers for direct-current work. At first, such circuit breakers were used in parallel with current-limiting resistors, but latterly improvements have resulted in their being used to break the circuit directly. The improved breaking capacity thus obtained is, on direct current, of the order of 100 000 kVA, whilst tests indicate that on alternating current considerably greater power could be broken. With a reasonable amount of development work, a circuit breaker could be devised for the control of the short-circuit current of a high-power alternating-current system. Asssuming, for example, a plant capacity capable of giving $1\frac{1}{2}$ million kVA on short-circuit, the output could be controlled by one circuit breaker per phase, as in Fig. 37, which indicates a usual arrangement of switching equipment with the oil circuit-breakers backed by means of high-speed breakers and current-limiting resistors. The high-speed breakers would, of course, open long before the oil switches and would reclose again immediately the oil switches controlling the fault had cleared it.

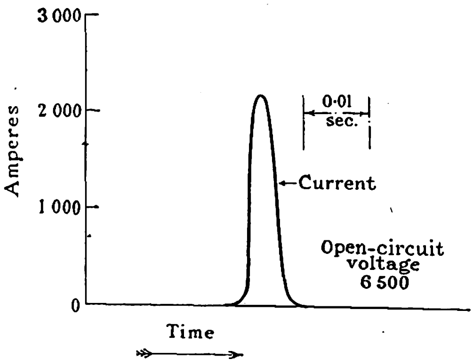

Fig. 38.—Oscillogram of high-speed breaker on 50 000 kVA (a.c.).

The maximum power to be interrupted by each high-speed breaker would be the earth-fault current of each phase multiplied by the drop across the series resistance. Assuming a system working at 11 000 volts, the kVA to earth per phase will be approximately 500 000. The high-speed circuit breakers should each be capable of handling 200 000 kVA (a.c.), so that the series resistances should be designed to reduce the short-circuit current from 79 000 amperes to 31 500 amperes, which would necessitate a resistance of $\sqrt{[(0\cdot 2)^2 - (0\cdot 08)^2]} = 0\cdot 183$ ohm. This breaking capacity under the unregulated condition is greater than the assumed maximum obtainable with oil circuit-breakers (of the order of 400 000 kVA per phase) but is lower than the regulated short-circuit power calculated above.

The assumed breaking capacity for the high-speed breaker could possibly be increased even when working on present lines with an air break, but a great improvement could be made by using an oil-break high-speed circuit breaker, with which very high operating speeds can be obtained and with which a neater lay-out can be made than with an air-break circuit breaker. Metal-covered connections could be used throughout and the apparatus completely enclosed, thus eliminating the bare connections which would be necessary with the air high-speed breaker. Fig. 38 shows an oscillograph record of the high-speed interruption of a 50 000-kVA alternating-current circuit, which demonstrates the feasibility of the foregoing contentions.

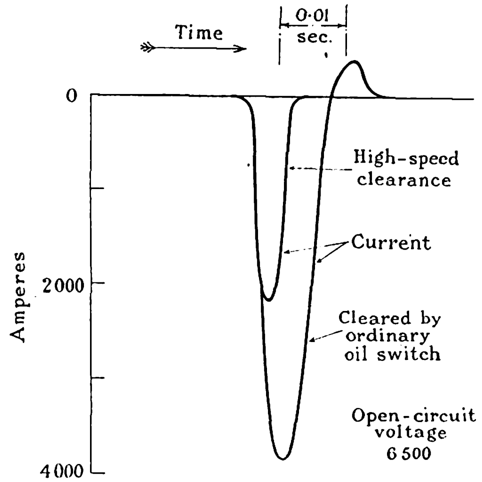

Fig. 39.—Oscillograms of power obtained on 50 000-kVA short-circuit when cleared by means of an ordinary oil switch and when limited by high-speed circuit breakers.

Alternatively, fusible cut-outs could be used either to sectionalize the power-generating plant or to insert limiting resistors, both arrangements producing the required reduction in current and so enabling the ordinary oil switches to operate safely at the reduced power. Fig. 39 shows an oscillogram of the power obtained when clearing a 50 000-kVA short-circuit by means of an oil switch of the usual form and, for comparison, a record of a high-speed fusible cut-out inserted in series to show the current reduction obtained.

Manipulation of the Excitation.—For some time past, Messrs. Brown, Boveri and Co. have sponsored a system of current regulation whereby the high-tension current on short-circuit is reduced by the insertion of resistance in the field circuits of the alternators concerned. With a method of this sort, an appreciable time must elapse before the excitation and consequently the short-circuit current can be reduced to a sufficient extent to permit the oil switches to operate. Moreover, a time interval must be allowed between the commencement of the short-circuit current and the opening of the field circuit breaker, or there will be set up across the field circuit-breaker terminals a voltage sufficiently high to damage the field winding. Nevertheless, this method has been adopted with some success on the French and Swiss power networks, particularly in systems wherein "loose linking" is adopted—usually from necessity owing to the spacing of the generating stations and the small amount of intervening copper—and where consequently the maintenance of synchronism of rotating plant under fault conditions is not part of the problem.

With an interconnected system the time interval necessary with the Brown, Boveri system is usually not permissible and rapid operation is essential. This is still more important on a system employing rapidly acting feeder protective gear such as the Merz-Price system, with which a fault can be completely cleared in 0·1 sec. to 0·3 sec. (depending upon the design of the circuit breaker) of its commencement. Therefore, much higher speed of field manipulation is necessary and some system becomes necessary* which employs a high-speed breaker in the field circuit, arranged in such a way that it opens and inserts resistance before the fault has actually grown and consequently before the armature reaction and excitation have been forced up (see Fig. 40). An operating time of the order of 0·01 sec. is required to obtain full benefit from the system. In this way the short-circuit current could be reduced to about one-half or one-third of the unregulated value. At the same time the power system protective equipment commences to operate and the switchgear will then have to clear the fault at the reduced value only.

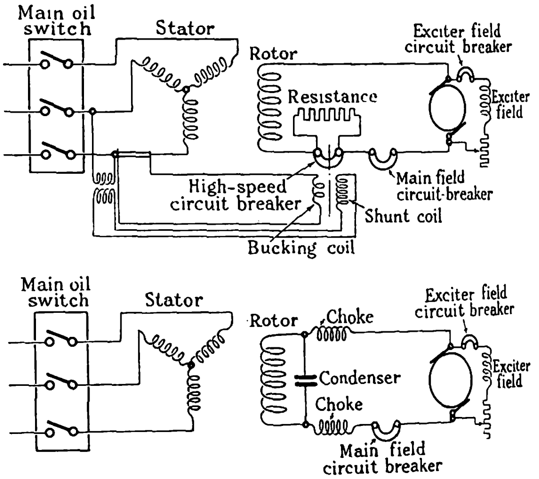
Main oil switch
Stator
Rotor
Exciter field circuit breaker
Resistance
Exciter field
High-speed circuit breaker
Main field circuit-breaker
Shunt coil
Bucking coil
Main oil switch
Stator
Rotor
Choke
Exciter field circuit breaker
Condenser
Choke
Exciter field
Main field circuit breaker

Fig. 40.—Diagram of alternator field control system for limitation of short-circuit power in main circuit.

Immediately the fault is cleared the high-speed breakers reclose and restore the excitation to normal. Actually, the high-speed breakers would be open for only about 0·1 sec., i.e. from the start of growth of the fault to the moment of clearance of the fault, the exact time depending upon the speed of working of the ordinary oil switches.

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* British Patent No. 21593/28.

DISCUSSION BEFORE THE INSTITUTION, 23RD JANUARY, 1930.

Mr. E. B. Wedmore: Circuit-breaking by the separation of two contacts under oil was first commercially exploited by Mr. Partridge, and the oil circuit-breaker was so effective that for a generation there was no substantial change; the typical large high-tension breaker of to-day differs from the original circuit-breaking device only in its bushings and other subsidiary features. There has been but little new development; the magnetic blow-out and the explosion pot have been exploited and some features of the former will be of permanent value. With the growth of plant capacity in recent years some disadvantages of the oil circuit-breaker and the inadequacy of information in connection with the subject have provoked further research. Circuit breakers must be judged primarily by a commercial criterion. If two circuit breakers have equal performance and reliability, no matter what the relative values of the arc energy or of the "distress ' may be, the cheaper circuit breaker will capture the market. The author's distress factor is not of universal application. What he has said, however, about 100 per cent performance is important. Circuit-breaking devices should not be regarded as satisfactory merely because they do not throw out excessive amounts of oil, smoke and flame. In other branches of electrical engineering something approximating to 100 per cent performance is expected and attained; I believe that within a few years circuit breakers will approach the same standard of efficiency. The author asserts that mistakes have been made in using arc energy as a criterion of performance. This is not the case so far as the Electrical Research Association is concerned. Our views have already been expressed in the *Journal* (1929, vol. 67, p. 591, col. 1, par. 2). The conclusions which the author reaches as to the complexity of the phenomena of circuit-breaking under oil and variations obtained in successive tests are in agreement with ours. The particular type of circuit breaker with which the paper deals undoubtedly shows a wide range of performance arising from numerous causes, one of which is the fortuitous action of the arc. The author uses the empirical method, a favourite tool of the engineer but one which has many disadvantages, one of which is that the results which it yields will apply only to the design which has been tested. If this is slightly altered the effect upon the action of the apparatus cannot be predicted. Despite its limitations, the method is one which many engineers have been forced to follow; in all civilized countries it is now giving place to scientific investigation in connection with the development of the subject of circuit breaking. Many more of the physical quantities involved in the problem of oil circuit-breaking have recently become known and evaluated. I wish the author had dealt in more detail with a narrower range of subjects. His published evidence does not adequately support his conclusions. He has, however, undoubtedly a mass of experimental data which might be of value to the industry if it were placed at the disposal of those who are able to apply more recent scientific knowledge to its analysis. The experimental measurement of distress appears to have been effected by observing the distortion of a metal disc (not prescribed) placed in the oil at a distance (not prescribed) from an arcing device (not fully prescribed). The force developed depends in part upon the test design. An irresistible force should not be opposed by an immovable body, but by one capable of moving easily. The effect of the force will then not be felt. I was for many years connected with the design and application of certain circuit breakers of the type dealt with, which fulfilled few of the conditions laid down in the paper and yet gave uniformly successful service. A flexible wall was provided and the size of the air cushion was much in excess of the limits suggested. It is clear, therefore, that the author's criteria are not suitable for universal application. Fig. 22, dealing with the effects of reactance in circuit, shows greater distress in the circuit breaker at 55° than at 90° phase angle. I see no theoretical justification for this and am disposed to attribute it to some peculiarity of his testing circuit. No doubt the author obtained greater deformation of his discs under the conditions indicated, but that is not sufficient evidence for the general conclusion that with all designs a phase angle of 55° or 60° puts greater strain upon the switch than a phase angle of 85°. Further, there is no inevitable relation between the ability to withstand certain stresses on the circuit-breaker wall and the preventing of the arc from re-establishing itself after the current has passed the zero value. Many factors, other than the possibility of distorting a well-designed tank wall, affect the performance of the switch. These cannot be observed with distress as the sole criterion. The author refers, for example, to speed of breaking as a feature of the oil circuit-breakers appropriate for experimental investigation by his methods. To begin with, there is no such thing as *the* oil circuit-breaker which may be taken for the purpose of establishing a law governing the variation of this quantity. Any figures for speed of breaking can only apply to the design tested or to other very similar designs. I do not follow the argument in which the author visualizes speeds so high as to force the current down and to increase the voltage on the system. The latter process might be dangerous; it is in any case unnecessary and lies outside the range of possibilities with any other than fresh designs. Illustrations are given to show that with higher speeds of breaking there would be a greater voltage, not on the system itself but across the circuit breaker; this would result from a longer arc. As to whether there is a real objection to either of the designs of which oscillograms are shown, I am not clear, partly because no scale is given. In Fig. 14 I cannot trace re-establishment of the arc as described, and in Fig. 16 the indications are that the arc has gone to earth. From the very nature of the phenomenon there must, however, be an optimum speed. An attempt to open a large circuit by slowly separating the contacts must result in the burning of the latter; ultra-rapid separation must increase the voltage across the arc by forcing up the resistance of the arc before the current has reached its normal zero value in the ordinary course of the cycle, thus resulting at least in the liberation of excessive energy to no purpose. Between these two extremes there must be, for a given design, an optimum speed at which excessive energy is not released and there is no excessive burning. That speed will depend upon many other factors which enter into the design. I am interested in the features which the author describes as having a stabilizing effect upon the arc, for I realized some years ago that it was undesirable to allow the action of the latter to become wholly fortuitous.* The author has devised means for preventing this accidental lengthening of the arc, although I am not quite clear as to the method adopted; it seems that the arc in the centre of the magnetic cylinder is essentially unstable and must be attracted towards the wall. The lengthening may be fairly uniform and may repeat itself satisfactorily. In my own work the aim has been to minimize the tendency to lengthening, and this can be accomplished by suitable devices in a particular design. I believe that future circuit breakers will have an arc length so small in comparison with the diameter of the arc that very little bowing will take place. The author shows an interesting multiple-plate " quenched-arc " switch, but he does not point out what are the new features incorporated in it. His contribution to the arc surely lies in these and not merely in the use of the multiple-plate design. Little information is given about the action, and without further information it is difficult to understand the formation of an annular form of arc. I cannot conceive of any magnetic device which would produce an annular or partially-annular arc. The E.R.A. carried out several years ago some experiments with certain multiple-disc devices under the same short-circuit power as the author has been using, when results similar to those which he has shown were obtained. We deferred this development mainly because we believed we had more promising lines to pursue.

Mr. H. W. Clothier : I have the greatest admiration for the free-lance manner in which the author has tackled the problems of breaking alternating-current circuits. He has had only moderate facilities in size of testing plant, but he has made the best of these small powers by trying out breaking capacities on models made to one-quarter full size or 1/64th the cubic contents. It is remarkable how much comparative information he has been able to collect and record from these and other contemporary researches. The world's practice to-day in oil circuit-breaker contacts is divided, but he contributes his experiences on these divergencies. For example, he finds that such devices as snap contacts, magnetic blow-outs and explosion pots all produce unsatisfactory recovery-voltage characteristics, but he demonstrates a large increase in breaking capacity for multi-break devices. He abandons the elusive method of judging the quality of performance on the " arc energy " or " break energy." Instead, he adopts the very practical method of comparing effective pressures by measuring the distortion of a disc fixed in the tank wall. Fig. 18 shows a reasonable relationship between the power broken and the pressure set up on the sides of the tank. The curve might just as truly be drawn as a straight line. The upward trend shown implies lower tank pressure per unit of power broken with increasing power, which is unnatural. In a broad way the author justifies the claim of strength of tank enclosure as a leading factor of breaking-capacity quality, which hitherto some experts have been loath to admit. For instance, Mr. Wedmore has just spoken of the design of tanks which yield to the pressure. It depends upon the accepted theory of circuit-breaking in oil. As I understand it, the main function is to prevent the restoration of the arc immediately after passing through zero. This is best effected in the gas bubble at maximum density. If the tank is allowed to yield, the bubble expands correspondingly and its pressure is reduced. I therefore prefer a tank which will not yield, with an air cushion above the oil, limited to about 5 per cent of the tank capacity. This seems to be confirmed by the author. I should be glad if he would say what the unit of deformation represents in lb. per sq. in. Has he correlated the pressures on the model to the actual full-size circuit breaker? Without knowing the tank stress the breaking-capacity limits on a full-size circuit breaker cannot be theoretically anticipated. Fig. 22, which shows variation in stress with phase angle, affecting the use of reactances, is another good step in research work, but again the conclusions are formed from a wide range of divergent results and may be misleading. Some differences must be narrowed down by more research with larger power before the conclusions can be taken as final. Fig. 25 and Table 9 have been ascertained from manufacturers' data, and so the formula at the top of page 1102 is actually derived from practical evolution in tank dimensions up to date, and includes recent innovations. The author is to be congratulated upon his investigations and derivations, which will be helpful in lining up manufacturing practice. The data now published for the first time so fully, however, must not be confused with the experiments on the small scale model. The latter are to the good so far as safe comparisons can be drawn, but I contend that there is insufficient evidence to warrant the author's sweeping assumption that ratings established by modern British practice must be divided by 2·5 to be what he calls " true " ratings. Some of the very early designs of circuit breakers were over-rated in the absence of power sufficient to obtain experience, but this does not warrant a wholesale writing-down of all ratings or of large modern breakers. On the contrary, some of the designs have been repeatedly tested, and in my opinion and experience they actually carry a safety factor. I do not agree that the designs are based on average experience. I have always held that manufacturers' designs are, or should be, based upon the maximum experience. The author expresses his opinion that the largest circuit breaker is capable of breaking 800 000 kVA. This opinion is based upon experience of designs in long use, the largest of which in this country has been rated at 1 500 000 kVA. The ratio of 1 500 000 to 800 000 is not $2\frac{1}{2}$ to 1 but only $1\frac{7}{8}$ to 1. One particular 1 500 000-kVA circuit breaker design known to me 10 years ago had originally a single break with conductors specially arranged for an increased magnetic field across the arcing space; but they are now of the 4-break type, and on the author's figures this would result in an improvement of 50 to 100. This design correction should therefore raise the true rating from 800 000 to something above its declared rating. The selection of a suitable rating for a circuit breaker in regard to the generator-plant capacity is important, and this is an occasion to ventilate standardization of demand. A circuit breaker is given a rating signifying its ability to make and break circuit, and to obtain a 100 per cent service it should be so selected that its rating exceeds the maximum possible short-circuit kVA that can occur at its terminals in service. If a smaller rating is selected, it is such use that brings about the risk of overstressing the circuit breaker. I consider that, as a general practice, circuit breakers should be so selected that their rating corresponds to the maximum symmetrical short-circuit kVA that can occur across their terminals in service. In this case the only risk of overstress is the very rare occasion of a break on a maximum unsymmetrical short-circuit. I welcome the search for what might be termed the "peaceful" method of arc extinction, aimed at in such devices as shown in Fig. 35, but, as in making other concessions for peace, one must be ever on the look-out for the effects of a breach. This particular form of sparking contact appeals to me, because it fits in with existing metal-clad practice. Although it acts so well up to a certain rating, the author's so-called "true" rating of 1 000 000 kVA must to a considerable extent be based upon empirical data and may therefore be wide of the mark. However, my company have had the privilege of making this apparatus to the author's designs, and in due course such long outstanding factors relating to large and small circuit breakers will be investigated by practical full-value tests on a large short-circuit testing plant which is now installed at Hebburn.

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* See British Patent No. 236293.

Mr. W. A. Coates: The author has devoted some three-quarters of the paper to the results of a series of experiments carried out on plant of limited power and voltage. A wider practical knowledge would probably have shown him the inaccuracy of some of his conclusions. A great deal of misunderstanding would be avoided in papers of this nature if results checked by tests were clearly distinguished from theories and extrapolations. The author proposes to take as his basis the first cycle of current of a short-circuit, whereas it has already been internationally agreed to calculate the breaking capacity on the current during the first half-cycle of the arc. The first half-cycle of the current does not have any direct effect upon the phenomena of arcing. Although I have carefully studied Table 6 I cannot see how the author's conclusions have been reached. The ratios which he has given in his conclusions regarding the table are not applied to the empirical formula given on page 1102. Most investigators are prepared to concede that for given circuit breakers under given conditions there exists an optimum speed of break; they would not agree to the suggestion that as the voltage rises the speed of break should decrease. During the last year further experiments have proved conclusively that it is beyond the present skill of designers to provide a circuit breaker which will work at a sufficient speed when the voltage is so high that the arc recurs several times. It is only at or about generating voltage that, with a good circuit breaker, there is a reasonable prospect of rupture during the period of one half-cycle. The speed of break of high-voltage circuit breakers is not very important because, at the higher pressures, the design of a circuit breaker is controlled by considerations other than those of gas volume and pressure on the tank. The theory of surging to which reference is made on pages 1096 and 1097 and which is illustrated in Fig. 17 is not a novel one. It was referred to in the paper* by Messrs. Wedmore, Whitney and Bruce which was read before the Institution last year. In the ensuing discussion I made the suggestion that the real merit of the explosion pot lay in the fact that it held the gas bubble in position at the maximum possible pressure. It seems to me not improbable that the slight advantage which has been found with the author's stabilized design really arises from the fact that the magnetic hood holds the gas under some control. On low voltages it is probable that the arc would be extinguished so rapidly that the gas would have no chance of escaping from under the hood. With regard to the author's pessimistic remarks about the modern circuit breaker, purchasers, including the firm of consulting engineers with which he is associated, expect manufacturers to stand behind their scorned "commercial" ratings, and in practice are justified in doing so. A large number of circuit-breaker failures are directly attributable to causes which have no connection with the design; this fact is ignored by the author. My own experience of the last 20 years has frequently proved that failure results from omitting to insert a tank packing or hanger bolt, from failing to clean the oil sufficiently often, or perhaps from choked vent-pipes. The author suggests that circuit breakers are designed for average and not maximum conditions. I can only state in reply that no designer or manufacturer would dare to risk his reputation by gambling in rating figures which could not be borne out in practice. It is totally unreasonable to apply the author's factor of 2·5 to commercial ratings. A few years ago I participated in an elaborate series of tests on a complete range of circuit breakers manufactured by a well-known firm. The plant gave a maximum of slightly more than 600 000 kVA in the arc. Throughout the tests not a single circuit breaker showed distress, in the sense of throwing oil or of emitting an undue amount of gas or smoke, at less than 110 per cent of its rating; and the majority had reached well over 125 per cent before distress occurred. The author's comparison between round and rectangular tanks is unfair to the round tank because, for a given strength, the rectangular tank would have to have walls of from 3 to 7 times the thickness (depending upon the use of 3 separate or 1 single tank) of those used for the round tank. The curve in Fig. 25 and the formula given on page 1102 are empirical; this requires special emphasis in view of the fact that many attempts have been made to evolve formulæ of this kind. As soon as any departure from the particular type of circuit breaker is made, such formulæ are of no use. On checking the values given by the author's equation I find that at high voltages the points lie well away from the straight line. The new design of contact shown in Figs. 35 and 36 is extremely interesting. Although thermal and magnetic effects are said to force the arc between the surfaces of the metal discs, I cannot see that this is possible. The gas will pass between the discs as it expands, but there is nothing to induce the arc to take the same path and it is manifest that there can be no magnetic effect, since the tests were made with a single-break switch. I conclude that the success obtained was due to the fact that the discs act as de-ionizing agents. The fact that adjacent metallic discs de-ionize the arc stream is well known. The master patents covering the application of this effect are held by the firm with which I am associated. Papers relating to it have been read before another Institution during the last two or three years; they indicate that such contacts as these have ruptured powers of the order of 300 000 kVA. I agree with Mr. Clothier that the author shows great confidence when, having tested a small switch capable of breaking 50 000 kVA and 6 000 volts, he submits a design which would presumably have a commercial rating of 50 000 000 kVA.

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* "An Introduction to Researches on Circuit Breaking," *Journal I.E.E.*, 1929, vol. 67, p. 557.

Mr. H. Trencham: In general the paper appears to be a wholesale condemnation of manufacturers' present breaking ratings and, apparently to avoid hurting the feelings of designers, the author refers to them as "commercial ratings." It is admitted that circuit breakers must be designed for a widely fluctuating duty, and an empirical method of design has been referred to by earlier speakers. Such a method of design, however, need not fall short of giving 100 per cent correct duty. If we assume that satisfactory breaking distance, speed of cross-bar, air cushions, etc., can be settled by test, correct empirical design necessitates that tests be made to cover the whole field of variation and, having defined its limits, to design for the worst possible condition. The breaker so designed takes into account the whole of the author's uncertainty factor. Breakers have been so designed from data obtained by numerous tests carried to very much higher breaking values than those mentioned as used by the author. It is contended, therefore, that the author is unfair when on page 1102 he states that "it would appear that the short-circuit powers which now have to be dealt with cannot be broken with certainty by any existing oil switch." There is probably some ground for belief that, especially in small sizes, commercial optimism has resulted in overrating, particularly where testing facilities have not been available, but for the heaviest class of oil circuit-breakers I believe that these can be, and are, designed to operate up to their maximum rating. In considering breaking devices in general, it must be remembered that they have also a current-carrying function and the modern plain circuit breaker, particularly for fairly heavy current, utilizes practically 100 per cent of the space occupied. Up to about 500 000 kVA, therefore, the standard type of breaker appears to be the best economical proposition for meeting requirements, notwithstanding the interesting breaking devices which have been investigated from time to time, because their introduction involves occupying more space and incurring greater cost. In reference to the author's quenched-arc switch, this is, as indicated by him, an application of an idea which is not new, though he claims to have made the first logical application of sound design principles to the idea in question. The breaker is, in fact, the third form of breaking device for which it is claimed that the fundamental conditions governing arc formation and extinction are attacked—the others being the Deion and gas-blast breakers. Contrasting this new application with the other two, I cannot see ground for expecting from it as good performance as from the others. It is clear that, to limit the emanations from the hot cathode which may be held to act as a feeding-point for the arc, some quick and positive smothering effect is required. The intensity of the effort to do this effectively must be of an order similar to the tenacity of the arc to its root. I do not know of any information which can be recorded as a reliable quantitative indication of this particular effort, but I fear it may be decidedly underestimated. The point of origin of the arc is probably small in area, whether the amount of current being interrupted is large or small and whether the contacts themselves are also large or small, and the tenacity above referred to may be expected to appear as some function of the melting temperature of the metal, and of the current—possibly as the square of the current or even as the square of the current density. It is in this respect that, in my opinion, scale models of circuit breakers have failed in the past and must continue to fail in the future. However that may be, it is clear that in the Deion breaker two strong magnetic fields are necessary—one to direct the arc into the cooling spaces and one to keep it moving quickly enough along a long path therein. In the gas-blast breaker a considerable expenditure of energy is directed towards the same end, by the liberation of compressed gas, and whereas when breaking small currents (of the order of 50 000 kVA) the contacts of the gas-blast breaker, though small, show only a slight etching due to the arc, when larger powers are involved (approximately 500 000 kVA), certain tests have shown the removal of 1 in. to $1\frac{1}{2}$ in. of material from the end of a heavy copper rod in a single shot. If I understand the illustration in the paper correctly, each of the cooling paths appears to be an annular space of short radial length leading to a *cul de sac.* Pressure behind the arc may have a tendency to drive it into the spaces provided, but this tendency will be strictly limited and magnetic forces are not likely to assist, because, as stated on page 1103, they tend to keep the arc in the centre of the pot. In any event, the cooling arrangements appear to be entirely inadequate for heavy short-circuits, in view of experience on other designs. Within the range of tests covered by the author there is almost nothing to be distinguished between the results obtained by him and the records of operation of a "properly" designed explosion pot on which much higher tests have been carried out. The word "properly" is advisedly used as many investigators have contented themselves by the use of any kind of an enclosure on the contacts and called it an explosion pot, whereas its correct design is the result of specialized study. I should expect the author's breaker to fail at short-circuit values much below those at which he rates his heavy design, owing to the inner walls of his cooling rings developing incandescent surfaces linked by a cascading arc. I can only admire the courage that enables him to extrapolate through a range of 10 to 1 in breaking capacity as between guarantee and tests carried out; I fear that his results might be found subject to errors even as great as those of which he accuses present-day manufacturers. Referring to the Appendix, it does not appear that much is to be gained by an endeavour to predetermine the power factor of faults. It seems to savour of a challenge to fate, and a better course is to look the situation straight in the face and undertake to cater, in the circuit breaker, for the worst conditions liable to arise.

Dr. W. B. Whitney: While I find it difficult to agree as to the validity of some of the author's conclusions on the evidence he has so far published, the paper serves the useful purpose of throwing into bold relief a number of questions of first-rate importance. These are bound to challenge discussion, careful examination and further experiment in the future, thus being of service in clarifying a subject which the author agrees to be exceedingly complex. The question of measurement of distress is one of great interest and is an important feature in the paper. There is, as is pointed out, a big variation in the internal behaviour of an oil circuit-breaker, but a question of major importance would seem to be the determination of the effect of this variation upon the final break-down condition of the apparatus. The device adopted by the author for indicating distress is simple and robust, but what physical quantity does it actually measure? It would seem, as explained below, that the mere distortion of a disc or small specially weakened area of a strong tank may have little or no relationship to the general pressure set up as measured, for example, in the cushion, excess of this latter type of pressure being, in my experience, a frequent cause of tank failures when these occur in experimental work. The author appears to base his conclusions as to the relative merits of various designs on the distress as measured by the above-mentioned renewable discs. In Section (5) he also uses this basis in connection with his estimate of volume and pressure-resisting quality of tanks to give 100 per cent breaking capacity. The value of much of the paper, from the point of view of its contribution to knowledge, thus seems to depend upon whether the criterion of distress (namely the distortion of a renewable disc) does actually give a correct measure of the bursting pressure set up within the tank in the process of arc rupture, and a weakness of the paper seems to lie in the fact that it contains no experimental or mathematical demonstration of a correlation between degree of pressure and disc distortion, existence of which seems to have been tacitly assumed by the author. Assuming, for the moment, that the author is able to demonstrate such a correlation, can he demonstrate that the discs are only distorted by rise of static pressure and are unaffected by the high-frequency pressure pulsation which, he agrees, also accompanies arcing, and one type of which is known to exert less and less pressure per unit area as the wave-front spreads out from the source? Unless he can show that the disc does not respond to this latter type of pressure it may be assumed that it will owe some of its distortion to the above-mentioned localized effect, which varies in strength according to whether the energy source happens to be nearer to or farther away from the disc surface, being greater when nearer and smaller when farther away. In the case of single-break tests such variation may take place owing to movement of the arc path away from the direct line of contact separation under the effects of magnetic field or surging oil, and in multiple-break switches owing to the same effect and to the geometric position of the breaks in relation to the measuring disc, and is likely to result in one arc exerting on the disc a force out of all proportion to the others. In addition it would seem, for the same reason, to be very unsafe to make comparison between distortion results with renewable discs in tanks of different sizes of geometrical shapes, and I hope the author will give us much fuller information on this subject in his reply. What precautions were taken, when bolting the discs to the tank, against distortion of the disc by uneven or excessive pressure of one or more nuts? Was the cushion volume kept exactly the same in all tests compared and were the switch tanks tightly sealed, or was there a vent or venting between top plate and tank? If there was such venting, a further uncertainty is introduced by the fact that the surging oil will at times fortuitously block the vent, thus causing higher pressure for the same gas output than at other times. The question of venting raises an interesting question as to the dangers that have to be avoided in extrapolating from the results of tests on small scale models. In most commercial designs, when the oil-level rises during arcing, some of the air in the cushion is forced out through the joint between the tank and top plate, unless special precautions have been taken to ensure accurately faced flanges. It will be seen, however, that, given a fixed ratio between initial cushion volume and tank volume, the ratio (vent area at the flanges)/(cushion volume) and assuming constant gap thickness, will decrease as tank volume increases, thus allowing relatively less and less pressure relief. Thus, unless allowance is made, for example for this factor, conclusions drawn as to the rating of large breakers from the results of tests on small ones are likely to be misleading. It would be useful to know the actual number of deformation records used by the author in arriving at the ratio of 2·5 : 1, between observed maximum and average distress used on page 1102, and to what extent he has established that the above ratio is independent of the number of tests. Section (3) is devoted to an attempt to show that break energy is unreliable as a measure of distortion of the pressure discs (i.e. " distress number "). In this connection I would mention that in a certain series of E.R.A. experiments on closed tanks, in which piezo-electric and other high-frequency pressure-recording instruments have been used, a good correlation has been found between total break energy and maxi-

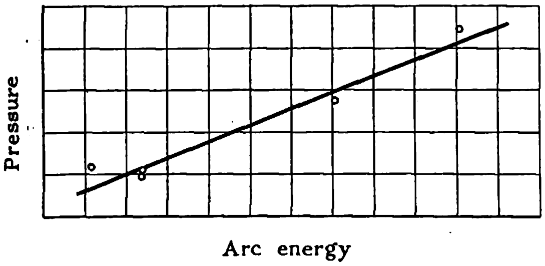

FIG. A.—Variation of pressure with arc energy in a closed circuit-breaker (E.R.A.).

mum cushion pressure tending to burst the tank (see, for example, my Fig. A). It thus seems fair to conclude that, where the author's results fail to show such correlation between break energy and disc distortion, such failure is due to the causes mentioned above or to the unreliability of disc distortion as a measure of pressure, and from the scientific point of view it would appear to be sounder to measure a quantity like break energy, which in general is related to gas volume and can be interpreted in terms of cushion pressure, than to measure one which, like the author's "deformation number," may have no simple physical meaning. Apart altogether from the meaning to be attached to the "distress numbers" in the paper as discussed above, Section (3) (in which much of the oscillograph data in the paper is concentrated) leaves the feeling that there is a rather uncritical handling of material. In Table 3, for example, which, it is stated, "shows that distress does not vary with break energy, as has frequently been assumed," the reverse conclusion would apparently be reached when the figure 5·15 for kW-sec. in the top line of the table is increased as the result of correcting for the error in fixing the zero line too high in the top oscillogram in Fig. 4. Also the results in Table 8, with the exception of one point, show quite a good correlation between break energy and "distress" (see Fig. B). Referring to Table 6, in which comparison is made between different numbers of breaks, are single, double and quadruple breaks being compared at the same speed of cross-bar separation, i.e. at increasing total velocity of contact separation, or is the cross-bar speed halved with each doubling of the number of breaks, thus keeping the total velocity constant, as should be the case if the tests are to be truly comparable? I ask the question as records similar to the quadruple-break test in Fig. 13 can at times be obtained with a *single* plain break in oil by using an appropriate high speed of contact separation at the same voltage and current as in Fig. 13 (see Fig. C). Does the figure of 15·4 kW-sec. for arc energy (Fig. 12 in Table 6) include the arc energy released within the tank in the arc to earth, which would have contributed to the distress recorded on the disc? Also, was the cushion volume in all the tests in Table 6 exactly the same? On page 1104 oscillograms 29(*a*) and 29(*b*) are given in comparing quadruple breaks with and without arc stabilizers. These records show approximately 30 and 50 kW-sec. of arc energy and 3 and 9 units of distress respectively. Can the author tell us what feature in design caused this 4-break switch (both with stabilized and unstabilized arcs) to give so much more break energy and distress than the quadruple-break switches shown in Table 6, seeing that the applied voltage and also the average current during arcing were practically the same? In regard to the quenched-arc switch, what steps were taken to control the velocity of contact separation? The oscillograms in Figs. D and C * show almost identical records obtained with the same circuit conditions by means of a single plain break in free oil at a sufficiently high speed of break, and it seems possible that pressure set up in the confined space in which the moving contact operates in the quenched-arc switch might have the effect of blowing the contact outwards at a speed of the

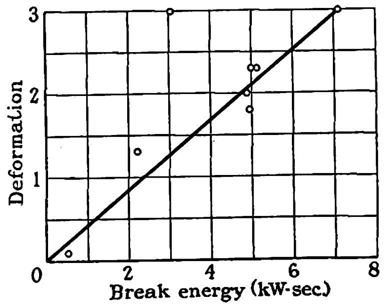

FIG. B.—Data from Table 8 (L. C. Grant).

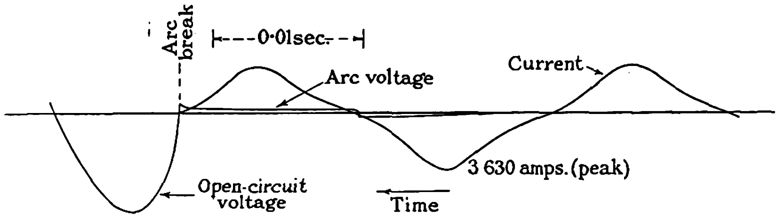

FIG. C.

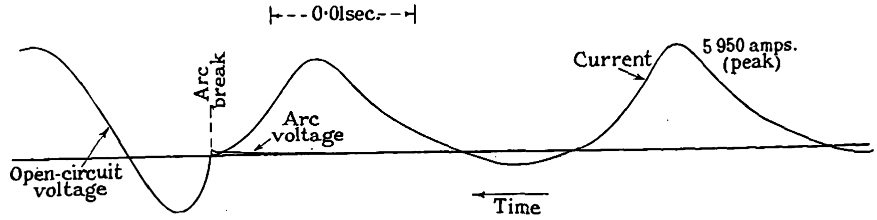

FIG. D.

FIGS. C and D.—Oscillograms of single-break oil switch clearing a dead short-circuit on a 6 000-kVA alternator at high speed of break.

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* Compare with the author's oscillograms, Figs. 32 and 34.

order of that used in Figs. D and C. Are the kVA in Table 10, single-phase kVA in all cases except the last, and to which results does the note at the foot of the third column apply? I wish that more space in the paper could have been devoted to data from "repeat tests" under identical conditions of speed, number of breaks and cushion volume, such as are given in Fig. 18. In the section dealing with phase angle and distress, the author shows some interesting curves in Fig. 22 which indicate that, on the generator and with the circuit breaker he was using, distress reached a maximum at about 55° phase angle instead of at 90°, as might have been expected from theoretical considerations, with a given wave of voltage. Our own results * seem to indicate a similar effect (see point 10, Fig. 11*a*). From investigations which the E.R.A. have carried out at different phase angles, on the voltage wave-form of the machine used by us, I am inclined to think that under certain conditions a rather higher voltage may be available in the neighbourhood of zero current with this machine on single-phase tests when the phase angle is between 50° and 60° than at larger or smaller phase angles. It is curious, however, that the effect, if any, of such higher voltage in lengthening the arc does not seem to be so apparent in Fig. 11 of our paper, though the tests were carried out on the same machine as those in Fig. 11(*a*). While the author has drawn attention to a phenomenon which may have important practical bearings, a fuller investigation into the available voltage at zero current and different phase angles (both on single-phase and 3-phase operation) seems to be called for on machines of other design than that used by him. Until this has been done, it seems unsafe to conclude that the peculiarity to which he has drawn attention, and regarding which no explanatory theory is advanced, is common to all power circuits and affects the use of reactors in the interesting manner he suggests.

Prof. J. T. MacGregor-Morris (*communicated*): On page 1104 the author refers to the stabilized-arc device, and he gives in Fig. 27 its application to an oil switch, and in Fig. 28 to a fusible cut-out. In common with a number of others, I should be glad if the author would give a scientific explanation of the action which he describes as "the cut-out being surrounded by a magnetic field which assists the tendency of the arc to keep in a straight line in the shortest path between the electrodes." In Figs. 27 and 28 he shows the cylinder as a magnetic cylinder, and therefore I presume that there is some magnetic action assisting. Has he tried replacing the magnetic cylinder with a cylinder of the same resistance but of unity magnetic permeability?

Mr. P. D. Morgan (*communicated*): The aspect of the paper with which I wish to deal is the author's method of estimating the distress of a switch. He estimates this distress from the amount of deformation of a lead disc inserted in the tank wall, i.e. he attempts to link up the deformation of the disc with the stresses in the tank material. It is evident that, so long as the tank itself is not strained beyond its elastic limit, the stress in its material is related to the internal pressure, so that the author's method of estimating distress really involves the correlation of the internal pressure in the tank with the deformation of the inserted disc. It is well known that, for a disc supported at the edges and loaded with a uniform intensity of pressure, the deflection at the centre is directly proportional to the intensity of pressure, *provided the maximum stress in the material does not exceed the elastic limit.* If, however, this limit is exceeded—and the author has indicated in his remarks that this was the case (as the deformation was a "permanent set" which could be measured after the tests)—the above-mentioned proportionality ceases, and the deflection becomes a function not only of the pressure but also of the time of application of the load. Bauschinger * has shown that this is especially the case for lead and tin. Therefore to correlate the stress in the tank (which is the assumed criterion of distress) with the deformation of the disc by the author's method, one of two alternative methods must be followed, viz.: (*a*) The duration of the pressure impulse due to arcing must be measured and the effect of the time of application of the load on the deformation produced also determined, or (*b*) the disc must be calibrated with impulses of the same duration as will be caused by arcing. The author, however, does not mention having adopted either of these methods. The first alternative, that of measuring the duration of the pressure impulse, is practically as difficult as measuring both the duration and the magnitude and this has been done successfully, as I will show later. The second alternative is practically impossible either with hydraulic pressure or by detonation of explosives in the tank, as neither of these gives a pressure impulse similar to that set up by arcing in the tank, which is a succession of impulses, the number, magnitude and duration of which depend on the arcing period and various other factors. These considerations lead to the conclusion that, to estimate the distress of the switch from the standpoint of the stresses in the tank wall, a pressure recorder must be employed which fulfils two conditions, viz.: (*a*) It will faithfully respond to impulses of relatively high frequency (above about 50 per second), and (*b*) the deformation produced must be within the elastic range of the recording material. Both these conditions are fulfilled by piezo-electric pressure recorders in which the pressure incident on a quartz crystal produces a potential difference across its faces. The Bureau of Standards have shown that the pressure and p.d. are directly proportional up to many tons per square inch. By means of a suitable amplifier the p.d. generated can be made to operate an oscillograph, and the E.R.A. have a number of records taken in this way, in which the instantaneous pressure due to arcing, the current through the arc and the p.d. across it are recorded on the same film by three separate oscillographs. To attempt to estimate a stress which is within the elastic limit of the tank material from a measurement of the inelastic distortion of a lead disc, seems to me unsound in principle.

[The author's reply to this discussion will be found on page 1126.]

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* *Journal I.E.E.*, 1929, vol. 67, p. 566.

* *Proceedings of the Institution of Civil Engineers*, 1891–2, vol. 107, p. 434.

EAST MIDLAND CENTRE, AT LOUGHBOROUGH, 21ST JANUARY, 1930.

Mr. L. M. Jockel: I am interested to find that the author has cast some doubt upon the use of reactors. I have myself had considerable doubt as to the efficacy of reactors, and the conditions are such that the reactor may or may not have a beneficial effect upon the rupture of a short-circuit. I had an experience some years ago of a dead short-circuit on a 6 600-volt network. The short-circuit occurred approximately 1 mile away from one of the main power stations. The switch on this particular feeder had been installed 15 years prior to the time of the accident and it was of excellent design, whilst reactors were used on the busbars. It was an oil-immersed switch and had phase-separation tanks. The calculated short-circuit current was 14 000 amperes and 163 000 kVA had to be broken by the switch. I assumed in these calculations that the reactance of the cable was comparatively small compared with its resistance. Happily, the switch broke the circuit, but we afterwards noticed that every window had disappeared from our switch house, all of them having been blown into the street. This is all that happened, and although there was no oil left in the switch the latter had broken circuit and saved the situation. I think this shows that switches designed in those early days were intended to deal with a total capacity of less than, say, one-third of the final plant capacity. If the quenched-arc switch described at the end of the paper proves to be a success—and these experiments suggest that it will—I think we shall be approaching a time when a first-class switch of comparatively small size will be available. This fact should be of great importance, as modern switch rooms are large and expensive and add greatly to the capital cost of a station.

Mr. J. F. Driver: The paper deals with *oil* switches, but I am interested to know whether, after all, oil is the most suitable material for the purpose. I am old enough to remember the performance of switchgear in the days when the switch was broken under water. The most serious trouble was that overheating boiled away the water. Will the author tell us how much has been done in the way of trying other liquids? The next question which is rightly stressed in the paper is that of the size of contacts. It seems to me that there is a tendency to use contacts which are far too small and have little heat capacity. I am interested in the remarks regarding speed of break, and feel that pressure-rises occur in many cases through the breaker operating too fast. When a rotary convertor flashes over, a high-speed breaker does not necessarily make such a big difference as we like to ascribe to it. With regard to the type of switch described by the author is there not a tendency for the switch to be forced open due to the fact that an electric circuit always tends to enlarge itself? In view of this additional force it would seem to be rather difficult to measure the speed of break. It would be interesting to know whether, under short-circuit conditions, the breaker really opens at the calculated speed. With regard to the question of measuring distress, the system adopted is simple and ingenious. It measures the "summation" of the distress, but it does not show how the distress takes place. Indicators are now being developed, particularly for use when testing Diesel engines, designed to reveal the various changes in pressure inside the cylinder and also to record time, giving such information as the exact times of valve opening, fuel admission, etc. I suggest that such apparatus could be adapted for use on an oil switch, so that we could ascertain how the oil pressure changes, and also the relation of the pressure variations to the position of the contacts. If used in conjunction with an oscillograph, some interesting information should be made available.

Mr. A. D. Phillips: Mr. Driver suggests that we try to clear troubles too quickly. My experience is that if troubles are not cleared quickly they are apt to give rise to something more serious. I think he also questions the possibility of accurately timing switch-operations. It is quite possible, with ordinary commercial instruments, to take time records accurate to 0·01 sec. I gather that the author claims that the most important thing is to control the arc, and that variation of the arc accounts for variable operation of a switch under conditions which otherwise appear to be similar. The experiments referred to in the paper are apparently designed to prove that variable operation is due to a different formation of the arc. The difference in switch design as suggested is of interest, but it would also be interesting to have some idea of relative costs.

Mr. S. H. Fowles: I should like to ask the author whether the factors given on page 1102 of the paper could be applied to typical switches to find out what such switches are capable of dealing with. I take it that they were calculated on the basis of typical switches. Referring to the quenched-arc switch, I think this is a device which will get us out of our difficulties.

[The author's reply to this discussion will be found on page 1126.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 27TH JANUARY, 1930.

Mr. B. H. Leeson: Towards the end of 1922, Mr. Clothier suggested that short-circuit tests should be carried out upon specially selected oil-immersed circuit breakers of various constructions in order to determine their relative behaviour. At that time few facilities existed for carrying out short-circuit tests commensurate with the kVA ratings of large modern circuit breakers, and the wisdom of the suggestion for testing at reduced scale has been justified by the interesting points which have arisen, and the developments which have taken place as the result of the investigations carried out by the author. In certain instances, however, I think that the results obtained may be capable of interpretations different from those recorded in the paper, and in view of this I think that some of the explanations and conclusions require further consideration. The author uses the term "nominal short-circuit power" to describe the product of short-circuit current and open-circuit voltage, and I suggest that the term is misleading unless power factor is also included in it. Why is the term "distress" used in the paper to describe the capability of a circuit breaker to withstand stress? A circuit breaker which has performed satisfactorily is no more distressed than is a boiler at its working pressure, and for this reason it is customary, and, I think, justifiable, to rate both of these in terms of the stress, in pounds per square inch, for example, which they will withstand with safety. The author finds that his "nominal short-circuit power" expressed in kVA, the break energy expressed in kW-seconds and the so-called distress in the tank apparently have chance relationships, but I think that this may be explained by considering Fig. E, which shows, in a general way, the manner in which a circuit breaker can dissipate the energy imparted to it by the circuit to which it is connected. It will be seen that the break energy can be dissipated in a large number of ways, and I suggest that it may be illogical to expect it to have a definite relationship to any one mode of dissipation, such as the stress upon the tank wall measured at one location, which only represents a percentage of the total energy dissipated. In connection with this question of energy balance, I should like to know whether the energy dissipated in the form of low-grade heat was considered. If so, was the temperature of the circuit breaker constant at the commencement of each test, was its temperature-rise measured after the test, and was the condition of the contacts, etc., identical in all the tests compared for the purpose of drawing the conclusions given in the paper? The author calculates the short-circuit kVA broken by a circuit breaker from the maximum or initial value of the short-circuit transient, whereas the break energy measured will have been caused by a smaller value of current, due to the decrement of the latter during the time when the circuit breaker was preparing to open its contacts. Why has he ignored the standard and, I think, better method of taking the R.M.S. current value at the instant when the contacts of the circuit breaker separate, that is, the value of the current in the arc at its inception? Thus, unless the decrement of the current transient, the inherent opening time of each circuit breaker and the condition of the arcing contacts, etc., are identical in every test, it seems illogical to expect any useful proportionality to exist between the short-circuit kVA broken, and the break energy in kW-seconds in the arc. I suggest that the author's conclusions on existing switching conditions might profit by consideration in the light of the foregoing comments, and I do not agree with the views expressed in the paper upon speeds of break, which ignore the need for a short arc duration; the upward trend of the curve in Fig. 18, which makes the kVA infinite for an appropriate distress; and the shape of the curve in Fig. 22, which is contrary to my experience, because I have not found that making the power factor worse reduces the stress in a circuit breaker. I think that the author attaches too much importance to the variability of the particular factors which he has selected for comparison, and to the distress factor, whilst more attention should have been given to making circuit and other equally im-

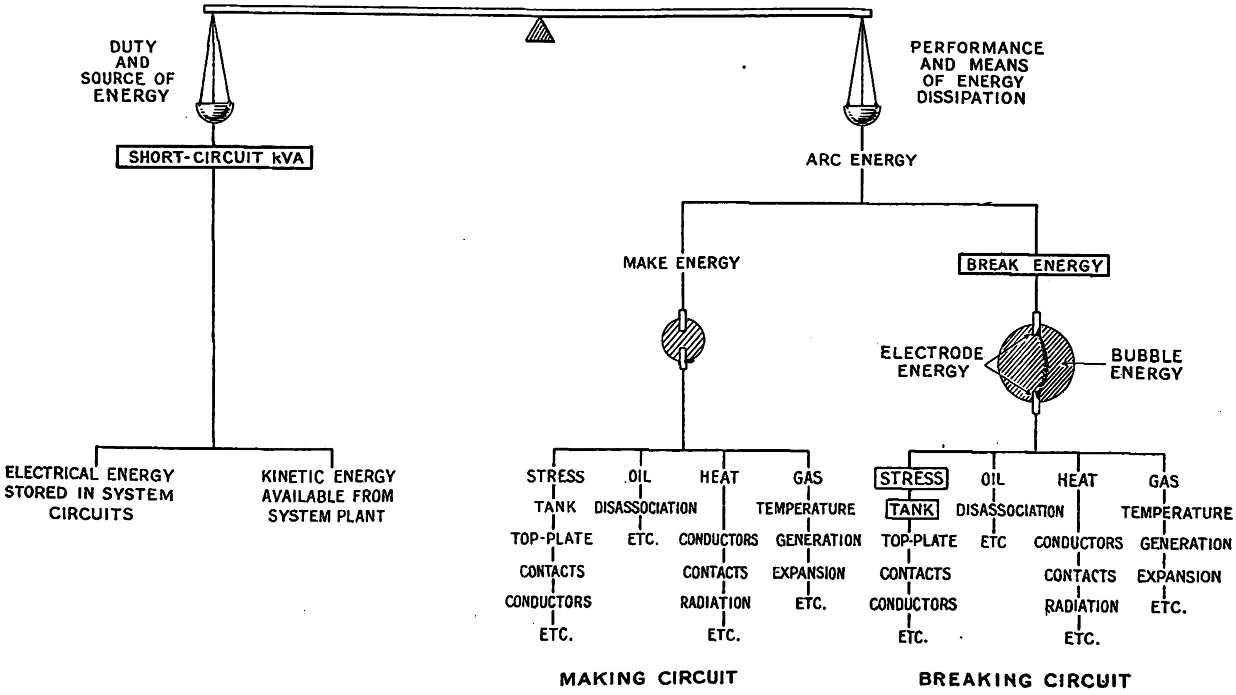
DUTY AND SOURCE OF ENERGY
PERFORMANCE AND MEANS OF ENERGY DISSIPATION
SHORT-CIRCUIT kVA
ARC ENERGY
MAKE ENERGY
BREAK ENERGY
ELECTRODE ENERGY
BUBBLE ENERGY
ELECTRICAL ENERGY STORED IN SYSTEM CIRCUITS
KINETIC ENERGY AVAILABLE FROM SYSTEM PLANT
STRESS
TANK
TOP-PLATE
CONTACTS
CONDUCTORS
ETC.
OIL
DISASSOCIATION
ETC.
HEAT
CONDUCTORS
CONTACTS
RADIATION
ETC.
GAS
TEMPERATURE
GENERATION
EXPANSION
ETC.
STRESS
TANK
TOP-PLATE
CONTACTS
CONDUCTORS
ETC.
OIL
DISASSOCIATION
ETC
HEAT
CONDUCTORS
CONTACTS
RADIATION
ETC.
GAS
TEMPERATURE
GENERATION
EXPANSION
ETC.
MAKING CIRCUIT
BREAKING CIRCUIT

Fig. E.—Diagram illustrating principle of energy balance for a circuit breaker. The three principal items compared by the author are shown enclosed.

portant factors which enter into the design, construction and application of circuit breakers. Thus, referring to the sixth test in Table 6, and assuming the tank to be satisfactory, the vital point is that a flash-over occurred to earth, and this is more important than that the distress was 10. Any mechanical device is subject to varying stresses when in action, and the criterion of its satisfactory behaviour in service is that its components have been designed and manufactured to withstand with a factor of safety the maximum stress to which they are likely to be subjected. Circuit breakers designed and constructed in this way are giving satisfactory performance in service, and I do not agree with the author in his generalized statement that the largest circuit breaker manufactured to-day should only be rated at 800 000 kVA. Applying his de-rating factor of 2·5 to a circuit breaker of smaller size, a breaking-capacity rating of 150 000 kVA would become a rating of only 60 000 kVA, yet such circuit breakers have performed satisfactorily when tested to well in excess of 150 000 kVA. They have for years proved equally satisfactory in practical operation in locations where the short-circuit kVA has at least been equal to their rating. Such practical experience, combined with tests conducted on companies' systems and special machines at least up to the author's maximum rating figure, have resulted in the curve of Fig. 25, which represents, broadly speaking, manufacturers' practice in respect to the dimensions of modern lower-voltage circuit breakers and their kVA ratings. Is all this collective experience, gained over many years, to be ignored entirely? Are breaking-capacity ratings to be arbitrarily reduced in the ratio of 2·5 : 1 in order to gain, according to the author, the comparatively small benefit of 3·5 per cent better efficiency? I suggest that the benefit to be gained by such a step is out of all proportion to the cost which it entails, and, apart from the question of improved technical performance, such de-rating is impracticable from the economic point of view. I agree with the author that all circuit breakers should be tested for breaking capacity and, incidentally, for making capacity as well. Mr. Clothier has indicated how this is being put into practice in this country. Unlike the author, I do not think that such tests will result in the need for de-rating, but instead I believe that they will result in improved details of construction and improved factors of safety over the present standard ratings, which will be retained. This latter, and preferable, policy is the one underlying the usefulness of the author's quenched-arc device. I hesitate, however, before being satisfied that it will effect so great an improvement as is indicated by the dimensions and ratings given in Fig. 35, namely, that a circuit breaker whose rating (I take it) complies with the 150 000-kVA standard (or 60 000 kVA as de-rated by the author) can be re-rated at 1 million kVA. The British Standard Specification for Oil-Immersed Circuit Breakers requires that the standard kVA rating assigned shall be based upon an operating duty which consists of making and breaking short-circuits successively, and I should like to know whether the 1 million kVA rating of the circuit breaker shown in Fig. 35 is assigned on this basis. Why is a circuit breaker of the dimensions shown in Fig. 36, which (I take it) complies with a 1 million kVA standard rating, credited only with a 2 : 1 improvement instead of the 6·6 : 1 improvement applying to Fig. 35? I suggest that the arc in the quenched-arc circuit breaker is not stabilized in the sense that the paper implies, i.e. that it is centralized, because the magnetic field causes, and is required to cause, the arc and its root to travel rapidly and laterally between the metal electrodes surrounded by gas at high pressure. These are the essential characteristics governing the satisfactory behaviour of the device. I have been privileged to witness some tests upon the quenched-arc circuit breaker and to inspect the resultant records, and, subject to the qualifications in the foregoing, I am of the opinion that the author's device shows great promise as a means of improving breaking capacity. I think that it functions upon the right lines, because it keeps the length of the arc down to a minimum and assists in dissipating the liberated energy in the form of low-grade heat rather than in stresses. For these reasons I consider that there is a future for its practical application.

Mr. R. W. Gregory: The limits which in practice have settled the breaking capabilities of commercial oil circuit-breakers have in the main been mechanical. The author has investigated, using direct and simple methods, the effects of variation in switching conditions and design by measurement of mechanical distress—the latter being gauged by the deformation of a renewable part of the switch tank. Many of his results confirm practical experience in the behaviour of circuit breakers. As an example from my own experience, a certain design of single-break switch has shown itself to be distressed more often and more seriously than a 4-break switch. Both the single-break and the 4-break switches were in tank structures of similar design and had rupturing duties of the same order. The author's results also confirm my experience that it is much more difficult to break a fault with reactance in the circuit, than to break the same kVA without reactance in the circuit. The breaking-capacity formula on page 1102 apparently represents the law according to which reputable British manufacturers design their switch tanks. The basis of the formula is $\sqrt[3]{(PV)}$, which appears to have given a satisfactory mechanical test for circuit breakers of the standard plunger type. The author's ratio of 2·5 : 1, for comparing the commercial breaking-capacity rating with the actual 100 per cent service rating, appears to be misunderstood by manufacturers. This ratio does not appear to me to imply that the service given by commercially rated circuit breakers is unsatisfactory on circuits where the breaking duty may reach the commercial rated breaking capacity, but it means that commercial circuit breakers cannot be expected always to break their rated fault kVA under service conditions. I take it that manufacturers do not claim this of their circuit breakers—at any rate they have never yet been able to prove that the rating of the circuit breakers which they sell for the highest rupturing duties meets the requirements of the B.E.S.A. definition of breaking capacity. There is a general feeling that the present design of oil circuit-breaker is by no means the final one, and the effect of research both in

Europe and in America is showing itself by the production of designs the main objects of which are to reduce, or even to eliminate, explosive switching. The air-blast circuit breaker of the B.E.S.A. and the A.E.G., and the American Deion switches are examples which show the trend of modern circuit-breaker design. The quenched-arc switch described in the paper is another attempt at the production of non-explosive switching. I was privileged to see the author's experimental circuit breaker under test at Carville, and its behaviour was most impressive. Power to the value of 50 000 kVA was broken time after time in a small container not much larger than a domestic coffee tin, without the least sign of distress; there was no oil-throwing and no smoke. These tests show that there is reason to expect a 2 million kVA circuit breaker within the dimensions given in Fig. 36.

Mr. H. W. Clothier : It has occurred to me that it would be of interest to recall the beginnings of the use of oil in connection with circuit-breaking devices, and I should like, therefore, to show lantern slides of the original Deptford air-break switches, the addition of an auxiliary oil-break by Mr. Partridge, and the first power-station switch designed specifically for oil-break, due to the late Dr. Ferranti and installed at Bankside power station. I would also draw attention to some actual examples which I have here of the last-mentioned switch, together with the oil-break fuse which was at that time the circuit breaker. Prior to the use of oil, a sort of air-blast was obtained by means of a spade-like portable insulator, which was manipulated by hand to chop through an over-persistent arc across the switch contacts.

Prof. W. M. Thornton : The measurement of distress when a structure is subjected to suddenly applied forces has long engaged the attention of engineers. It came to a head, perhaps, in the consideration of questions of damage to ships by explosion of mines in water. The point at issue was whether the damage was proportional to the pressure developed by the explosion, or whether it also involved time. The view which met with most acceptance at the time was that the destructive effect varied as $\int P dt$, the actual distress depending upon the strains produced, such as those indicated by a crusher gauge, to which the author's lead-plate deformation is closely analogous. There can be little doubt that an arc changes type during the period of break. The cinematograph records show this clearly, and they are similar to the photographs obtained by Mr. Harle in my laboratory some years ago, when investigating the properties of short transient arcs in reference to the ignition of gases. At a critical arc-length and current the volume of the arc increases suddenly, most likely as a result of the conductivity of the metal vapour coming into action. The suppression of this latter effect is the explanation of the success of the high-speed break. To extinguish the arc before the metal vapour takes charge would seem to be the right thing to do. This is borne out by the remarkable success of the author's divided-plate breaker, and in any case large contacts have a striking influence upon the properties of arcs. When sparks are made between thin or light contacts in highly explosive gaseous mixtures, and the current is adjusted so that there is ignition every time, the mere changing from light to heavy contacts (everything else remaining the same) entirely prevents ignition. A real change in the properties of an arc is therefore brought about by using heavy contacts. The question of an arc re-striking concerns both the voltage and the conductivity of the gas in the bubble. If the metal-vapour stage can be suppressed it becomes a question of electric strength alone, and the problem can be investigated by static experiments. The introduction of metal vapour complicates matters, however, for the ionization of a mixture of metal vapour and the vapours from "cracked" oil is different and less well known. Fig. 25 is interesting and valuable. If we may assume that the test pressure P has been chosen by experience to be proportional to the actual pressures which the tank has to carry when breaking a circuit of the given kVA, and that the volumes of the tanks are those necessary for safety, the reason for the relation would seem to be as follows. Consider a spherical enclosure of radius r containing a liquid, at the centre of which a pressure P_0 is suddenly set up. The pressure at any point in the fluid varies as the inverse cube of the distance from the centre. Thus the pressure at the boundary is kP_0/r^3, where k is a constant. The volume V of the enclosure is $\frac{4}{3}\pi r^3$, and for these conditions $\sqrt[3]{(PV)} = (\sqrt[3]{\frac{4}{3}\pi r^3})(kP_0/r^3) = c\sqrt[3]{P_0}$, depending only upon the pressure at the centre. If in Fig. 25 we replace $\sqrt[3]{(PV)}$ by $\sqrt[3]{P_0}$ we find that the values of distress kVA are proportional to this quantity. The pressure P_0 is proportional to the volume of gas generated by the arc and to its time of formation. Assuming the latter to be much the same for all oil-break switches, P_0 is proportional to V_0, the volume of gas generated, and $\sqrt[3]{V_0}$ is the radius of the bubble. It would therefore seem that the radius of the gas cavity around the arc should be proportional to the kVA broken, in the case of a single-break switch in a spherical tank. That $\sqrt[3]{(PV)}$ is so closely proportional to the kVA in the figure is an indication that manufacturers have found by experience that such a relation holds for the more complex oil-break switches. The forces set up in the oil by the expansion of the walls of the gas cavity, through the pressure of the gas generated to its maximum radius before the burst into the air space, are the cause of the tank distress which determines the breaking capacity of the switch. That this distress limit is proportional to the radius of the equivalent single gas cavity formed is the simple rule behind Fig. 25, though for practical purposes the curve gives the desired information.

Mr. T. Carter : I will refer first to what the author terms the "stabilized" arc. A switch fitted with this device is shown in Fig. 27 and a fuse in Fig. 28. So far as I can gather from both theory and practice, an arc in a container such as that illustrated in Fig. 28 will stay accurately in the centre if it is there initially; but in the more likely event of its being even slightly displaced from the centre it will tend to approach the side of the container because of the unsymmetrical magnetic pull set up by its eccentricity. This being so, there must be some cause, other than automatic centralizing by the magnetic field, for the difference between the two oscillograms shown in Fig. 29. I suggest that in the switch of Fig. 27 [Fig. 29 (*a*) was presumably obtained from a device similar to this] the container on each pole acts as a shield for the other pole from the effect of the presence of a loop in the circuit (see Fig. 15). No oscillograms like those of Fig. 29 are given for the fuse shown in Fig. 28; but again, if the general effect of the magnetic field is as I have suggested, and if the author intends it to be understood that results like those of Fig. 29 (*a*) and Fig. 29 (*b*) are actually obtained from the fuse, with and without the container respectively, must it not be the case that the arc is stabilized because the container shields it from draughts or other mechanical disturbances, and not because of the magnetic field? There is no loop in the circuit of Fig. 28, and even without the container one would think that the arc would tend to be more stable than in the switch of Fig. 27, where a definite loop exists. Has the author investigated the possible differences in behaviour to which I have referred between the switch and the fuse? Secondly, I will turn to the quenched-arc circuit breaker. On page 1105 the author refers to a forcing of the arc by magnetic and thermal action into the radial extinguishing openings, and apparently the greater the amount of power the greater is the force. The magnetic action referred to is not explained, and it would be very useful to have some further particulars. Superficially, indeed, there seems to be almost a contradiction; for at the end of the same paragraph it is stated that arc stability is produced partly by the concentric iron container. Judged by the author's statements in regard to stabilized arcs, this must mean that, in his opinion, the iron container tends to centralize the arc. But it is not desired that the arc should remain central: arc instability would rather appear to be what is desired. This whole matter is so important that I hope the author will amplify the statement in his reply, with a view to indicating how it is that one magnetic action forces the arc outwards, while another, set up by the iron container, stabilizes it. Is the word "stabilize" perhaps used in two different senses? Lastly, I will say that I have read section (5) of the paper a good many times, but I cannot altogether follow the reasoning that leads to the author's adoption of the "safety" figures which he proposes. In any case, I have not much confidence in such wide deductions when they are drawn, for example, from data representing so comparatively small a number of faults as 170 in all, and when a much smaller number like 11 is the final guide to the difference between certainty and uncertainty. Further, the origin of the divisor 2·5 is not at all clear. This question also is so serious that it deserves more ample treatment, and I hope that the author will give fuller details in his reply.

Mr. J. A. Harle: The variability of the phenomena of arcing in oil has been emphasized by the recent papers read by members of the Electrical Research Association, and I therefore welcome the author's efforts to overcome this variability by suitable circuit-breaker designs. I agree with the statement regarding contact sizes on page 1091, but I would point out that there is a limit in size beyond which improvements by such means cannot be found, as for each arc current a certain crater size will occur and the contact dimensions can only be increased to some function of this if the material is to be used efficiently. The author's method of measuring pressure stress by the use of diaphragms appears to be an ingenious and practical scheme, but such devices indicate a pressure which includes the static pressure as well as some component of the dynamic pressure waves set up in the oil, and consequently the readings obtained by such a diaphragm are only reliable as to the stress if a number of results are taken and averaged. How many such discs were used in the tank during each test, and where were they fitted to the tank walls? Unless a number were used in each test the stress indication would only apply to one point and it would not be a reliable indication of the total stress on the tank, especially in view of the effect of the pressure waves upon the results. The accuracy of the devices as reliable stress recorders is questionable, and I would point out that they do not indicate the distress of the switch in any way, as the author suggests. With regard to the conclusions as to break energy, the variability appears to confirm the Research Association's published work and, wherever possible, designers must allow for the worst conditions. I agree that the arc energy of any individual test is no guide to the stress, but I think that from a group of tests an average value and a maximum value could be obtained. I consider that a similar group of tests is desirable if the stress results obtained by the author's method are to be compared with any other results, and unless this is done misleading conclusions may be drawn. The oscillogram of Fig. 4 is interesting in that the voltage wave appears to have a displaced zero line, which would have the effect of decreasing the arc energy. If this were not so, the first half-cycle of the current wave would apparently be accompanied by negative arc energy: this would be rather a phenomenon in view of the fact that no arc energy would have so far been delivered to the arc. I should like to ask whether the arc-energy value given in Table 3 was based on this line, or whether it was calculated upon some other basis. I am interested in the author's conclusions regarding the number of breaks, and I should like to know whether the distress value indicated was obtained from a single diaphragm. Where was this located relative to the arcs, in each case? I do not entirely agree with the statement on page 1096 that the final size of the bubble depends upon the ratio of air cushion to oil volume. I consider that it is purely a function of the air cushion and of the arc energy, and that in the end, after the arc energy has reached a certain value, it becomes practically a function of the air cushion alone, unless oil is vented from the tank. No absolute empirical rule exists as to the best value of air cushion, as this is a function of arc energy, ultimate tank strength, clearances, etc. Each design has its own best value of air cushion, and this enables a balanced performance to be obtained. I agree with the author regarding the necessity for an adequate head of oil, so as to prevent the gas bubble from breaking through in an incandescent state. Are the conclusions regarding symmetry (page 1095) based upon the data in Table 8? If so, it would appear that the author is comparing an unsymmetrical current of about 750 amperes with a symmetrical current of about 1 200 amperes, whereas on the same circuit a symmetrical fault-current value would be associated with a higher unsymmetrical current value. Also, if he averages the break energy for the symmetrical conditions and compares it with the average for the unsymmetrical condition, ignoring the freak case therein, he is comparing an average of 3·42 kW-sec. with 5·23 kW-sec., and a deformation of 2·03 with one of 2·4. If he allows for an unsymmetrical current of approximately 1·5 times the symmetrical value and corrects the unsymmetrical values for this, there appears to be an increase in arc energy to 12·6, and in deformation to 5·4, based on an increase of arc energy and stress proportional to the kVA involved. This would indicate that a switch opening a symmetrical short-circuit would produce less arc energy and stress than one opening an unsymmetrical short-circuit on the same circuit. I should welcome the author's views on this, as the figures do not appear to support his conclusions. The switch shown in Fig. 35 is interesting and sound, but I consider that the author's conclusions in this connection are optimistic. I think that the device will be very critical in action, being perfectly satisfactory up to a certain kVA value even for a number of operations, but on breaking any faults above this value the switch will be destroyed due to complete breakdown. I consider it unsafe, therefore, to assume that, because a switch of this type has opened 230 000 kVA successfully and quietly, its ultimate rating is 1 million kVA. The policy adopted by the author is sound in that he sets out to improve the circuit breaker and not to de-rate it. With regard to Fig. 37, I should like to know the author's opinion as to the effect of suddenly switching on a power load across the machines, as he suggests. This would appear to mean suddenly switching over three times full load on to the machines, judging from the value of resistance suggested on page 1110. In the case of Fig. 40, his proposal would not, I think, reduce the peak value of the initial current rush to any extent, as this is mainly governed by the stator reactance, but it might reduce the decrement to some extent. I fear that this reduction, however, would only be of the second order on a modern solid-rotor machine. Preliminary experiments carried out by switching an inductance into the rotor circuit on a small machine appear to confirm this.

Mr. R. H. Brierly: It is of considerable interest to note the conclusions drawn by the author from his comparative tests on circuit breakers fitted with single, two or four breaks. Generally speaking, it may be stated that the behaviour of a 4-break switch is twice as good as that of one fitted with a single break; this improvement compares favourably with the results obtained by other investigators, in particular Messrs. Brown, Boveri and Co., who published results of similar tests in the *Brown Boveri Review* of March 1923. The improved behaviour of the multi-break switch is probably due to the splitting-up of the arc into a number of smaller arcs, each of which is less stable than one large one. The gas bubbles produced by these multi-arcs have a total cooling surface much in excess of that produced by a single arc, and the switch may be so designed that they are distributed throughout the available space in the tank. As a result of this extra large cooling surface and the better disposition of the bubbles, the quenching limit of the oil is not exceeded and excessive carbonization is reduced. It was found in practice that when an old type single-break switch operated on severe faults the oil was so badly carbonized that it was essential to take the switch out of commission, filter the oil and clean all horizontal insulators. On the other hand, multi-break switches operating on the same value of fault kVA have been replaced in service immediately, with the oil hardly discoloured. In addition to this important point in favour of multi-breaks, their construction is particularly suitable for obtaining the long length and high speed of break required for high voltages. The author states that in his opinion a lower speed of break should be used for the higher voltages than for the lower ones, and he gives a value of about 10 ft. per sec. for a voltage range of 3–20kV. I agree that such a figure may be approximately correct for this range, but not that a lower figure should be used for higher voltages. The primary object of a circuit breaker is to disconnect a faulty section from the system as rapidly as possible and, since experience shows that the arc length is much greater on high than on lower voltages, it follows that with the same speed of break a high-voltage switch would take considerably longer than a low-voltage switch to clear the fault. The break energy produced would in all probability be excessive, producing pressures in the tanks that would strain them unnecessarily. In connection with the author's tests, it would have been interesting if the values for the speeds of break used for the single-break and multi-break switches had been given. It would appear essential, when comparing relative performances, that the switches should be identical with regard to speed of break, head of oil, etc., the only difference being that of the number of breaks. The principle of the stabilized-arc switch and stabilized-arc fuse is interesting, but I should like to ask how the stabilization effect is obtained. It would appear that the satisfactory performance of this type of gear is due more to the high pressure developed in the stabilizing pot, than to any centralizing of the arc due to the metal screen. This being so, it is probable that this type will suffer from the same disability as the explosion pot, i.e. although it may behave well on a limited range of fault currents, if this range is exceeded the container may burst; if the upper limit of the range is not reached, a pressure sufficiently high to ensure satisfactory operation is not obtained. Again, although from the results of extensive researches it is now possible to predetermine the behaviour of an open-arc type of circuit breaker with a certain degree of accuracy, it is still quite impossible to obtain any idea of the performance of an explosion-pot breaker without making tests. The author's decision to take the first cycle of the short-circuit current as the value broken by the switches during his tests is somewhat unusual. Unless particulars are given of the reactance and decrement of the test generator, and of the times between the commencement of the short-circuit and the separation of the contacts, it is impossible to obtain the current or kVA value broken by the switch. A delay of at least 4 or 5 cycles is usual between the commencement of the short-circuit and the separation of the contacts, and during this period the value may be expected to fall away rapidly. It would be of considerable interest if the author could show an oscillogram of the 230 000-kVA test mentioned in Table 10.

[The author's reply to this discussion will be found on page 1126.]

WESTERN CENTRE, AT CARDIFF, 10TH MARCH, 1930.

Mr. S. B. Haslam: I think that the paper is extremely important, and the somewhat revolutionary design with which it deals will undoubtedly play a great part in the future development of high-tension switchgear. Hitherto the chief efforts of the designers of switchgear to meet the enormously increased rupturing strains have been concerned with enlarging and strengthening the tank, and it must be agreed that the strength of the tank plays an important part. The main function of the break in oil is to make it difficult for the arc to be re-established after passing through a zero, and this is best effected by keeping the pressure of the gas bubble at maximum. Any yielding of the tank causes a corresponding expansion in the bubble, with a subsequent reduction in pressure. A tank, therefore, which will not yield, and which at the same time will provide only a limited air cushion above the oil, seems to be the best practice, and in all probability the author will confirm this. I am glad that the author refers to the ratings of rupturing capacity. I do not think that he is quite justified in stating that the ratings established by present-day practice must be divided by 2·5 in order to obtain the true rating. No doubt this may have been so in earlier designs, due probably to lack of sufficient experience, but I have no hesitation in stating that in a great many of the best designs a safety factor will actually be found. That much may depend upon whether the designs are based on average experience is a point on which I cannot agree with him. Design should be based on maximum experience, and the responsibility for accepting anything less than this should be put upon the user. With regard to the question of the quenched-arc circuit breaker, according to the paper the arc is " forced by magnetic and thermal action into the radial extinguishing openings," but I cannot quite understand how the magnetic action operates. In the first place, it is stated that the stability of the arc is partly produced by the concentric iron container—a remark which appears to imply that this container tends to centralize the arc. On the other hand, it is specially desired that the arc should not remain central, and I should be glad of further explanation on this point. It appears that one magnetic action tends to force the arc outwards while another one tends to stabilize it in the centre.

Mr. T. C. Christianson: Referring to page 1092—with regard to power broken, break energy and distress—other investigators' test-results have shown that in a given breaker the break energy and the signs of distress vary over wide limits for given powers broken. The general opinion, however, is that break energy and distress vary in proportion to the power broken. Such test-results have also shown that, for a given power broken, the average break energy and distress vary in different designs of breaker. Were these not the facts, there would be no possibility of improved breaker designs. Referring to snap contacts, some explanation of the curves in Fig. 14 would be of interest. The arc voltage is shown to rise slightly and then suddenly shoot up to a peak. Is the initial rise due to badly designed shunts on the snap contacts? The curve in Fig. 14 is apparently not representative of the performance of the best designs of snap-contact breakers. The author's suggestion of a 2·5 : 1 ratio for commercial to true breaking capacity cannot be accepted in regard to present-day designs. His suggestion seems to be based on somewhat confused reasoning and matters of opinion. The summary on page 1089 refers to the fundamental limit of breaking capacity as the short-circuit power which can be broken time after time by a given breaker without breakdown. Commercial breaking capacities are based on B.S.S. No. 116, viz. a 2-shot cycle (i.e. B—2—MB—2, meaning, break the declared kVA—2 minutes' interval—make and break the declared kVA—2 minutes' interval), after which the breaker is to be fit to make and carry normal full-load current without dangerous temperature-rise. It is implied that the breaker will be examined at the first convenient opportunity thereafter, and, if necessary, will be fettled before breaking any further short-circuits. Referring to page 1100, the author starts off from the basis that present designs of breakers are suitable for average stress conditions; this is a matter of opinion and his assumption may be an understatement or an overstatement of the facts. I suggest that for properly maintained British breakers of reputable make it is definitely an understatement. On page 1101 the factors which mainly determine the breaking capacity of the conventional design of breaker are stated to be the volume and strength of oil container and the number of breaks in series per pole. Many further factors, however, are of considerable importance, e.g. the disposition and shape of the arcing contacts, the relative impedances of the main and shunting or arc-contact paths, the thermal capacity of the contacts and conductors, and the strength of the conductors, insulators and mechanism. Thus, while tank volume and strength alone form a convenient measure of breaking capacity, they are by no means the sole determinants. The breaker shown in Fig. 27 is practically the conventional explosion-pot breaker with an enlarged throat-opening. If Fig. 29 is representative of average performance with the Fig. 27 breaker, it is difficult to believe that the oscillogram of Fig. 16 is representative of the conventional explosion-pot type. With reference to the quenched-arc breaker, the author's theory of its action appears to be open to doubt where he says on page 1105 that the arc is " forced by magnetic and thermal action into the radial extinguishing openings." The more probable effect would appear to be that the hot gases are forced into the inter-plate spaces. Referring to Fig. 35, it would appear that the insulation of the metal plates to each other and to the " pot " would have to be of a particularly reliable nature—capable of standing up to high temperatures and possibly carbonized oil and volatilized metal deposits. It would be useful to know the amount of maintenance that breakers of this type would require. It is generally accepted that it is desirable to examine ordinary breakers after opening two or three short-circuits, and it is then frequently necessary to dress the arcing contacts and sometimes to renew the oil. With the quenched-arc breaker considerable risk of failure might exist if the insulation of the metal plates were not carefully maintained. Such maintenance might prove somewhat troublesome and costly as it might involve frequent renewal of the insulation. Insulation maintenance may prove to be the limiting feature in the breaker's ability to function within its rating. I have scaled the drawings in Figs. 35 and 36 and have thereby deduced the volumes of the two tanks, assuming 31-in. and 60-in. 3-phase tank lengths respectively for these two breakers. The volumes so deduced are 6·25 and 40·5 cub. ft. respectively, for what the author suggests would be breakers of 1 million and 2 million kVA (true rating) breaking capacity. I have neglected the fact that the author's dimensions would have to be increased to permit the accommodation of main contacts large enough to carry the normal load currents. Present conventional breakers of 1 million kVA declared breaking capacity would have a tank capacity of 35 to 55 cub. ft., and those of 2 million kVA declared breaking capacity would have a tank capacity between 100 and 150 cub. ft. Taking average figures of 45 and 125 cub. ft. respectively, for the above commercial ratings we get, say, 7 and 3 times the quenched-arc breaker tank-volumes deduced as above. It will thus be seen that if we can even approximate to the author's suggestions a considerable reduction in dimensions will be possible. It is not clear from the paper whether any of the tests carried out by the author on the quenched-arc breaker were made by " closing on the fault " or whether all were conducted merely by " opening on the fault." We have found that these two conditions can lead to greatly different effects and distresses. With the quenched-arc switch one can imagine a greater order of variation under these conditions, e.g. if the metal-plate insulation were low the " closing on the fault " effects might be disastrous. Another point of interest is that " other load " in parallel with the fault circuit can have considerable effect on the duty of the breaker in the fault circuit. Referring to the Appendix, page 1111, is the time of 0·1 sec. a misprint for 1·0 sec. or longer? In a paper * by Mr. J. A. Kuyser interesting figures on the rate of fall of alternator field current under different conditions of opening were given. These indicated that when opening the main field without discharge resistance a period of about 0·1 to 0·2 sec. is necessary for field-current reduction from the no-load value to 50 per cent thereof, and a greater time with discharge resistance.

Mr. G. E. Whitehead: I am convinced that the future will prove the author's effort to be an important forward move. In the switchgear of to-day there is a tendency for manufacturers blindly to copy those designs for which other makers have created a market, irrespective of whether the designs in question still meet the changed conditions. For many years I have not been able to understand why switchgear designers cannot get away from the earliest practice based on utilizing three knife switch-blades (later, V-bars) mounted on a common baseplate and placed in an oil container. This was to me particularly inexplicable during the period when it was found necessary, owing to the rapid increase in size of generating units, to concentrate on the question of rupturing capacity. It has always seemed to me that switchgear makers generally blundered during that period by developing on the earlier lines and concentrating merely upon length, speed of break and mechanical strength of baseplates and tanks. Surely, during the critical period when the various manufacturing firms were concentrating upon this problem, there was ample scope for initiative in other directions. From my own experience of the manufacture of switchgear, it seems as though the commercial side was always predominant and that the users contributed to the lack of real progress by their conservatism and their tendency to consider only the types in vogue. To confirm this point one has only to consider truck-type switchgear, which at one stage fulfilled a very useful purpose. There are now about 16 firms in this country manufacturing truck-type cubicle switchgear, and I think I can safely say that the majority of these set out to cater for a market which had been created by the pioneer firms, and that the maximum effort put forward by the former was merely to copy existing makes of trucks and to concentrate less on improvements than on cheapening. The usual procedure is to secure prices and designs of existing makes, permit their designers to inspect one or two installations supplied by other manufacturers and go ahead. The departure being entirely new to these particular firms and their salesmen, in their enthusiasm they were unable to appreciate the fact that the (to them) progressive venture (along the already well-beaten track) was a fiasco as, owing to the changed conditions, truck-type switchgear was not a good proposition for 100 000 kVA and upwards. I am convinced that in the near future switchgear will be designed on totally different lines. There are, to my mind, three alternative solutions to the switchgear problem and the author's has gone 80 per cent of the way in one direction. I believe that his claims as regards the increased efficiency of his breaker with the resultant far-reaching saving in size will be confirmed in due course. Any new departure of this description is fated to meet with a hostile reception from manufacturers generally, probably because of vested interests in existing plant and designs and the conservatism of the users. One of the real obstacles to progress in the past has been the time-lag or period of delay until some user, not waiting for others to make the first tests, took the initiative. If manufacturers had developed their designs without studying existing types overmuch there would have been no necessity for the monstrosities at present being manufactured, as there are wide fields for development in so many directions. I have not the least doubt that it is possible to design circuit breakers of, say, 350 000-kVA rupturing capacity which would be practically indestructible, accessible and safe to handle and which could be brought down to within 25 per cent of present-day dimensions and costs. There are three obvious solutions and a simple combination of these presents a simple, practicable, commercial proposition without the necessity of introducing compressed air or gas.

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* " Protective Apparatus for Turbo-Generators," *Journal I.E.E.*, 1922, vol. 60, p. 761.

Mr. W. A. H. Parker: Several important points dealing with the operation of circuit breakers under fault conditions have been raised by previous speakers, and the question of breaking a circuit under these conditions has been gone into fully, but the making of the circuit after fault conditions have arisen seems to me to be of equal importance. In fact, it may be of greater importance, and I think that more time should be spent on so designing breakers that the contacts will close quickly, irrespective of the speed of operation of the reclosing mechanism. One can readily conceive what will happen when the handle is operated slowly with the standard type of reclosing mechanism, and in the paper several illustrations of contacts which show distress after opening the circuit are shown; I have seen contacts similarly marked after a switch has been closed on a faulty circuit. The author shows that the short-circuit impedance of the circuit should be calculated before the speed of break of the switch is determined, but it seems to me that from the practical point of view this would entail constant changes, as the circuit conditions vary from time to time, and unless we can vary the speed of break after the switch is installed we cannot take full advantage of his proposals. The number of tests which the author has made on the new switchgear has necessarily been limited, whereas the standard type of switch has been well tried out under actual working conditions. In America they are spending more and more time on actual field tests over periods of years instead of the usual factory and laboratory tests, and I believe that this is the only satisfactory way to arrive at a true estimate of the performance of this type of gear.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, LOUGHBOROUGH, NEWCASTLE AND CARDIFF.

Mr. L. C. Grant (*in reply*): The disc method of distress indication has been severely criticized, but not always with justification or with complete understanding of it. Other devices such as the piezo crystal, the crusher gauge, the quartz crystal and even the microphone were considered. These all have their limitations. For example, the piezo crystal is hygroscopic and its calibration is thereby affected. The crusher method masks results because of inertia effects. Quartz crystals are susceptible to electrical and other influences and have highly resonant characteristics. The microphone, although used in America, has undoubtedly very serious and well-known limitations. Moreover, the actual measurement of pressure (even if a completely accurate method could be devised) goes only part of the way. There are two further steps which must be taken: (*a*) the determination of the amount of energy passed to the tank walls, and (*b*) the effect which this combination of pressure and energy will produce on the tank. The object of the disc method is to indicate directly, and without an intermediate step, what would happen to the oil-switch tank; and this is, after all, what we want to know. The methods just enumerated were therefore abandoned in favour of the discs, which in my opinion give more direct and consistent results than any of the other methods.

A whole gamut of pressures may be set up with, at one extreme, waves of steep contour and, at the other, sustained pressures similar to those set up in a boiler. The measurement of pressure waves of varying steepness is in itself a baffling problem. What, then, is to determine the method in oil-switch work where any combination of kinetic and potential energy may exist? Surely it is better to use the disc method which shows what is happening to the switch container and thus indicates the vitally important condition of that container. That the disc method does indicate accurately the condition of the tank has been proved by detailed experiment and also, perhaps crudely but none the less fundamentally, by the consistent behaviour of two discs under similar testing conditions.

I do not agree with Dr. Whitney's contention that the various forms of pressure—in particular, the two extreme forms of pressure pulsation and sustained static pressure—need be separated. The switch tank has to withstand these two forms, and the pressure discs are affected by both forms. Why, then, separate them or employ indicating devices which attempt (very indifferently) to differentiate between them? What the switchgear user wants to know chiefly is whether his switch tank is strong enough mechanically: he is not so interested in what goes on in the arc or even in the body of the oil. The interesting problem is whether the switch is likely to remain a useful factor in his calculations; and the ground which is common both to the designer and to the user is the container.

It is interesting to note that Dr. Whitney's experience and the E.R.A. experiments show an agreement between break energy and bursting pressure, but Mr. Wedmore apparently does not agree with this. The measurement of break energy may be scientific intrinsically, but it fails to explain actual results. Where is there any connected science in the action of an oil circuit-breaker, and what is there that is scientific in properly applied empirical methods? The pre-arcing sequence is as dependable as any electrical phenomena, but immediately arcing commences the connectedness is broken, the arc takes charge and becomes the determining factor in what follows. In short the arc destroys the relationship of circuit conditions, and thermal and pressure effects, just as effectively as Lac Leman destroys the identity of the two parts of the Rhône. Mr. Wedmore's high opinion of flexible-wall circuit breakers does not seem to have been justified by results, and modern switch design tends in the opposite direction. It is perhaps superfluous to point out to him that an "irresistible force and an immovable mass" cannot have simultaneous existence. It is rather difficult to deal with some of Mr. Wedmore's statements owing to a lack of supporting evidence. He should not be discouraged because oil switches attract attention from all shades of technical opinion. Every day brings new light to bear on the problem, and even a streak of Apemantusian philosophy may in time prove to be not without its results.

Mr. Wedmore refers to *the* circuit breaker, whereas *several* circuit breakers of different designs were used in the experiments. I cannot find it stated in the paper that there is an inevitable relationship between the ability to withstand stress and the prevention of the arc from re-establishing itself after the current has passed through zero, and I did not imply that the distortion of the tank wall was the only factor which affected the performance of the switch. Mr. Wedmore apparently agrees that very rapid breaking must increase the voltage across the arc by forcing up its resistance, that slow breaking is equally bad, and that there must be an optimum value of speed. This is the main contention of Section 4 of the paper. I do not agree that excessive speed of break is unlikely in present designs; it is suggested in the paper that the actual linear speed of breaking of present-day switches is of small importance compared with the maximum speed at which the arc may be lengthened, for instance by arc distortion, which may give an excessive momentary speed super-imposed on the relatively low linear speed of the main contacts.

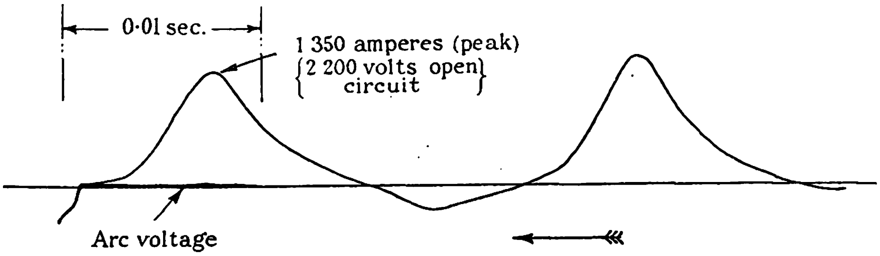

Fig. F.—Oscillogram of short-circuit at 2 200 volts (open circuit).

The quenched-arc circuit breaker and its action were discussed at some length in 1927 with Mr. Wedmore, with whom it was agreed that the Electrical Research Association's work was on different lines from mine. In the quenched-arc circuit breaker, the arc is rooted in the discs or plates, whereas the Association's work dealt with breaking methods employing discs to cool the *gases* from the arc. Mr. Wedmore is not quite correct in stating that the E.R.A. used the same short-circuit power as I did. In addition to this source of power, the quenched-arc switch was tested with 250 000 kVA. Several speakers, indeed, appear to have overlooked the fact that a power source of this magnitude was used in the tests. Part of the "mass of experimental data" was expeditiously analysed by the application of an extremely up-to-date method due to Mr. J. C. Preston, M.Eng., of Liverpool University, and brought to my notice by Prof. F. J. Teago. This is a much quicker method than that generally used by investigators and appears to be worthy of more extensive adoption.

The cross over the zero line in Fig. 4, referred to by Dr. Whitney, is due to the thick line used for reproduction, so that Dr. Whitney's argument in regard to Table 3 is inapplicable. With regard to Table 8 and Fig. B, surely Dr. Whitney does not seriously suggest plotting a curve from eight points when one of the eight is more than 100 per cent out of line and when Figs. 2, 3, 4, 5, 6, 7, 8 and 9 show the reverse effect. Dr. Whitney inquires what precautions were taken to guard against distortion of the pressure-indicating discs. The total thickness of the flanges between which the discs were bolted was 1 in., and the effective diameter of each disc was 3 in. The precautions to which Dr. Whitney refers were all observed, and where model switches were used the whole model was carefully scaled down. It does not seem to be generally realized that most of the "models" were quite as large as commercial breakers; some, indeed, *were* commercial breakers. They were described as models only because of my postulation of $1\frac{1}{2}$ million kVA as the normal short-circuit power of a full-scale system. Not at any time were the "models" or the testing conditions on a smaller scale than the work of the E.R.A.* Dr. Whitney and others should bear this in mind in comparing my results with other investigations. The speeds of cross-bar supports were the same in the single-break, double-break and 4-break tests so that the speed of arc drawing would be greater in the 4-break tests than in the single and 2-break tests. Fig. 12 includes the energy which flows to earth. The air cushion in all the tests in Table 6 was the same. Dr. Whitney should read the paragraph below Table 6. With regard to the tests on the stabilized-arc switches, the chief reason the stress is different is because the switches tested were of different design and size. I am rather surprised that Dr. Whitney should select *two* tests from his research work and compare them with a *group* of tests; his Figs. C and D can be obtained from any ordinary oil switches if selection is resorted to; for instance Fig. F shows the same effect in a test which I carried out. The oscillograph records and data given for the quenched-arc switch show its normal performance, whereas the oscillograph records of oil switches of normal design are exceptional; in fact they represent the lower end of the scale referred to in one of the E.R.A. Reports,† and they support my contention. No "principle of selection" was adopted for Fig. 18; the tests were taken at random. It is noted that the last point in Table 7 is not recorded. With this point included, the curve will become straighter and will obviously strengthen the argument; it will also reply to Mr. Leeson's question.

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* For instance, see the E.R.A. Report in *Journal I.E.E.*, 1929, vol. 67, p. 557

† *Journal I.E.E.*, 1929, vol. 67, p. 557.

I am glad to have Dr. Whitney's confirmation that the E.R.A. investigation on the effect of phase angle and inductance shows a similar effect to that which I obtained.

Doubt has been expressed of the adequacy of the evidence supplied to support some of my statements. It is interesting, therefore, to compare this evidence with the published information emanating from the three bodies who have the facilities for carrying out similar tests. Let us call them A, B and C. Each has been responsible for sponsoring a new switching device which A and B have developed to a commercial stage and upon which A has carried out 82 tests, B 27 tests and C 33 tests. On the quenched-arc switch more than 100 tests have been carried out. C has carried out considerable detailed experimental work similar to mine. On three lines of research taken at random (they deal with number of breaks and effect of phase angle) C offers 12, 9 and 14 tests as supporting evidence, while I submit respectively 20, 10 and 25 tests and an equal number of "bracketing" tests. In the same tests C's average per point on given curves are 8·7, 3·2 and 2·3; in two instances two tests only are deemed sufficient to justify plotting a point and in two other cases one test suffices. The smallest number of tests per point in any of the work covered by my paper is 5.

It is gratifying to have the support of Mr. Clothier to the scope and extent of the paper. His choice of the word "illusive" in connection with the use of arc energy and break energy as standards of quality and performance seems apt. It has already been pointed out that the curve on page 1097 when redrawn to include the last point in Table 7 would tend to become a straight line. The pressures obtained have been noted with switches capable of breaking up to 250 000 kVA. I believe that with a sufficiently extended curve Fig. 18 would, in practice, become a straight line. The results shown on the curve in Fig. 22 have been confirmed to some extent by observations made with a source of power capable of giving 1 million kVA on short-circuit. The ratio of 2·5 : 1 was obtained from the experimental work described in Section 5, and it is the ratio of maximum distress and average distress set up under fixed circuit and power conditions. It was not obtained from a comparison of commercial switches. The arrangement of busbars in Fig. 37 is purely illustrative; it could be developed into a ring or a duplicate busbar system without modification to the principle. Mr. Clothier's suggested arrangement of resistances and short-circuiting switches on the star side of the generator windings appears to be sound. It would necessitate a larger number of switches and resistances, but would have the advantage that, if desired, insulation could be reduced. My extrapolation of the quenched-arc switch shown in Fig. 35 up to 1 million kVA represents an extrapolation ratio of only 4 : 1, not 10 : 1. A quenched-arc switch of the dimensions shown has broken 230 000 kVA, which is double the rating of the same switch without the quenched-arc arrangement.

Mr. Coates does not appear to have read the paper very carefully. He says that the ratios given in the conclusions from Table 6 are not embodied in the breaking capacity formulæ on page 1102; yet on that page this information is given at length. Again, it is the essence of Fig. 25 and the formulæ given on page 1102 that they are based on data obtained from commercial switches and are thus empirical. The formulæ are of practical value only because they *are* empirical. Mr. Coates will also find that attention is drawn in the paper to the need for caution when dealing with large high-voltage switches. The formulæ have been applied successfully in at least 95 per cent of the cases. What Mr. Coates calls "the theory of surging" is not novel. As he states, it is referred to in the E.R.A. Report in 1929, and it is also mentioned in my paper in 1926.* The magnetic ring used in the stabilized-arc switch is open at the top and bottom and, although there has been noticeable simplification of the explosion-pot circuit breaker lately, the latter is not yet entirely open at the top and bottom. I am unable to understand what Mr. Coates means by implying that manufacturers' breaking-capacity ratings can be proved in practice. The series of tests in which Mr. Coates participated on a 600 000-kVA plant go less than half way to prove present-day ratings. I have carefully followed the field and other tests carried out during the last few years, chiefly in the United States and on the Continent, and so far have found no tests which prove that any existing circuit breaker will break 1 500 000 kVA. My comparison of round and rectangular tanks was made from an examination of manufacturers' designs. Mr. Coates will find on referring to the paper that attention is directed to the anomaly of the apparent weakness of round tank switches and for the need of the physician to heal himself.

"De-ionizing" has been recognized since the earliest days of electrical engineering. The work of Prof. Thornton and of Prof. Compton is fundamental and of long standing, and there cannot be any master patents for the application of this effect. I have followed the development of the "de-ion" circuit breaker with great interest and have noted its good performance. Practical application, however, appears to lie with the so-called "de-ion grid" breaker, a device of quite different conception. Comparisons of the "de-ion," the "de-ion grid" and the "quenched arc" circuit breakers will be found at the end of my reply. Mr. Coates accuses me of not being practical enough, while Mr. Wedmore alleges the opposite; I aimed at a middle course.

Mr. Trençham rather refreshingly admits that circuit breakers are designed from practical experience, but I do not agree that the resultant circuit-breaker ratings take into account the "uncertainty factor" of 2·5 : 1. To Mr. Trencham's list of new types of circuit breakers should be added the de-ion grid breaker, which appears to have out-paced the de-ion breaker. Mr. Trencham is correct in assuming that the cooling paths of the quenched-arc breaker form a *cul de sac*, if by this he means that the arc does not travel beyond the annular enlargement; but this is true only so far as the arc is concerned, and oil and gas can pass and escape at the edges of the plates. I have compared the tests on the quenched-arc breaker with numerous tests on explosion-pot breakers, and I find that the arc voltage in the quenched-arc breaker is less than 1/100th of the arc voltage of the explosion-pot breaker, and that whereas the quenched-arc breaker is completely consistent in its action (the " uncertainty factor " does not exist), the explosion pot breaker still possesses the inconsistency of the conventional oil breaker. If these two fundamental differences are " almost nothing," the problem of designing a scientific and peacefully operating circuit breaker has never existed. Mr. Trencham appears to have the impression that the de-ion breaker has been tested on considerably larger amounts of power than the quenched-arc breaker, whereas both have been tested up to 250 000 kVA (see also my reply to Mr. Clothier).

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* *Journal I.E.E.*, 1926, vol. 64, p. 920.

In reply to Prof. MacGregor-Morris, the magnetic cylinder of the stabilized-arc switch increases the permeability of the flux path round the arc which strengthens the field round the arc and increases its natural tendency to complete a straight line between the co-axial electrodes; it also forms a magnetic ring which screens the arcs from one another and from exterior unstabilizing influences. A non-magnetic cylinder of the same resistance has been tried, with quite different results.

In reply to Mr. Driver, few liquids other than oil have been tried in switches; water and carbon tetrachloride and "Excello fluid" are the chief ones. Not infrequently, switches are forced open electromagnetically, as Mr. Driver suggests. Undoubtedly, many circuit breakers open at a speed depending upon the current passing. The formulæ on page 1102 can be used on the generality of oil switches.

In reply to Mr. Leeson, power factor is taken into account in Section 4 of the paper. Mr. Leeson's analogy of a circuit breaker with a boiler must be a very limited one, as the latter works under fixed conditions of pressure. I do not agree that a circuit breaker is no more distressed than a boiler. If the boiler analogy is good, why does Mr. Leeson test his circuit breaker tanks by means of explosives? It is reasonable to rate the mechanical strength of an oil switch in pounds per square inch if the various pressures and rates of pressure-change can be referred to a common base. Mr. Leeson is not correct in stating that the remarks in the paper on breaking speeds ignore the need for a short arc. This requirement is constantly referred to in the paper. Mr. Leeson's Fig. E shows in an assimilative manner the relationship between the modes of dissipation, and while " arc energy " can be divided in the manner shown in the chart, there is little hope of it ever being a measure of stress (or distress). Mr. Leeson's comment on Fig. 22 is noted (see my reply to Dr. Whitney). Mr. Leeson apparently considers that while the factor 2·5 : 1 may exist, the comparatively small operating benefit of 3·5 per cent may not be worth the cost; then he paradoxically suggests that the resultant efficiency is low, but 96·5 per cent efficiency of service is not necessarily low. If, however, it is suggested that the " derating " factor of 2·5 is incorrect, the only logical course I can see is for manufacturers to demonstrate by full-scale tests what are their actual safe breaking-capacity ratings. I do not " ignore the collective experience gained over many years." On the contrary I have great respect for it, and devoted the best part of Section 5 of the paper to it.

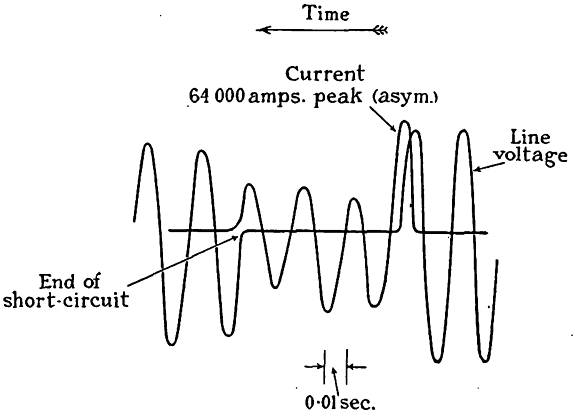
Mr. Leeson confirms the performance of the quenched-arc breaker on 230 000 kVA. In the switch shown in Fig. 35 stability is produced by drawing and maintaining a short arc of constant length. Examination of that figure will show that no matter how far the arc may be bowed out, the arc length will always be constant. This is a vital requirement of circuit breakers and it is possessed, as far as is known, only by the quenched-arc breaker. In some of the single-pole experimental switches a mechanical stabilizing system was used. Markings on some of the circular plates taken from quenched-arc switches suggest that the arc expands as a ring. The reason why the switch shown in Fig. 36 is credited with only 2 : 1 improvement (instead of 6 : 1 as in Fig. 35) is because Fig. 36 shows a higher-voltage circuit breaker which requires larger insulation clearance.

As Mr. Gregory assumes, the breaking-capacity formulæ on page 1102 represent the law according to which reputable British manufacturers design their switch enclosures, and the basis of the formula $\sqrt[3]{(PV)}$ is now used to formulate mechanical tests for circuit breakers of the standard type. There is undoubtedly a universal feeling that present-day oil circuit-breaker designs are not final; the introduction in recent years of several new switching devices is good evidence of this.

Prof. Thornton's authoritative support of my method of distress measurement, the properties of arcs and the ignition of gases is welcomed. His calculations of the relationship between pressure and distress is similar to calculations which I carried out some time ago. He also shows that the law demonstrated in Fig. 25 is that the stress limit is proportionately to the radius of the equivalent single gas cavity.

Mr. Carter is correct in his assumption that the ring in the stabilized arc switch acts as a magnetic shield; the ring probably also shields the arc from turbulence and other disturbances. Stabilization in the switches shown in Figs. 35 and 36 is carried out electrically, and by the method, referred to on page 1104, of using the metal discs as guiding contacts. British Patent No. 9714 referred to in Section 7 covers methods of stabilizing by magnetic, electrical and mechanical means. In the circuit breakers referred to by Mr. Carter, stabilizing is effected by keeping the arc of a constant fixed maximum length and of maximum cross-section. In the two switches illustrated in Figs. 35 and 36 the arc is similarly of constant length. Properly controlled, a moving arc is not an unstable arc: in the quenched-arc breaker the arc moves and is stable.

I agree with Mr. Harle that there is no advantage to be gained by increasing the contact size beyond certain limits. A very large number of tests would be necessary in order to obtain the average and maximum values of arc energy as Mr. Harle suggests; and, when obtained, the results still remain unrelated to the mechanically stressed condition of the tank walls. The pressure discs were arranged to be as near as possible to the arc, and they were always embedded in the tank walls. Table 8 is not a comparison but actually shows inconsistency of results. Not only the quenched-arc breaker, but any switching device, would be critical in its action at the point implied by Mr. Harle, that is when exceeding its maximum breaking capacity, and I anticipate no difficulty in so designing the quenched-arc switch that proper limits are not exceeded. The switch shown in Fig. 35 has been tested on short-circuit on considerably larger amounts of power than it would handle as a plain oil switch. Its breaking-capacity limit must therefore be greater than that of a conventional oil switch of the same general dimensions. The maximum breaking capacity will probably soon be determined by means of the testing plant referred to by Mr. Clothier. In the arrangement shown in Fig. 37, there is no intention of switching additional load on to the machines. Switching would take place only under fault conditions and the value of the power to be broken would be considerably less than with a short-circuit under ordinary (unregulated) conditions. I agree that the reduction in the peak value would probably only be of the second order on a solid-rotor machine, but such reduction is still of useful magnitude. The test carried out by Mr. Harle was valueless because of the small amount of inductance used.



Open-circuit voltage = 5 000 (R.M.S.)

FIG. G.

In reply to Mr. Brierly, I do not suggest that the designed speed of a high-voltage breaker should be lower than for a low-voltage breaker. I contend that there is a factor which points to the need for a lower speed: there are other factors which argue a higher speed (see page 1095). It has already been pointed out that pressure cannot accumulate inside the stabilizing ring of the stabilized-arc circuit breaker. In my investigation I adopted the first cycle of current in preference to the method advocated by the International Electrotechnical Commission, in order to avoid possible confusion in measuring the duration of the pre-breaking time. There should not be any difficulty in calculating the current at the moment of breaking; only the decrement is required and this can be obtained in a moment from an oscillograph record. Fig. G shows an oscillograph record of a test of the magnitude referred to by Mr. Brierly: it shows the quenched-arc breaker in Figs. 31 and 35 dealing with over ½ million kVA.

COMPARISON OF DE-ION GRID AND QUENCHED-ARC BREAKERS.

De-ion Grid.	*Quenched-Arc.*
(1) Employs plates of Fullerboard, which would appear to be liable to charring or burning by arc.	Employs thick metal plates: nothing to burn.
(2) Arc is lengthened and bowed out by magnetic field, which produces instability and a considerable amount of heat.	Arc is maintained of constant form and of limited fixed length; is a fraction of the length of the "de-ion grid" arc.
(3) Arc is drawn between two adjacent slots formed in Fullerboard strips. There would appear to be danger of arc and gas bubble spanning the gap and short-circuiting the breaker.	Arc is drawn in a symmetrical condition and is surrounded by metal plates. Is insulated all round, thus no danger of arcing across.
De-ion Grid.	*Quenched-Arc.*
(4) Operation depends upon gas bubble breaking through arc, and is thus explosive in action; moreover, the two arcs of a given pole may be blown together.	Action quiescent. Arcs are isolated from one another.
(5) Construction relatively delicate, embodying a pile of Fullerboard sheets and a similar pile of magnetic horseshoes.	No magnetic system required.
(6) Oscillograph records show an arcing voltage envelope of considerable area; comparable with, and having the characteristics of, an ordinary arc in oil or oil gas.	Arc wave-form is smooth and much smaller in area, about one-tenth.
It is stated that energy released in arc is 1/12th to 1/15th of that in an ordinary oil circuit-breaker, and this implies that breaking capacity is proportionately greater than in oil circuit-breaker.	Energy released by arc 1/100th of that in ordinary oil circuit-breaker.
(7) In consequence of foregoing, heat available for explosive effects is relatively large.	Non-explosive action.
(8) Oil has free access to arc.	Arc is almost completely shielded from oil and practically no cracking can take place.

It is debatable whether the expression "de-ion grid" is properly used to describe this circuit breaker. It implies a parallel to the " de-ion " air circuit-breaker, but the strips of laminated material in the 'de-ion grid " are Fullerboard (not metal) and are *necessarily* used to support the magnetic field system, which must be laminated otherwise it would short-circuit and bridge the main contacts.

COMPARISON OF DE-ION AND QUENCHED-ARC BREAKERS.

De-ion Breaker.	*Quenched-Arc Breaker.*
(1) Large number of plates to limit voltage to about 150 volts per gap.	Small number of discs at about 1 000 volts per gap.
(2) Thin metal is used for the plates and appears to be liable to severe burning.	Heavy discs or plates are used. (About 8 times as thick as the " de-ion " breaker plates.)
(3) Magnetic field is required to force arc into plates. The magnetic field is provided by coils which have to be excited from some outside source, or from the high-tension circuit, and which are near the arcing zone.	The arc travels automatically between the discs and no magnetic field or parallel assistance is required.
(4) Air break—probably greater chance of flash-over (out of 82 published tests there were 2 internal short-circuits in the breaker).	Break is surrounded by oil and out of 100 short-circuit tests no breakdowns have been experienced.
(5) Air insulation—consequently great space required for clearance.	Oil insulation which prevents hot gases short-circuiting conductors or forming a path to earth, and economizes in space.
(6) Arc is drawn in narrow slot between large numbers of thin metal edges.	Arc is drawn in a hole in the midst of the plates against metal faces approximately ½ in. thick.
(7) Construction is relatively complicated.	Construction relatively simple.
(8) Requires entire circuit-breaker structure to be re-designed, thus necessitating the commencement *de novo* of circuit-breaker design troubles.	Can be built into existing circuit-breaker structures, thus eliminating " teething " troubles.
(9) Maximum power interrupted on test is 300 000 kVA at 12 700 volts open circuit.	Maximum power interrupted on test is 250 000 kVA.

LOW POWER-FACTOR MEASUREMENTS AT HIGH VOLTAGES.

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[From the National Physical Laboratory.]

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SUMMARY.

The paper describes a study of methods of measuring dielectric losses which has been carried out with the object of determining the nature and magnitude of the various errors to which different methods are liable. The most important errors are those due to stray capacitance currents, which affect especially the phase angle of the currents in resistors commonly used in wattmeter methods. A method is developed of shielding a simple resistor of flowing water, so that the current is in phase with the voltage within about 0·0001 radian. A resistor has been developed on these lines for 150 kV.

The standard of reference has been a specially designed air condenser of the parallel-plate type. The separation of the plates is variable; and at 10 cm separation, suitable for 100 kV, the capacitance is about 500 cm. The curvature of the edges and of the guard plates was decided as a result of studying the electric stress distribution by models in an electrolyte. The use of a condenser with the Schering bridge form of circuit has been found to be almost free from errors of importance which are difficult to allow for. The work has been carried out for the British Electrical and Allied Industries Research Association, more particularly with reference to the measurement of the power loss in cable dielectrics.

INTRODUCTION.

For some time past work has been in progress at the National Physical Laboratory on the study of methods of measurement of dielectric loss at power frequencies and high voltages, and satisfactory methods and apparatus have been evolved for use at voltages up to 150 000 or 200 000 volts.

The work has been directed chiefly to methods applicable to high-voltage cables. The power absorbed in the dielectric is one of the few physical properties of a cable which can conveniently be measured, and its variation with temperature, voltage and frequency is regarded as affording valuable information as to the quality and condition of the cable.

Measurements at high voltages, and apparatus suitable for high voltages, are liable to certain types of error due to interaction between different parts of the circuit. Owing to capacity effects, currents are introduced into the measuring apparatus which alter the phase relation between current and voltage and seriously affect the accuracy of the measurements.

The power factor of modern high-voltage cables is usually less than 0·01. It is important to be able to measure this quantity with some accuracy, and sensitivity and accuracy to a value of 0·0001 have been aimed at and achieved. Power factors, when small, if expressed as a fraction of unity denote, as a fraction of a radian, the amount short of a right-angle by which the current leads the voltage, and phase angles of resistors and other measuring apparatus expressed in the same unit can be directly added.

LINE OF INVESTIGATION.

By various methods, including those in general use, the power factor of a condenser load was measured, and the results obtained by the different methods were compared. For this purpose a load of constant power factor was desirable, and a mica condenser of 5 000 $\mu\mu$F capacity, designed for radio frequencies and 40 kV, was kindly lent by the Dubilier Condenser Co. This condenser was found to have a power factor of 0·0013, which proved to be a convenient value for the various methods. During the earlier part of the work the apparatus available—high-voltage wattmeter, resistor and air condenser—was only suitable for 20 000 or 30 000 volts.

Large discrepancies were observed between the results obtained by the different methods; but, partly through studying the variation of discrepancies with frequency and voltage, the various sources of error were eventually determined and agreement to 0·0001 power factor was reached by all the methods.

At this stage it was clear which methods were suitable for carrying on the work to higher voltages, and that an air condenser and some form of resistor were required. An air condenser and a water resistor for 150 kV were developed, were checked directly against each other as standards, and led to similar results when used to measure the power factor of a length of cable. Accounts of the condenser and resistor are given in the section dealing with standard apparatus.

METHODS OF MEASUREMENT.

The methods available may be divided into those which measure power, requiring also the measurement of voltage and current; and those which, measuring the phase angle, give the power factor directly. For the former some kind of wattmeter is required, while in the latter case a circuit adjustment is made to balance some type of bridge arrangement or to reduce to zero the deflection of a wattmeter.

The method least susceptible to error is that which uses a high-voltage electrostatic wattmeter,* the full voltage being applied to the needle and the quadrants being connected to the ends of a variable resistance in series with the capacity load, as shown in Fig. 1. Readings with different values of quadrant resistance are taken, and extrapolation to zero resistance gives the power loss required. Observations by this method proved of great value in indicating the errors in other measurements. On account of its dimensions, however, an instrument suitable for 20 kV has a long period of swing and is troublesome to use; several observations are necessary in order to obtain a value for the power factor, and the instrument has not the desired sensitivity. For these reasons the method was not developed for higher voltages.

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* E. H. RAYNER: "High-voltage Tests and Energy Losses in Insulating Materials," *Journal I.E.E.*, 1912, vol. 49, p. 3.

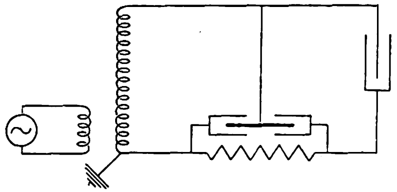
FIG. 1.—Electrostatic wattmeter. Full voltage on needle.

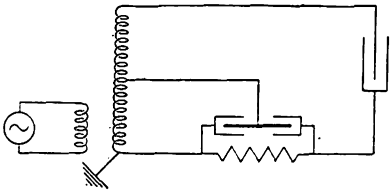
FIG. 2.—Electrostatic wattmeter. Half voltage on needle.

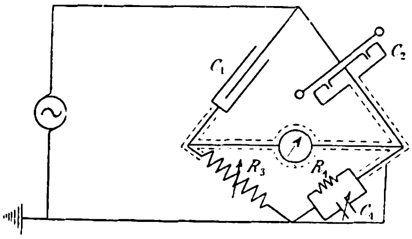

FIG. 3.—Schering bridge—shields earthed.

Low-voltage wattmeters, either electrostatic or electrodynamic, may be used with some arrangement for supplying a low voltage or current in phase with the high voltage. A step-down transformer, tertiary winding, or a tapping on the high-voltage winding of the transformer are frequently used for this purpose, but are liable to errors. The method is illustrated by Figs. 2 and 6. The low voltage can be more satisfactorily obtained by a resistance potential-divider of suitable design. Capacity effects introduce error into a very high resistance; but by shielding with screens maintained at suitable potentials the error may be reduced to zero or accurately calculated * (Fig. 5). With such a resistor a low-voltage wattmeter may be used either to measure power loss, or by a null method to measure the power factor direct. The resistor current flows to earth through one element of the wattmeter, and the condenser current flows to earth through the other element. Figs. 7 and 8 illustrate these methods. If, in the null method, the resistance of the wattmeter element is small compared with the total resistance to which the high voltage is applied, the magnitude of the high resistance does not enter appreciably into the expression for power factor. The wattmeter element, of resistance R, is shunted by a variable capacity C, or alternatively, in the Emanueli circuit, has a variable inductance L placed in series with it, a resistance S being connected across the two. When the value of these has been adjusted so that the deflection is reduced to zero, the power factor is given by the expression $RC\omega$ or $L\omega/(R + S)$, where ω

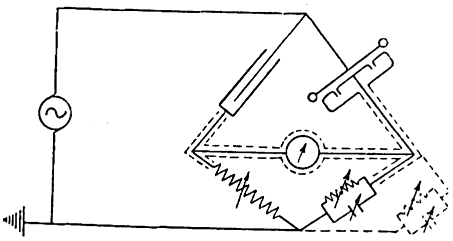
FIG. 4.—Schering bridge—shields balanced.

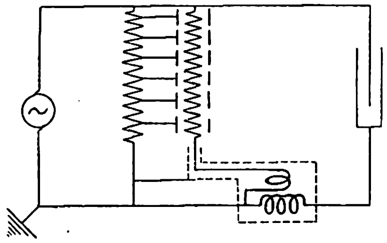
FIG. 5.—Dynamometer direct method with shielded wire resistor.

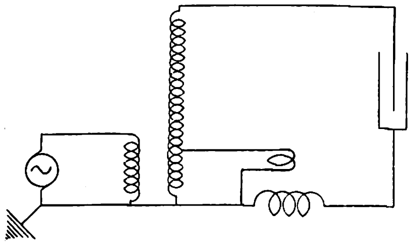
FIG. 6.—Dynamometer with transformer tapping.

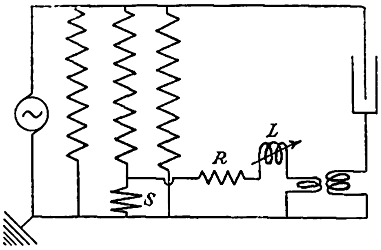

FIG. 7.—Compensated dynamometer, with shielded water resistor. Inductance compensation.

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* E. ORLICH and H. SCHULTZE: *Archiv für Elektrotechnik*, 1912, vol. 1, p. 88. SILSBEE: Scientific Papers of the Bureau of Standards, No. 516; R. DAVIS: "The Errors associated with High Resistances in Alternating-Current Measurements," *Journal of Scientific Instruments*, vol. 5, pp. 305 and 354.

$= 2\pi \times$ frequency. The compensated methods are particularly convenient. The capacity compensation is the more sensitive, as a greater current passes through the wattmeter element. It is desirable to keep the resistance of the wattmeter elements low, and for this reason, and on account of its robustness, a dynamometer is a more suitable instrument than an electrostatic wattmeter. An advantage of the null method is that the magnitude of the high-voltage resistance, if sufficiently large, does not affect the balance adjustment. Flowing water, the resistivity of which varies with voltage and rate of flow, can therefore be used, and provides the only type of resistor feasible for use at high voltages without very great trouble and expense.

A resistor of uncertain magnitude would be practically useless, however, for bridge measurements requiring constancy of circuit quantities. The most suitable form of bridge is the Schering bridge arrangement, having condensers in the high-voltage arms and resistances in the low-voltage arms. For such methods a high-voltage condenser of known power factor is required as a standard. A loss-free condenser is a simpler problem than a resistance without inductance or capacity; and the Schering bridge is the most convenient of all the methods to use.

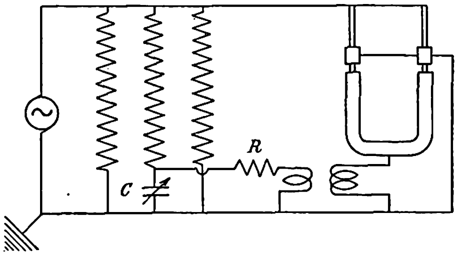

FIG. 8.—Compensated dynamometer. Capacity compensation.

Figs. 1 to 8 show the various methods tried.

SOURCES OF ERROR IN POWER-FACTOR MEASUREMENTS.

Errors in High-Voltage Apparatus.—With the exception of the high-voltage electrostatic wattmeter method, which is cumbersome and unsuitable for very high voltages, all the methods make use of, or must be calibrated by, a standard of phase angle—either a resistor or a condenser. The design of standards of known phase angle is considered in the section dealing with standard apparatus, and particulars are given of types which have proved satisfactory at 150 000 volts.

In methods using a low-voltage wattmeter the voltage element is sometimes excited by a step-down transformer, or by a tertiary winding or a tapping on the secondary winding of the high-voltage transformer. These devices may introduce large phase-angle errors; in the case of a transformer with a 1/200 tapping, errors between 0·005 and 0·01 radian were observed. Such phase angles naturally vary with transformer load and voltage, and equipments of this kind require calibration under actual conditions of use.

Errors in Low-Voltage Apparatus.—Errors may be inherent in the wattmeter used. The effect of self-inductance in the wattmeter elements in series with very large impedances is negligible, and so is the effect of mutual inductance, except in the case of a dynamometer if some of the turns are short-circuited. Self-capacity, however, may shunt part of the current in one element, causing a power-factor measurement to be high if the effect occurs in the current element. Self-capacity in the voltage element makes the measurement give too low a reading, so that this error can be detected by interchanging the current and voltage elements, if their current-carrying capacities permit. An instrument with very small values of inductance and capacity is desirable, and a sensitive dynamometer made by Messrs. H. Tinsley and Co. has proved of great use. The coils are all contained in a space about $1\frac{1}{4}$ in. square by $\frac{1}{2}$ in. The moving coil has a resistance of 40 ohms and is rated at 20 mA. The fixed coil is in 10 sections which can be connected in series-parallel arrangements for 0·02, 0·04, 0·1 and 0·2 ampere, the resistance of all sections in series being 450 ohms. At first no appreciable difference was observed between ranges, but later the lowest range developed an error of 0·0003 radian. By interchanging voltage and current coils and taking the average reading this error has been eliminated. It is thought to be due to increase of self-capacity of the fixed coils, due perhaps to softening of insulation through overloading. The effect would naturally be greatest on the range of highest resistance.

It may be necessary to make a correction for the loss in the coil carrying the condenser current. If this coil has a resistance r, and the condenser has a capacity c, the power-factor reading is too large by the amount $rc\omega$.

Low resistances of 1 ohm or less, used for large capacity currents in bridge measurements when considerable lengths of cable are tested at high voltages, may be slightly inductive. Their phase angles, of the order of 0·0001 or 0·0002 radian, can be easily measured at low voltage by audio-frequency bridge methods. When such resistances are used in a Schering bridge, care should be taken that the earth and galvanometer connections are made to the proper points, as the inductance added by using a foot or so of lead may appreciably alter the phase angle of a low resistance.

Errors due to capacity effects.—In high-voltage measurements there is often electrostatic interaction between different parts of the circuit, and errors may be caused by capacity between the low-voltage apparatus, or the leads connected to it, and high-voltage conductors. The magnitude of such errors depends on the equipment and set-up; but it is usually essential for the low-voltage lead from an air condenser or resistor to be protected from this source of error, though in the case of a load of high capacity (such as a cable coiled on a drum) protection may not be necessary. The simplest way of removing these errors is to shield the low-voltage leads and apparatus by metal screens connected to earth, as shown in Fig. 3. In Schering bridge equipment the leads and galvanometer can conveniently be shielded at their own potential by connecting their shields to the guard plates of the air condenser, placing a resistance between these and earth, and balancing against the other arms of the bridge, as indicated in Fig. 4. Sometimes, instead of earthing the transformer an earth connection is made to an auxiliary pair of balanced bridge-arms, for example, to the guard plates of the air condenser, a resistance being connected between these and the transformer. This device, termed a " Wagner earth," eliminates the effect of the earth capacity of the galvanometer and the leads. When leads are shielded by earthed screens one source of error is increased. If R be the resistance of the low-voltage arm of a bridge, or of a wattmeter element, and if the lead to it have a capacity C to earth, a phase error $RC\omega$ is introduced. If the error is on the side of the standard, a power-factor measurement gives too low a value; if the error is on the load side the value obtained is too high. These errors may be eliminated by shielding the leads by screens connected to auxiliary apparatus at the same potential; but this arrangement is not always convenient and requires a separate balance adjustment, as seen from Fig. 4. The magnitude of the errors may be observed by taking observations with different values of resistance. The error is proportional to the resistance, and extrapolation to zero resistance gives the value required. Alternatively, the capacity may be measured and the error calculated.

Electromagnetic Effects.—With a sensitive instrument like a vibration galvanometer of the type used in bridge measurements, electromagnetic as well as electrostatic shielding may be required. Near the high-voltage transformer it was found impossible to use a moving-iron instrument, except inside a case of magnetic material. Some distance away the effect was negligible.

Errors associated with the Load.—In the measurement of the properties of small lengths of cable two precautions are necessary. Owing to leakage and tangential electric stress in the paper insulating material, a considerable loss of power occurs at the ends. To eliminate this from the measurements guard rings should be placed over the paper beyond the lead, as shown in Fig. 8, otherwise the error may be as large as the quantity being measured. Even on a 200-yard length the effect may not be negligible, if the stripped ends are protected against flash-over, e.g. by semi-conducting paper,* for measurements at very high voltages. A few inches of guard-ring beginning 1 in. or ½ in. beyond the lead covering may suffice. In the case of some measurements on a 50-ft. length of 66-kV cable a gap of 1 in. was found to introduce an error of 0·0001.

The other possible source of error is connected with the capacity between a high-voltage line and its cable sheath. If ionization is present around the line, impure capacity current, which is in parallel with the cable under measurement, has a bad power factor and may introduce a serious error. On a 50-ft. length of cable an error of 0·001 was observed when using a high-voltage line of No. 18 S.W.G. wire at 100 000 volts. The capacitance between the line and cable sheath was only 1/200th of the cable capacitance, but its power factor was about 0·2. The error was removed by using a high-voltage line 1 in. in diameter, at which size ionization did not occur, or by shielding the cable sheath with an earthed screen of wire netting.

Effect of Wave-form.—A consideration of power factor and power-factor measurements with a voltage supply of bad wave-form is given in Appendix 3.

STANDARD APPARATUS.

In the absence of ionization, the loss in air under electric stress is so small that an air condenser having sufficiently small resistance in its plates and leads is practically a pure reactance, and forms the most reliable and easily constructed standard for measuring phase angles at high voltages. Care is necessary to ensure that the low-voltage plate is influenced by nothing but the high-voltage plate, and only through air dielectric. The errors due to incomplete shielding of the low-voltage plate are sometimes surprising, and some account of the magnitude of such errors, met with in the development of the N.P.L. condenser for 150 kV, may be of interest.

Design of Condenser.—Condensers for high voltages may be of the flat-plate or cylindrical form, but for research purposes of the type dealt with in this paper a plate condenser has advantages; and it was decided to use a high-voltage plate between two low-voltage plates. A capacity large enough for direct comparison with a resistor standard by a dynamometer method can conveniently be obtained with this design, and the two sides of the condenser can be compared under different conditions, which was found to be a most valuable feature.

TABLE 1.

Separation of plates	Flash-over voltage	
	Unpolished	Polished
cm	kV	kV
10	100	135
15	135	185
20	165	220
30	200	260

NOTE.—These figures are subject to considerable variation, and higher values have been observed.

The condenser is illustrated in Fig. 14, and is described in Appendix 1 with a consideration of the shape of the plates to avoid ionization at the edges.

Conditions affecting the Behaviour of the Air Condenser: Effect of Surface on Power Factor.—A few sharp protruding edges and points on the surface of the plates can introduce a power factor, depending on the voltage, through local ionization. Removal of the points, and the smoothing of scratches into hollows without sharp edges greatly reduces the trouble. An error of 0·0004 radian was removed in this way.

Effect of Surface on Flash-over.—The flash-over voltage was observed for various separations, in order to determine at what voltages the condenser could be used. Measurements made with one side polished and one unpolished are given in Table 1, and show a considerable increase due to polishing.

Effect of Time on the Surface.—About 10 weeks after the initial polishing, phase-angle measurements were made before and after repolishing. No change was detected. Hence the polishing process need not be frequently repeated.

Effect of the Wooden Framework carrying the Low-

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* E. A. BEAVIS: "Some Developments in the Routine Pressure-Testing of High-Voltage Cables," *Journal I.E.E.*, 1928, vol. 66, p. 1086.

Tension Plates.—It is necessary to ensure that no insulation which can affect the low-voltage plate is subject to high-voltage electric fields. Such insulation must be surrounded by a conductor at a potential which cannot introduce error into the condenser. Referring to Fig. 14, the struts CC were found to introduce a power factor of 0·0006 for a separation of 40 cm. At this separation the wood is evidently to be regarded as part of the dielectric between the high-voltage plate and the surface (DD, Fig. 14) of the low-voltage plate, and it introduces loss. Covering the struts with tinfoil connected to the guard removed this error.

The horizontal members of the frames, the portion to which the porcelain supports were bolted and the concrete floor under the condenser, were found not to produce a measurable effect.

Effect due to Porcelain Insulators.—The low-voltage plate is supported by 10, and the guard plate by 12, porcelain insulators (EE, Fig. 14) which pass through holes 10 cm in diameter in the back of the guard plate. It was found necessary to cover the exposed porcelain and the holes with tinfoil connected to the guard plate, otherwise an error of 0·0007 negative power factor was introduced for a separation of 40 cm between plates.

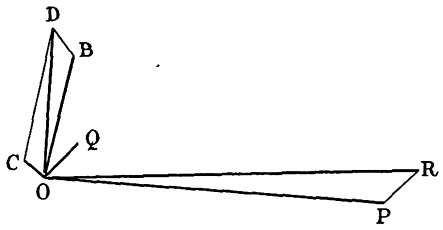

FIG. 9.—Vector diagram explaining apparent negative power factor.

OR = voltage on condenser.
OP = voltage between h.t. line and porcelain.
OQ (= PR) = voltage on porcelain.
OD = capacity current to porcelain.
OC = current from porcelain to low-tension plate.
OB = current from porcelain to guard.

The effect was only observed on that side of the condenser facing the high-voltage line, and the following explanation is suggested: The porcelain insulators have a small capacity to the high-voltage line and so receive a small current leading by 90° relatively to the voltage. This current goes partly to the guard plate and partly to the low-voltage plate. The exposed porcelain is quite close to the guard plate but relatively remote from the low-voltage plate. Thus the capacity between the porcelain and the low-voltage plate has a considerable air space as dielectric and will have small loss, while the capacity between the porcelain and the guard plate is likely to be larger and to have a bad power factor. Reference to the vector diagram (Fig. 9) will show that the current from the porcelain to the low-voltage plate may be in advance of the voltage on the condenser by considerably more than 90°; so that, although very small in magnitude, it may have an appreciable influence on the phase angle of the total current reaching the low-voltage plate. The total current at the low-voltage plate may thus be more than 90° in advance of the voltage, the condenser having, apparently, a negative power factor.

Effect of the High-Voltage Connection.—With a separation of 40 cm a connecting wire of No. 18 S.W.G. in the position FF (Fig. 14) increased the power factor of this side of the condenser at 90 kV by 0·0005 above that with the conductor vertical. The error was reduced by 0·0004 by using a conductor 1 in. in diameter. The effect is evidently due to some capacity between the conductor and the surface DD, combined with power loss due to ionization at the surface of the wire.

Potential of the Guard Plate.—By inserting a suitable impedance between the guard plates and earth and balancing the guard potential against that of the measuring plates, ideal shielding of the low-voltage plate may be effected. Usually, however, it is more convenient to earth the guard system. The capacity between the low-voltage plate and the guard system then shunts the low-voltage apparatus in series with the condenser and acts as an addition to C_4 (Fig. 3); such capacity must, in consequence, be allowed for.

The importance of a good connection between earth and the guard system may not be obvious; but serious errors may be caused by a high resistance in this part of the circuit. A resistance of 1 000 ohms, for example, may cause the guard plates to acquire a potential of a few volts in quadrature with the voltage on the condenser, and to introduce into the low-voltage plate a small current 90° in advance of the condenser current from the high-voltage plate, producing an apparent negative power factor. Such a contact resistance of 1 000 ohms put the N.P.L. condenser in error by 0·0008 radian. An error of this nature was found in a condenser sent to the Laboratory for examination. The error disappeared on making a more positive connection.

The importance of definiteness of contact in apparatus and instruments for dealing with capacitance currents at low and high voltages cannot be too much emphasized. In the case mentioned, reliance had been placed on the contact between the flange of a hole and the nut of a bolt 1¼ in. in diameter passing through it, which would normally suffice for large currents. Though in many cases a moderately high resistance in circuits involving electrostatic currents may have no appreciable effect on the measurements made, yet such resistances may at times be very high indeed until broken down by an appreciable current passing. For such reasons it is sometimes found that unsatisfactory results are obtained owing to obscure causes which are remedied by a sufficient current, such as flows on the flashing-over of a high-voltage condenser by raising the voltage until this occurs. In fact, experience shows that the occasional flashing-over of an air condenser, making measurements on some load before and after, may be found useful as a test of its condition. A "cleaning up" effect of flashing-over is not uncommon. Though every care may be taken to keep condenser plates clean, it very frequently happens that the first of a series of flash-overs made between surfaces at high voltage is notably less than the later ones. An increase of about 20 per cent may take place.

Design of Water Resistor.—A column of flowing water forms a valuable resistor for use at high voltages because of the high loading which is possible. High resistances of negligible capacity for use at high voltages are impracticable, but by using a material which can be continually discarded as it becomes hot the dimensions, and hence the capacity, of such resistances can be greatly reduced. The disadvantage of a water resistor is its indefinite and variable resistance, making it unsuitable for use as a precision resistor or for measurements of power by a direct wattmeter method. For phase-angle measurements by a compensated wattmeter method, however, this variability does not matter, and such methods are more convenient to use than deflectional wattmeter methods, and give the extra sensitivity usually associated with null methods.

The effect of earth capacity on an unshielded resistor may be illustrated by the case of a column of resistance material 2 m long, 1 cm in diameter, and of resistance 1 megohm. The current in such a resistor would lag at the low-voltage end behind the voltage across the whole by about 0·001 radian, and would lead at the high-voltage end by about 0·002 radian. 1 megohm at 150 kV would dissipate more than 20 kW, and higher resistances for such voltages are generally desirable to reduce the energy to be provided and the difficulty of its disposal. It is important to note that the error is proportional to the resistance and to the length; so that increase of length for the sake of reduction of the power consumed causes a rapid increase in the phase displacement between current and voltage.

TABLE 2.

	(Power factor of air condenser) + (Angle by which resistor current leads the voltage)			
	Low-voltage end		High-voltage end	
	Measured	Calculated	Measured	Calculated
Uncompensated resistor with bent tubes	+0·0002	—	+0·0005	—
Uncompensated resistor with straight tubes	0·0000	−0·0002	+0·0005	+0·0004
Compensated resistor	+0·0002	0·0000	0·0000	0·0000
Effect of compensation	+0·0002	+0·0002	−0·0005	−0·0004
Compensated resistor with centre tubes 1 cm high ..	+0·0004	—	0·0000	—
Effect of raising centre tubes 1 cm	+0·0002	+0·0001	0·0000	−0·0001
Compensated resistor with centre tubes 1 cm low ..	0·0000	—	+0·0001	—
Effect of lowering centre tubes 1 cm	−0·0002	−0·0001	+0·0001	+0·0001

Capacity errors would be eliminated if the resistor were shielded at every point by an electric field at its own potential. This is to a very considerable extent practicable by surrounding the main water column by others to which the same voltage is applied. Various arrangements have been assembled with 0, 3, 6 and 12 guard tubes, of resistances in the central water column from 1 to 4 megohms, and of lengths from 2 to 4 metres. The reduction in capacity under practical conditions may be 95 per cent. Methods of calculating the capacity effects are described in Appendix 2. The close agreement (to 0·0001 or 0·0002 radian) between calculation and experiment indicated the possibility of the construction of resistors which could be regarded as standards, their phase angle being determinable from their design. The number of guard tubes used in the final construction was 12; but the main water column has still a small capacity to earth as the shielding is not complete. The effect of this may be counteracted by prolonging the main tubes beyond the guard tubes at the high-voltage end. By this compensation the current in the main tube at both high- and low-voltage ends can be caused to be in phase with the applied voltage.

A description of the resistor finally constructed and used at 150 kV is given in Appendix 2, together with methods of calculating capacities and capacity effects, and the temperature-rise of the water. On account of the large temperature coefficient of the resistivity of water, the temperature-rise depends considerably on the inlet temperature. For voltages of 50 kV and upwards the local water supply, of resistivity 3 000 ohms per cm^3, was unsuitable, and distilled water of 30 000 ohms resistivity was used in a circulatory system containing a cooler. Even with water of this resistivity temperatures were reached at which serious distortion of the tubes occurred. Experiments on sample tubes of a new mixture of Keramot recently supplied indicate much greater mechanical rigidity in the new material at temperatures near 100° C., and a resistor of more satisfactory geometrical stability might be constructed of this material.

COMPARISON OF AIR CONDENSER AND WATER RESISTOR.

The two sides of the large-plate air condenser were compared directly by a Schering bridge, and measurements were made against the resistor by a compensated dynamometer method at voltages up to 150 000, and by a bridge method up to 80 000 volts, above which the resistance of the water was not sufficiently steady for bridge measurements. When the errors referred to earlier had been eliminated it appeared that the condenser had the same power factor at all distances up to 30 cm, and at all voltages up to 150 000 volts. (There appears to be a slight increase of power factor with voltage at 40 cm separation.) This is strong evidence that the power factor is small, for any power loss would be expected to vary with one of the variables, either distance or voltage. The measurements against the water resistor give the sum of the power factor of the condenser and the phase angle of the resistor. The results are given in Table 2 and the figures agree closely with the calculated angle of the resistor, confirming the conclusion that the power factor of the condenser is negligibly small. Measurements at the high-voltage end of the water tube could not be made above 100 kV, as the wooden frames carrying the guarded plates of the air condenser would not withstand higher voltages. They were made of pitch pine. If methods involving the use of the measuring plates and instruments at high voltages were regarded as important, it would be better to use American whitewood which, in a plain unvarnished condition, has been found to have exceptionally good insulating properties.

The results obtained, indicating close agreement between such different types of apparatus, appear sufficient to justify the use of condenser or resistor for making phase-angle measurements with an accuracy of the order of 0·0001 radian.

Recent measurements of air condensers sent by cable manufacturers for comparison have provided confirmation of the " purity " of the N.P.L. condenser. As far as the evidence goes (i.e. up to 150 kV), no measurable power factor appears before flash-over, and at 20 cm separation the condenser appears to be suitable for use at 200 kV. Measurements on a length of cable of about 50 ft. have actually been made at 190 kV. The condenser is simple in theory and design, requiring no high precision in dimension. It involves no great difficulty (beyond that of space) on account of the high voltage.

On the other hand, a resistor using a closed water circuit is a relatively troublesome piece of apparatus requiring the maintenance of high resistivity in the water and geometrical accuracy in construction. For these reasons it is not so convenient or so reliable a standard as an air condenser of good design.

CONCLUSION.

The authors' conclusions are that an air condenser designed on the lines indicated in this paper is the most reliable standard for phase-angle measurements, and that by its use, and taking the necessary precautions, accurate measurements should be obtained on a Schering bridge. If other methods are employed it is desirable to calibrate the equipment under actual conditions of use against an air condenser.

It is to be noted that the most suitable methods of measuring power factor have proved to be those which measure the quantity desired most directly and conveniently. Of the two principal methods available, the Schering bridge and the compensated wattmeter method, neither requires a knowledge of voltage, current, or power. The required information is obtained as a time/phase relation given in terms of the frequency and of simple variable capacitances, inductances and resistances.

APPENDIX 1.

A diagrammatic scale drawing of the condenser appears in Fig. 14. The plates are made of aluminium, riveted to steel angle-frames. The high-voltage plate is situated between the two low-voltage plates, and has a rounded edge of 3 in. radius to avoid ionization of the air. The two low-voltage plates have a surface 8 ft. (240 cm) long by 4 ft. (120 cm) high, giving a total capacity to the centre plate, at a separation of 10 cm, of about 500 $\mu\mu$F. The guard plates project 20 cm beyond the measuring plates, and cover them at the back except where holes are cut to admit porcelain supports. The low-voltage and guard plates are supported on a wooden frame by porcelain insulators of the pin type, all pins in the wooden frame being connected to guard or to earth. The frames are mounted on rollers so that separation between high- and low-voltage plates may be varied.

The high-voltage plate is suspended by porcelain rods at the two upper extremities, one from three and the other from two points in the roof. Large flat plates are difficult to obtain, and the high-voltage plate (14 ft. × 7 ft.) is 1 cm out of flat at the centre, i.e. about 10 per cent of the separation when the latter is 10 cm.

Design of the Edges of the Plates.—The design of the edges of the plates was based on the results of an investigation of the electrical stress at the surface of model electrodes immersed in an electrolytic tank. The method is used by the Aerodynamics Department of the National Physical Laboratory for studying flow past aerofoils, the hydrodynamical problem being mathematically identical with the electric-field problem. Equipotential surfaces are traced out by a pantograph attached to an exploring electrode in a tank 4 ft. 3 in. × 2 ft. 3 in. × 1 ft. deep, a valve amplifier transmitting to telephones the potential difference between this electrode (a fine platinum wire projecting from a thin glass tube) and a point chosen on a potential divider connected across the supply (Fig. 10). The main object was to study the increase of stress at the edges of the plates, trying various curvatures, so that the design could be founded on a knowledge of what reduction of working voltage might be expected due to local increase of the electric field. Typical results of these experiments are given in Figs. 12 and 13. The section of the condenser is shown diagrammatically in Fig. 11. The boundaries to be considered are the edge of the high-voltage plate (radius Q), the external edge of the guard plate (radius S), and the adjacent edges of the guard and low-voltage plates (radius R). It is desirable to make

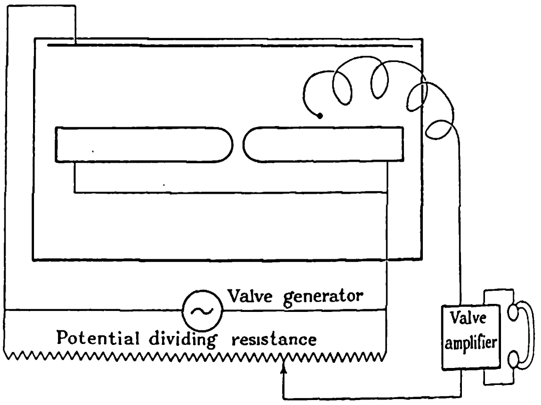

FIG. 10.—Diagram of connections in experiments.

the radius R fairly large compared with the irregularities of the flatness of the surfaces and comparable with the dimension X of the gap between the guard and low-voltage plate. From general principles, the increase in electric stress at the surfaces near such gaps in the case of a parallel-plate condenser will depend chiefly on the ratio of the curvature to the size of gap, and will be nearly independent of the distance of the high-voltage plate when this distance is fairly large compared with the gap and the curvature. A series of experiments was made, varying the gap X for a given value of R. These measurements were made for varying values of the main separation D, and the results are given in Table 3, which indicates the increase of the electric stress in the neighbourhood of the gap X, the experimental results for various gap distances being shown in Fig. 14.

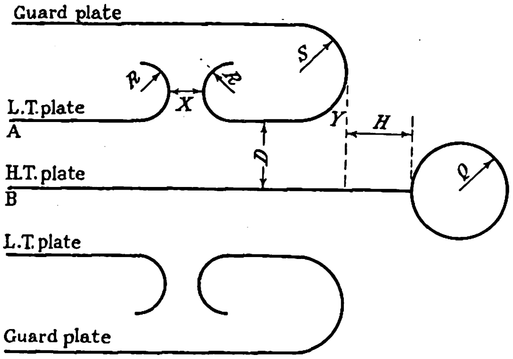

FIG. 11.—Proposed section of air condenser.

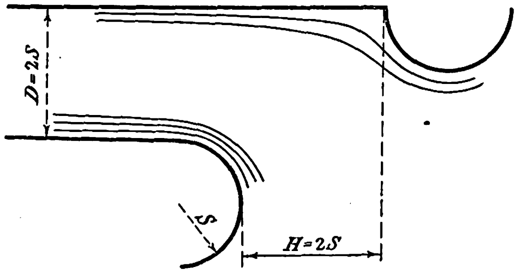

FIG. 12.—Curvature of edge of guard plate.

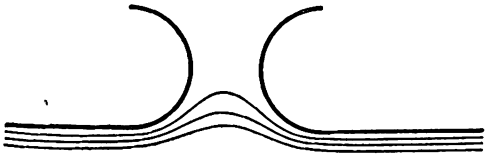

FIG. 13.
Separation $D = 2R$
Gap $= R$

The "crowding ratio" is defined as $(a - b)/a$, where b is the distance between equipotential surfaces near X where they are most crowded, and a is the distance apart of the same surfaces where the gradient is uniform at some distance from the edges. The sensitivity and consistency of the measurement of the crowding ratio, using models of a radius of curvature of 2 in., was about 0·05 and the values are given to this accuracy, with sometimes a plus or minus sign to indicate a little more or less when the measurements appeared to justify it. Table 4 gives the results for the exposed edge of the guard plate; a corresponding experimental diagram is shown in Fig. 12.

The increase in stress at the adjacent edges of the low-voltage plate and the guard plate does not appear to vary appreciably with the distance from the high-voltage plate when this distance is fairly large (Fig. 13). If the edges are rounded with a radius of a value more than twice the gap between them, the local increase in stress appears to be less than 10 per cent, at any rate for edges having a radius greater than 0·1 of the distance between high- and low-voltage plates. Smaller radii could not be accurately studied with the equipment available. The radius, S, required for the outer edge of the guard plate for the same local increase appears to be at least 0·75 of the distance between the high- and low-

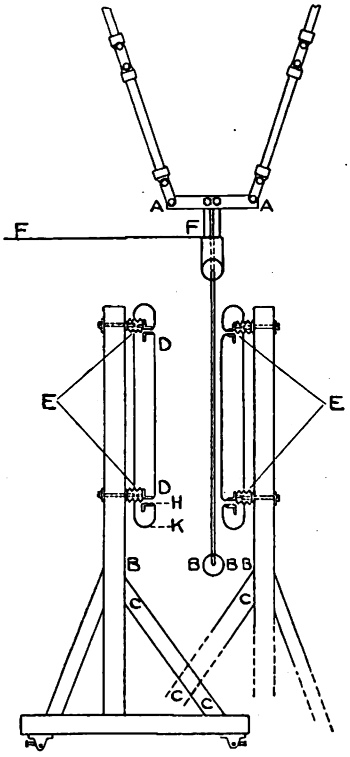

FIG. 14.—Diagrammatic drawing of air condenser.

TABLE 3.

Separation D	"Crowding ratio" at X (approximate increase of stress at bend)				
	$X = 0$	$X = 0{\cdot}5R$	$X = R$	$X = 2{\cdot}5R$	$X = 5R$
$2R$	0·1−	0·1	0·1+	—	—
$2{\cdot}5R$	0·1−	0·1	0·15−	0·2−	—
$5R$	0·1−	0·1	0·1+	0·2	—
$10R$	0·1−	0·1+	0·1+	0·15+	0·25

voltage plates. The radius Q of the edge of the high-voltage plate depends on the shape and proximity of walls, floor, etc., and may reasonably be about the same as S, that of the outer edge of the guard plate.

The values adopted for the condenser have been $X = \frac{1}{2}$ in., $R = 1$ in., $S = 3$ in., $Q = 3$ in. and $H = 7\frac{1}{2}$ in.

The results, as indicated in the description of the experiments made on the condenser, have shown that the design has proved a satisfactory engineering compromise between the various factors involved. When the voltage is raised to the flash-over point it has been found that, if the separation is 10 cm, spark-over usually occurs to the measuring plate, sometimes at the measuring plate and sometimes at the guard at 15 cm separation, and at the guard plate at 20 cm separation; so that the edges of the plates do not appear to be a source of weakness at working distances. A separation of 10 cm is suitable for measurements at 100 kV, and a separation of 20 cm for 200 kV.

TABLE 4.

Separation D	"Crowding ratio" at Y. Radius $Q = S$				
	$H = S$	$H = 2S$	$H = 3S$	$H = 4S$	$H = 6S$
S	0·1	0·05	—	0	0
$1{\cdot}25S$	—	0·1	—	0·1	0·1
$1{\cdot}5S$	0·15	0·1+	0·1+	—	0·1
$2S$	—	0·2	0·2−	—	0·15
$4S$	—	0·35	—	—	0·3

The problem of electrical stress may also be investigated mathematically.* The theoretical treatment appears to give higher values for the increase of stress at edges than those obtained by the experimental method.

APPENDIX 2.

The measuring section of the resistor consists of 2 tubes in the centre about 1 in. apart, and the guard system of 12 tubes symmetrically spaced on a circle of 9 in. diameter around the main tubes. The tubes are 2 metres long. The water flows up half the tubes and down the other half; it is circulated through the tubes and a tin-lined cooler by a small centrifugal pump lined with tin to prevent contamination. A 20-gallon galvanized reservoir is also included in the circuit. The end connections of the tubes are constructed of gun-metal castings and $\frac{1}{2}$-in. copper tubes and are also lined with tin. Glass tubing was found to be too fragile, and specially-drawn Keramot tubing was obtained from Messrs. Siemens Bros. and Co. The guard tubes are of $\frac{3}{16}$ in. internal by $\frac{1}{2}$ in. external diameter, and the main tubes of $\frac{7}{16}$ in. internal by $\frac{9}{16}$ in. external diameter, and all tubes of one size were forced through the same die in order to ensure uniformity of cross-section. Two lengths of 1 metre are joined to form a unit, and the mid-points of the "up" and "down" tubes are connected together electrically so as to maintain equality of potential distribution when the temperature-rise is considerable. Cocks are fitted, and the flow is adjusted to allow the same temperature-rise in main and guard tubes. The main tubes are supported at the top by porcelain from the guard casting, and at the bottom are connected by lengths of rubber hose to earthed joints in the water circuit. The water in these connections has a high resistance whose shunting effect on measuring apparatus is negligible, but it is shielded from the high-voltage field by an earthed screen and the shunting effect of its earth capacity must be allowed for. The tube system is surrounded by an earthed wire cage 6 ft. square.

Calculation of Capacity.—The assumption of a uniform distribution of charge implies an approximately uniform potential along the tubes. An approximate value for the capacity can therefore be derived on this assumption, and the capacity of the resistor can be regarded as approximately uniformly distributed.

Phase Angle of Resistor with Uniformly Distributed Capacity to Earth.—If at a point of the resistor the distance to the earthed end be x, the voltage V, and the current i, the total length, resistance, and capacity of the resistor being l, R, and K respectively, then the current and voltage relations are:—

$$-(dV/dx) = (R/l)i$$
$$-(di/dx) = (jK\omega/l)V$$

Writing V_1 for the applied voltage, I_1 for the current at the high-voltage end, and I_0 for the current at the low-voltage end, we obtain:—

$$(V_1/I_0) = R\,(1 + \tfrac{1}{6}jRK\omega - \tfrac{1}{120}R^2K^2\omega^2 \ldots)$$
and
$$(I_1/I_0) = 1 + \tfrac{1}{2}jRK\omega - \tfrac{1}{24}R^2K^2\omega^2 \ldots$$

The angle between V_1 and I_0 is therefore $\frac{1}{6}RK\omega$, I_0 lagging, and the angle between V_1 and I_1 is $\frac{1}{3}RK\omega$, I_1 leading.

Potential Distribution along Resistor.—The previous calculation assumes a uniform distribution of potential along the resistor.

The actual deviation from a uniform distribution is given by the expression $V_1(x/R)(\frac{1}{6}K\omega j)\{R - (x^2/R)\}$ which has a maximum value of $(jRK\omega/15{\cdot}6)V_1$ when $x = R/\sqrt{3}$.

For the guard system of the resistor described this value is about 0·001, corresponding to a length of about 2 mm of tubing, an amount which will not affect the efficiency of the shielding of the main tubes.

Compensation for incomplete shielding.—If the capacity between main tubes and guard be C_{MG} and the main tubes be prolonged at the high-voltage end by $\frac{1}{n}$-th of their length beyond the guard tubes, the phase angle of the current in the main tubes is altered and its lead increased by $\frac{RC_{MG}\omega}{6n}$ radian at the low-voltage end, and its lag increased by $\frac{RC_{MG}\omega}{3n}$ radian at the high-voltage end. The errors introduced by the capacity, C_{ME}, of the main tube to earth can therefore be eliminated by making n equal to (C_{MG}/C_{ME}). In the case of the resistor described, calculations of capacity were checked by audio-frequency measurements, whence C_{MG} and C_{ME} were found to be about 40 and $1{\cdot}3$ $\mu\mu$F, and compensation was obtained by increasing the length of the central tube by 7 cm.

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* J. D. COCKCROFT: "The Effect of Curved Boundaries on the Distribution of Electrical Stress round Conductors," *Journal I.E.E.*, 1928, vol. 66, p. 385.

Temperature-rise of the Water.—The relation between the resistivity of a solution and the temperature varies with the solute and the concentration, but experiments on the water used in the resistor described indicated that the specific resistance at $t°$ C. could be expressed in the approximate form $\rho_t = 40\rho_{20}/(20 + t)$. Probably this relation holds approximately for most water supplies.*

Using this expression it is possibie to calculate the temperature-rise in a water column.

Let ρ_t = specific resistance at $t°$ C. (ohms),
t_1 = temperature at inlet (° C.),
t_2 = temperature at outlet (° C.),
I = current (amperes),
A = area of column (cm^2),
u = velocity of water (cm per sec.),
V = voltage applied, and
l = length of column (cm).

Assuming that all the heat is carried away by the water, then at a distance x along the column:—

$$dt = \frac{I^2 40\rho_{20}dx}{4{\cdot}18uA^2(20 + t)}$$

giving
$$t_2 = \frac{20 + t_1\left(\frac{1}{2} + \frac{167\cdot 2\rho_{20}lu}{V^2}\right)}{\frac{167\cdot 2\rho_{20}lu}{V^2} - \frac{1}{2}}$$

In the case of the resistor described, with ρ_{20} equal to 30 000 and a velocity of about 80 cm per sec., the application of a voltage of 150 000 should produce temperatures of 15° C. half-way up an " up " tube, 20° C. at the top, 26° C. half-way down a " down " tube and 33° C. at the outlet, the inlet temperature being 10° C. When the inlet temperature is 20° C., the temperatures produced will be 26° C., 33° C., 41° C., and 50° C. respectively. During very cold weather, with the inlet temperature below 10° C., an outlet temperature of 25° C. was observed. In more usual conditions the following readings were taken:—

Resistor inlet	22° C.
Resistor outlet	52° C.
Cooling-water inlet	15° C.
Cooling-water outlet	20° C.

Maintenance of Water Resistivity.—During the experiments the resistivity was well maintained at 30 000 ohms for 4 months. After refilling for experiments at higher voltages than 150 000, however, the resistivity, though higher at first, was after a few days lower than before, and the question of contamination appears to be troublesome if higher resistivities are required.

APPENDIX 3.

Power Factor and Power-Factor Measurement on a Non-Sinusoidal Wave-form.—The power factor of a condenser with series resistance will be proportional to frequency, and that of a condenser with shunt leakance inversely proportional to frequency. Loss due to dielectric hysteresis, however, may be a constant quantity per cycle, thus increasing with frequency at the same rate as capacity current and maintaining a constant power factor. In the following reasoning a power factor independent of frequency is assumed, and some measurements made at frequencies from 25 to 90 cycles per sec. suggest that this may be a sufficiently good approximation for the purpose.

Power Factor.—Power factor is usually defined as watts/volt-amperes, so that power loss can be calculated from cable data. Alternating-current ammeters and voltmeters give R.M.S. values, so that the power factor determined by such instruments will be

watts/[volts (R.M.S.) × amperes (R.M.S.)].

Let e_q = R.M.S. value of qth harmonic of voltage,
i_q = R.M.S. value of qth harmonic of current, and
$a = \cos\phi$ = power factor on a sinusoidal wave-form.

For a capacity load, $(i_q/i_1) = q(e_q/e_1)$ and the expression watts/[volts (R.M.S.) × amperes (R.M.S.)] is equal to

$$\frac{\frac{\omega}{\pi}\int_0^{(2\pi/\omega)}\Sigma e_q\sin(q\omega t + \theta_q)\Sigma i_q\sin(q\omega t + \theta_q + \phi)dt}{\sqrt{\left\{\frac{\omega}{\pi}\int_0^{(2\pi/\omega)}[\Sigma e_q\sin(q\omega t + \theta_q)]^2dt\right\}}\sqrt{\left\{\frac{\omega}{\pi}\int_0^{(2\pi/\omega)}[\Sigma i_q\sin(q\omega t + \theta_q + \phi)]^2dt\right\}}} = \frac{\Sigma q\left(e_q^2/e_1^2\right)}{\sqrt{\left\{\Sigma\left(e_q^2/e_1^2\right)\right\}}\sqrt{\left\{\Sigma q^2\left(e_q^2/e_1^2\right)\right\}}}\cdot a \quad . \quad (1)$$

Measurement by Schering Bridge.—Using a tuned galvanometer, the harmonics do not affect the reading and the fundamental value is obtained.

Measurement by Compensated Wattmeter Methods.—The current in the wattmeter voltage-element is caused to lag by an angle $L\omega/(R + S)$ or $RC\omega$ (page 1133). If this angle be β for the fundamental, the angle for the qth harmonic is $q\beta$, so that the dynamometer measures

$$\frac{2\pi}{\omega}\int_0^{(2\pi/\omega)}\left[\Sigma e_q\sin(q\omega t+\theta_q-q\beta\right]\left[\Sigma i_q\sin(q\omega t+\theta_q+\phi)\right]dt$$
$$=\Sigma e_q i_q(a-q\beta)$$

The dynamometer reads zero, so that

$$\beta = \frac{\Sigma e_q i_q}{\Sigma q e_q i_q}\cdot a = \frac{\Sigma q\left(e_q^2/e_1^2\right)}{\Sigma q^2\left(e_q^2/e_1^2\right)}\cdot a \quad . \quad . \quad . \quad (2)$$

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* J. S. Carroll: "Some Features and Improvements on the High-Voltage Wattmeter," *Transactions of the American I.E.E.*, 1925, vol. 44, p. 1010.

Inspection shows that this expression is less than a, so that a low reading is obtained.

Applications to a Bad Wave-form.—During the earlier work at low voltages, measurements were made on a length of cable using a supply of approximately triangular wave-form. The results are given in Table 5.

TABLE 5.

Measurements on a Triangular Wave-form.

Method of measuring power factor	Power factor	
	At 10 kV (R.M.S.)	At 20 kV (R.M.S.)
By wattmeter (direct) ..	$0{\cdot}007_0$	$0{\cdot}016_2$
By compensated wattmeter	$0{\cdot}006_2$	$0{\cdot}013_6$
By Schering bridge ..	$0{\cdot}007_0$	$0{\cdot}016_4$

The wave-form was analysed and the formulæ (1) and (2) were calculated. The ratios given by calculation and those obtained by measurement are compared in Table 6 and, in view of the sensitivity and accuracy of the measurements at that stage of the investigation, can be considered to be in agreement.

TABLE 6.

Measurements on a Triangular Wave-form.

Ratio	Observed		Calculated
	10 kV (R.M.S.)	20 kV (R.M.S.)	
$\left(\frac{\text{Direct wattmeter value}}{\text{Schering bridge value}}\right)$ ..	$1{\cdot}0_0$	$0{\cdot}9_9$	$0{\cdot}9_5$
$\left(\frac{\text{Compensated wattmeter value}}{\text{Schering bridge value}}\right)$	$0{\cdot}8_8$	$0{\cdot}8_3$	$0{\cdot}8_5$

The Schering bridge value at 10 kV is the same as that obtained on a sinusoidal wave-form. That at 20 kV is higher, being $0{\cdot}016_4$ compared with $0{\cdot}011_6$. The cable was evidently in bad condition with much ionization at 20 kV, particularly with the triangular wave-form, which would have a higher peak voltage.

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 4TH APRIL, 1930.

Dr. L. G. Brazier: An important paragraph of the paper states that although "large discrepancies were observed between the results obtained by the different methods, . . . the various sources of error were eventually determined and agreement to 0·0001 power factor was reached by all the methods." This is a fine result, and I feel that the paragraph must cover many hours' work, and the solution of many complicated problems. As Dr. Rayner has pointed out, it is difficult to assess the absolute accuracy of power-factor measurements, and this is particularly the case when the cable is buried and the lead sheath earthed. I find it rather disappointing that the special difficulties that arise in this case have not been discussed in the paper, for it is an essential condition of a large proportion of cable research work that the cable should be buried. In carrying out these measurements an alarming number of factors which cause serious errors have been discovered. As an example, there is some curious interaction between the primary and secondary of the transformers, particularly in the case of the unscreened transformers, so that errors of 100 per cent and greater can be introduced by manipulating the primary connections; for example, by changing the voltage-regulating device from the live side of the primary to the neutral side. However, we have been able to make successful power-factor measurements on buried cables up to 10 miles in length. It is interesting that at this length the effects due to the wavelength of the 50-cycle waves are beginning to become important. The result is that the apparent power factor of the cable is always greater than the true power factor of the dielectric, and on a 10-mile length the difference may amount to nearly 0·5 per cent power factor, or 50 times the accuracy aimed at by the authors.

Mr. T. N. Riley: The paper is long overdue, and would have been invaluable 10 years ago when the question of dielectric loss in cables began to assume major importance. At that time apparatus was available in convenient form for few of the methods described, the Duddell-Mather wattmeter being practically the only type on the market. Owing to the lack of information such as the authors have now put forward we carried out in the laboratories of Messrs. Standard Telephones and Cables, Ltd., a series of comparative tests by a number of methods, including three which the authors have not mentioned in addition to those which they have described. These were the a.c. potentiometer method, the Heaviside bridge method, and the thermal wattmeter method. Time does not permit a detailed description of these to be given, but it may be of interest to say that we found the Heaviside bridge at least as accurate as, and in some respects more convenient than, the Schering bridge. The thermal wattmeter, employing a Moll thermopile, was somewhat insensitive for short-length tests, but appeared to be worth further consideration for field tests on long lengths where heavy charging currents had to be dealt with. Our conclusions were generally in accordance with those of the authors, viz. that a bridge method is most suitable for accurate work, though I do not agree that the Schering bridge has any special advantage over the Heaviside which would justify its being set up as an absolute standard. Wattmeter methods are satisfactory only if the test-results have been checked against a bridge method. The former objection to the bridge methods—that they could not be satisfactorily employed on a 3-phase test—has now disappeared, since the 3-core cable without equipotential sheath or its equivalent is now practically obsolete and only single-phase tests need be carried out. The authors' method of grouping errors according to their source may shorten the paper, but I think it would be much simpler to read if, apart from cable terminations, the errors were associated with the methods which are subject to them. The arrangement hardly brings out sufficiently that the main advantage of the bridge is not so much its freedom from errors as that, when properly set up, the errors do not vary with the applied voltage as they do in other methods. In Fig. 5 the authors show the direct potentiometer method with a shielded wire resistor. While I agree that this is the most satisfactory arrangement, there are a number of testing outfits in existence having oil-immersed resistances without the shielding. In such resistances capacity between sections causes the wattmeter to read high, whereas capacity to earth causes the wattmeter to read low. Over certain limited ranges of voltage these two effects may appreciably neutralize each other, so that the corrections to be applied are not serious even without the shielding. This applies to instruments on the low-tension side as shown. If the instruments are placed on the high-tension side the errors are cumulative, both causing the wattmeter to read high. In discussing the errors arising from a non-sinusoidal wave the authors have confined their remarks to the effect on the values as measured by different methods of test. The question should really be considered from three standpoints: (1) The real change in the loss or power factor caused by a non-sinusoidal wave, i.e. if the test results are different, is it because there is a change in the quantity to be measured rather than an instrument error? (2) The effect of the non-sinusoidal wave on the measurements made by different methods, i.e. what is the instrument error? And (3) the estimation of field losses from factory tests. (1) The watt losses are always higher with a non-sinusoidal wave than with a sine wave of the same R.M.S. value. The power factor at temperatures of the order of 30° C. is practically the same on either the sine or distorted waves. At higher temperatures the power factor is rather lower for the distorted wave, since the product of R.M.S. volts and amperes increases more rapidly than the watt loss with the higher harmonics. (2) Our conclusions as regards the effect of the non-sinusoidal wave on the methods of measurement are in accordance with the authors', but as regards the direct wattmeter method I think it should be made clear that, although the measured power factor may be the same as or slightly lower than that measured by the Schering bridge, the watt losses actually measured are higher than with a sine wave. If, therefore, a guarantee is to be met in terms of watt losses, this may be exceeded if measurements are made on a distorted wave, although on a sine wave the loss would meet the guarantee. If comparative tests are to be made on the same sample in different localities under different conditions they should therefore be made by a bridge method and in terms of power factor. (3) If the value of the power factor as measured on the Schering bridge in the factory at the fundamental frequency is used to calculate the expected field losses with the cable warm, the value obtained will, in general, be higher than the real losses if the field supply is non-sinusoidal. Any error in estimating watt loss from factory tests is therefore likely to be on the safe side.

Mr. T. R. Scott: The paper gives an excellent résumé of an extremely thorough and accurate investigation carried out by Dr. Rayner and his colleagues during the last few years. Only those in direct contact with the problems associated with dielectric-loss measurements can assess the amount of painstaking work on details required to produce the degree of accuracy in measurement recorded. It is possible, however, that the condensed version of this prolonged investigation given in the present paper may create a false impression in that it may be presumed that all the problems have been worked out and simplified to such an extent that the degree of accuracy mentioned in the paper can always be obtained in practice. This is hardly the case, for when the methods of measurement are transferred from the laboratory to the routine test-bay—or even in certain tests in the laboratory—new aspects of the general problems indicated in the paper are encountered and, in many cases, the solution of these new problems is extremely difficult. It may be of interest to examine three examples of difficulties encountered which are only touched on or altogether overlooked by the authors, viz. (1) the protection of condensers from impurities in the atmosphere, (2) end losses in cable measurements, and (3) measurements with cable sheath earthed. The authors advocate the use of one of two types of air condenser, namely, the flat-plate type as described or the cylindrical type, and infer the use of ordinary laboratory atmosphere as the dielectric. When such condensers, however, are employed in test bays in the factory, especially in locations subject to fog or impure atmosphere, troubles due to the variation of the atmosphere and its impurity are encountered. Dust, either suspended in the air or settled on the apparatus, introduces undesirable features into the dielectric characteristics of the condenser. Humidity is another enemy of accuracy and, since the relative humidity is in general continually varying, the characteristics of the condenser may also vary continuously. Data recently published[*] suggest that air condensers apparently free from loss at 50 per cent relative humidity may acquire phase angles of the order of 0·0002 radian at relative humidities in the neighbourhood of 80 per cent. This variation of characteristic constitutes a serious danger, since the condenser is the sole standard of loss, and acquisition of loss in the standard may be unobserved for some time. In this connection we have found that tests with high-voltage direct current and/or high-frequency alternating current are useful in checking up the general state of the condenser from day to day, although, of course, they do not indicate the precise loss characteristic of the instrument. While robust air condensers screened off from contamination by the atmosphere can be constructed, and are in fact in commercial production, for voltages of the order of 100 kV, the position is not so satisfactory for test pressures of the order of 150 kV. This voltage is rapidly becoming of commercial importance and, since protected air condensers appear to be difficult to construct for voltages of this order, it may become necessary to employ some other type of dielectric. Compressed gases and oils have been considered in this connection and, since both types of dielectric exhibit low loss and reasonable constancy of loss, there appears to be no objection to their use, at least as factory sub-standards. Turning to the question of end losses in cables, it is somewhat remarkable that while the authors devote more than a page to the design of the boundaries of the low-tension plate and guard ring of their air condenser, they dismiss the subject of end losses in cables in a few lines. In passing it might be remarked that, considering the cable as an impure condenser, the problem of the end losses is much more difficult than that of the air condenser in that the value of the specific inductive capacity of the dielectric is tripled and the leakance characteristic may be considerably greater. Since, as the authors state in their introduction, the variation of the power absorbed in the cable with temperature, frequency, etc., affords valuable information, it is of the greatest importance that the results obtained should be independent of end effects. Doubtless owing to the condensed nature of the paper, the authors give the impression that the difficulties encountered may be overcome easily. This may be so in particular cases such as those quoted by the authors, but in the general case, particularly where short lengths of cable have to be examined, the problem is more difficult. In a paper read before the Institution two years ago by Mr. Riley and myself* the importance of the problem was indicated and certain curves illustrating the effects encountered were given. Table A gives an excellent idea of the magnitude of the error involved. The values are abstracted from the curves quoted.

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[*] J. A. Scott, H. W. Bousman and R. R. Benedict: ' A Thermal Method of Standardizing Dielectric Power Loss Measuring Equipment,'' *Transactions of the American I.E.E.*, 1928, vol. 47, p. 824.

TABLE A.

Voltage	True power factor	Apparent power factor at guard-ring spacings of			
		¼ in.	½ in.	¾ in.	1 in.
5 000	0·0055	0·0080	0·0086	0·0091	0·0093
3 000	0·0050	0·0066	0·0074	0·0078	0·0080

The tests were taken by the Schering bridge method, the guard ring being earthed. In our experience guard rings at spacings of ¼ in. to 1 in. are totally ineffective, although it is obvious that each special case must be considered separately and the guard-ring system designed to meet the characteristics encountered. There appear to be no sound published data on the subject, and recent papers† indicate that the mechanism of end loss is imperfectly understood, although the importance of elimination of the effects is thoroughly appreciated. An investigation on the lines of that carried out by the authors in Appendix 1 on the "crowding ratio" in a case where leakance has also to be considered would appear to be considerably overdue. Dr. Brazier has already touched on certain aspects of the problem of measuring dielectric losses in cables which have their sheaths earthed. This type of test is rapidly becoming of importance, since efforts are now being made to determine the dielectric characteristics of cables actually in service or under conditions which simulate those encountered in service. A whole series of new problems are encountered in such tests, but I shall confine my remarks to one particular problem. As mentioned by the authors on page 1134, errors may be caused in any method of measurement by capacity effects between the high-voltage apparatus and the low-voltage apparatus. Certain of these effects are between the high-voltage apparatus and apparatus at earth potential. It will be observed that if the earth connection in (say) Fig. 4 is transferred to the cable sheath the capacity currents will flow through R_3 and be measured as parts of the cable loss. To eliminate this error it is necessary to take two readings, one with the cable disconnected and one with the cable connected. A considerable portion of the correction factor thus deduced may, however, be due to the capacity and leakage effects in the transformer. In cases in which, for test purposes, an auxiliary loading transformer is introduced the transformer contribution to the correction factor is inevitably large. It is found also that the stray currents in this part of the circuit vary with the load on the transformers, so that the correction factor deduced from open-circuit tests or tests under light load conditions is only an

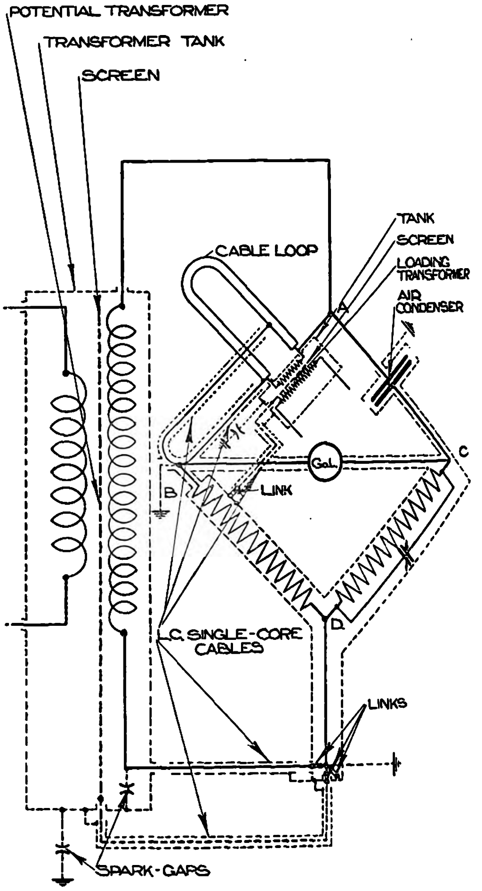

FIG. A.—Schematic diagram of Schering bridge for power-factor measurement on high-voltage power cables.

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* "Insulating Oils for High-Voltage Cables," *Journal I.E.E.*, 1928, vol. 66, p. 828.

† E. H. SALTER: "Guarding and Shielding for Dielectric Loss," *Transactions of the American I.E.E.*, 1929, vol. 48, p. 1294.

approximation. To overcome this difficulty we have incorporated in our latest test plant screened transformers lightly insulated from earth. These enable us to eliminate this type of error completely. The schematic diagram of the circuit is shown in Fig. A. It will be seen that the transformer tanks and screens may be connected to the bridge screens and linked into the bridge circuit at the D point (which in this type of test is disconnected from earth), thus shunting the R_3 measuring arm. Other stray currents to earth enter the bridge circuit at B and are measured, so that the test with the cable disconnected is still necessary. This test, however, now gives a firm correction factor instead of one associated with the degree of loading on the transformers. A careful study of the circuit in Fig. A shows that the arrangement is very flexible and that the various sources of error can be determined separately if desired, and measures taken to eliminate or reduce undesirable effects. The points referred to above indicate, I think, that, notwithstanding the success obtained by the authors in standardizing certain test circuits, there is still need for a considerable amount of research work on the subject of practical dielectric-loss measurement. Many of the outstanding problems are urgent and it is to be hoped that at no distant date a series of papers on the many aspects of the subject will carry on the work so ably introduced by the present paper.

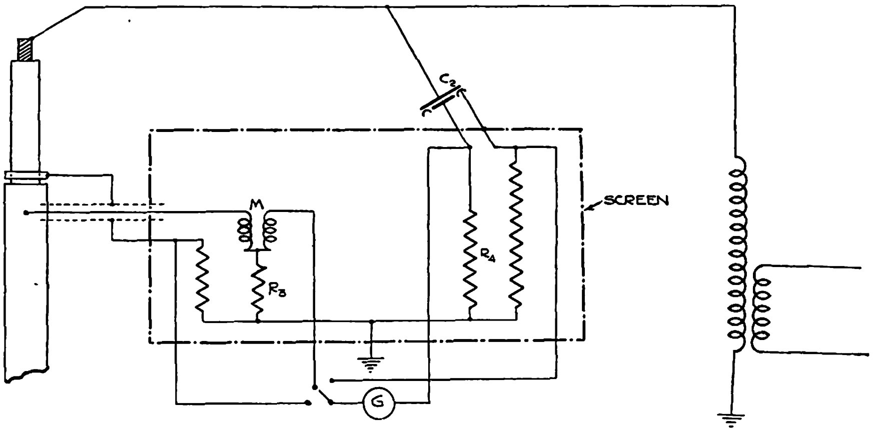

FIG. B.

Mr. R. A. Brockbank: The subject of the paper is rapidly becoming of considerable importance in general electrical research and in many branches of industry. During the last 5 years we have carried out an enormous amount of work on the measurement of dielectric losses, and the authors will, I think, agree with me that the accurate determination of such exceedingly small losses under the particular test conditions is a very fine art. After specializing on the subject for some time, we can get to know the main precautions and safeguards which have to be taken, but there still arise at times certain little discrepancies in power loss which may take a lengthy and painstaking investigation to single out. The apparent negative power factor of the authors' standard condenser is a case in point. The suggestion given is quite logical, and we have obtained a similar result. The authors have dealt mainly with the compensated wattmeter and the Schering bridge type of measurement. For these circuits they have developed resistance and capacity units which are, as far as possible, free from phase defects. One or two other circuits employing a pure resistance or capacity are also worthy of attention. The bridge circuit shown in Fig. B is closely related to the Schering bridge, and was first proposed by Prof. Dawes of Harvard University in 1926. It looks rather more complicated than it actually is, as the complete guard and shield connections have been inserted. The only difference between this circuit and the Schering bridge is that the primary of a mutual inductance M (astatic winding) is in series with the cable, and the secondary is connected in the galvanometer circuit. This variable mutual inductance replaces the Schering bridge condenser (C_4). Balance is obtained by varying M and R_4, and the power factor for normal-loss angles is given by $\omega M/R_3$. We have used this circuit for over 2½ years and have found that it possesses certain advantages over the Schering bridge. The circuit shown is quicker to manipulate, and its sensitivity is an improvement upon that of the ordinary Schering bridge type of measurement. Fig. C shows the thermal wattmeter, which was introduced about 6 or 7 years ago but has not been more fully developed lately. Although I do not suggest that this circuit rivals the Schering bridge or the modified Heaviside bridge, it is remarkable because of its ingenuity, simplicity and

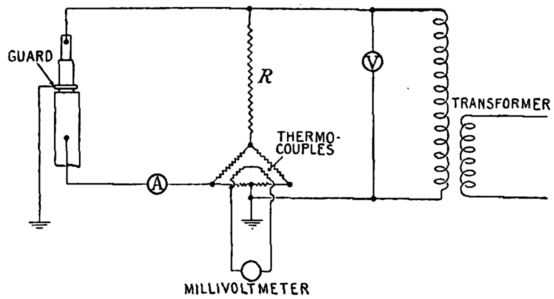

FIG. C.—Thermal wattmeter method of dielectric-loss measurement.

Watts = KR × millivolts.

general robustness. The circuit is unique in that no adjustments have to be made, for, the high-tension resistance having been fixed, it only remains to read the watts from a millivoltmeter. It is suggested that the instrument has a useful sphere in routine measurements on factory lengths of cable and on supply networks, where it could possibly be adapted to give a continuous record of the state of the system. I think that these two methods of obtaining satisfactory power-factor measurements should have been incorporated in the paper; the first because of its practical utility and advantages over the Schering bridge, and the second because it possesses certain spheres of usefulness capable of development in the future. I should like to ask whether as a general practice the authors utilize the circuit of their Schering bridge for maintaining the guards at the same potential as the galvanometer points, or rely on the use of low-value resistance arms and a knowledge of the capacity of these arms to earth. Do they find this quite sufficient in practice? I should like to point out that in the formulæ (page 1133) relating to the compensated dynamometer the authors seem to have neglected the inductance and resistance of the dynamometer and the inductance which they put in series. In their experiment these may have been negligible, but this is not normally the case in practice. R and L must include the total resistance and inductance, respectively, in the branched circuit. The authors have made a condenser 14 ft. long with a capacity of 500 $\mu\mu$F which permits it to be checked directly against the water resistor, but we have had to try other means of correlating the methods. A very usual method adopted to check the accuracy of two different methods of dielectric-loss testing is to take a power-factor run on a cable by each method in turn. This, however, is not entirely satisfactory for accurate calibration, as the state of the cable depends on its previous history; also, during the change-over, variations may occur in temperature, condition of the cable-ends, etc. We have found that it is usually possible to take loss readings by two methods at the same time on one cable. Thus one operator can work a Schering bridge, in the cable arm of which is the current coil of a dynamometer for the compensated wattmeter method, which in turn is balanced by another operator, and simultaneous readings are obtained. Suitable switches can be provided to ensure that no interference exists between circuits. This method has proved very useful and ensures a high degree of accuracy.

Mr. J. F. Watson: I have experienced considerable difficulty in the accurate measurement of the dielectric loss on short lengths of cable such as 5 to 6 yards, even when guarded, the apparent error appearing to be in excess of 20 per cent when the lead sheath of the cable was insulated. When working with lengths of 200 and 250 yards of 66-kV single-conductor cable, however, the error introduced by not guarding appeared to be quite negligible up to pressures of 80 kV. It is quite important from a manufacturing point of view to make accurate measurements on short pieces of cable, so as to find any weak spot there may be on a length of cable, as a defective portion may be as short as 1 or 2 ft. in a length of 200 or 250 yards. Thus, if we assume that one length of cable has a power factor of 0·004, another length having a power factor of 0·0044 may have somewhere along its length a defect of a serious nature. Such a variation of 10 per cent in the power factor, however, does not necessarily point to such a condition, but may be due to a general variation in the dielectric throughout the entire length of the cable, in which case no unsatisfactory performance in operation need be expected.

(*Communicated*): Since making the above remarks at the meeting I have been in touch with Dr. Rayner and his associates, and have carried out further experiments on the measurement of dielectric loss on short lengths of cable. I am now satisfied that, with effective guarding, accurate measurements can be made on lengths of cable as short as 2 yards at pressures up to 80 kV.

Mr. J. K. Webb: In connection with the electrolytic model (Appendix 1), for plotting the field at the surface of model electrodes, the authors' circuit implies the use of audio frequencies. Mr. Emanueli stated in a recent series of lectures on "High-Voltage Cables" which he gave at this Institution that, owing to capacity effects, high-frequency alternating current is unsuitable for such tests, and that he had found a frequency of 50 periods per sec. to be the most satisfactory. I should like to ask the authors what their own experience has been in this connection.

Mr. E. Fawssett: I want this Section to realize that this piece of work is of international importance. It has already formed the basis of a suggested and agreed method for measuring very low power factors, and one which may become the standard in Britain and, further, by the good offices of the International Electrotechnical Commission it may become the agreed international standard, in which case it will greatly simplify comparisons between the products of different countries. I wonder whether meter and instrument engineers realize the extent of the advance which the authors have made in obtaining an accuracy of 1 per cent in the measurement of 1 per cent power factor. Until a short time ago, 10 per cent was considered to be as good an accuracy as could be expected in the measurement of low power factors of the order of 1 per cent. To reduce the figure to one-tenth of this value must have meant a great amount of patient work, as is shown by the fact that this subject has been on the agenda of the Research Committee for 5 years. On page 1133 the authors mention various forms of voltage supply, including tertiary windings and step-down transformers. I would emphasize that our experience in other directions shows that the tertiary winding is particularly apt to give an incorrect ratio, and that it is to be avoided in the absence of most careful tests to prove that the ratio is as expected. The whole work is really summed up on page 1134: "A loss-free condenser is a simpler problem than a resistance without inductance or capacity; and the Schering bridge is the most convenient of all the methods to use." On page 1136 it is mentioned that great trouble was experienced with the contact between the flange of a hole and the nut of a bolt. I should like to ask what was the real cause of this, whether it was merely dirt, an oxidized surface, or the aluminium contact, which is apt to be uncertain.

The method of studying the electrical stress at the edges of the plates by analogy with the hydrodynamic problem is particularly ingenious, and well illustrates how a principle may often be applied to a totally different problem. In Appendix 2, dealing with resistors, it is stated that glass tubing was used at first, but later Keramot tubing was substituted. I am doubtful whether a Keramot tube would keep its proper physical shape at the temperatures which are liable to exist under certain conditions of water supply. Possibly if 50° C. were not exceeded it would be satisfactory, but I should be afraid of trouble if, owing to loading or to warm water at the inlet, the temperature rose much above this figure. The figures with regard to temperature-rise (page 1141) show how quickly the inlet temperature rises. If the inlet temperature is 10° C., which is too low for a south country water supply in summer, the temperature of the water rises 23 degrees above this, and if the inlet temperature is 20° C. the rise is 30 degrees. The increase is very rapid if the inlet temperature is any higher than this, so that this cumulative effect makes the apparatus rather difficult to control and emphasizes one's preference for the condenser.

Mr. C. Dannatt (*communicated*): I am particularly interested in the authors' air condenser, having been associated myself with the design and construction of air condensers for working voltages up to 300 kV. The flat-plate condenser illustrated in Fig. 14 has undoubted advantages from the point of view of the investigatory work described, but I am rather surprised that the authors state in their conclusions that such a condenser is a reliable standard. It appears to me that in designing their condenser they set out with a very inadequate appreciation of the effects of uncontrolled mutual capacitance between the low-tension plate and other parts of the related circuits. Were this not so, I feel they would have avoided the troubles necessitating the subsequent shielding of the insulators supporting the low-tension plate, or the sheathing of the members C (Fig. 14). I prefer to mount the low-tension plate direct from the inside of the guard-ring member. Such mounting avoids the necessity of separately shielding the insulators and earthing the pins of the insulators, which the authors found to be necessary. No specific reference is made to the ratio of guard-ring width to gap spacing, a ratio which should be made as large as is necessary to prevent any mutual capacitance between the low-tension plate and extraneous objects such as leads, or, for that matter, between the low-tension plate and the edges of the high-tension plate where discharge might occur. The effect of too small a value for this ratio is to cause an impurity dependent on the location of surrounding objects and the modification in the electric field produced by them, so that tests with one set of conditions may be no guide to the possible impurity which might arise in other circumstances. The fact that the authors' tests showed the impurity obtained to be dependent on the size of the lead FF, shows their condenser to be liable to such trouble. No attempt has been made to make the condenser a standard of capacitance as well as a standard of purity, in view, I suppose, of the immediate object of the work, but it is an undoubted advantage to cover both requirements in a standard air condenser if possible, and one feels that their work would have been much more valuable if the authors had considered this further aspect of air-condenser design at the same time. With regard to the test results, the authors are to be congratulated on the excellent agreement of the phase-defect tests made on two widely different types of apparatus. It would, however, have been of considerable use if they could have stated more explicitly the range of conditions covered in the tests with regard to stress in the air dielectric, humidity and temperature of the atmosphere, and precautions taken against dust and dirt deposits on the air-condenser surfaces. It is, for instance, quite feasible to use working stresses of 13 or 14 kV (R.M.S.) per cm with good machined surfaces, and as considerations of space occupied are very important with high-voltage condensers it is desirable to use as high a stress as is consistent with purity. The authors are also doubtless aware of certain results advanced in America regarding the effect of humidity on the power factor of air condensers. I should be glad to know their views on these matters.

Dr. E. H. Rayner and **Messrs. W. G. Standring, R. Davis** and **G. W. Bowdler** (*in reply*): It was far from our intention to suggest that the accurate measurement at high voltages of dielectric losses had now become a simple problem, and we agree with Mr. Scott that continual vigilance is necessary in making such measurements. For this reason, and also to avoid repetition, it was thought preferable to describe various types of error according to their source, suggesting to the experimenter how errors might arise, rather than hoping to give him " foolproof " instructions. The shielding of the condenser is described in detail to give an idea of the magnitude of the errors due to inadequate shielding, and the plate form proved useful for demonstrating this. The condenser was designed for use with a separation of 10 to 20 cm between the plates, and at these working distances the wooden framework did not require shielding and the high-tension conductor had no effect. The necessary dimensions of the guard depend on the proximity of neighbouring objects; but in general it may be taken that the guard plates should extend beyond the measuring plates a distance at least as great as the separation between high- and low-voltage plates. With regard to the end shielding of cables, each case must be treated on its merits, the dimensions and spacing of the guard rings depending on the length and diameter of the cable. The Keramot tubing of the water resistor has undergone distortion and this troublesome piece of apparatus is not now used as a standard, though in proving the air condenser it was considered invaluable. No effect of humidity on the phase angle of the condenser has been observed, and in the American papers referred to in the discussion there is not sufficient information to make it clear that the effect produced was due to the air and not to ineffective design or to the insulating materials used in the construction of the condenser. Considerable experience over the whole range of frequency from zero to 10 million cycles per sec. indicates that ordinary humidities do not affect the power factor of air as such, to the accuracy aimed at in this work. Secondary effects due to design and use of solid materials are another matter. The condenser described in this paper was developed as a standard of phase angle. The plate form was considered simplest for investigatory work. It enables a variable capacity to be obtained large enough for direct comparison with a resistor at different voltages. For bridge measurements a large capacity is not necessary, and for a standard of capacity the cylindrical form is certainly preferable. We now have a nitrogen-filled condenser of fixed capacity for 290 kV at 15 atmospheres gas pressure. This seems the most suitable form for a standard of convenient dimensions. The maximum electrical working stress of the plate condenser, estimated from the tables in Appendix 1, is about 13 kV (R.M.S.) per cm, occurring at the edges of the guard plates. The error referred to in a cast-iron condenser as assembled by the makers was due to a bad contact between iron and steel; this may have been caused by traces of paint. In the electrolytic experiments for plotting equipotential surfaces the water resistivity was 3 000 ohms per cm cube and the effects of capacity were negligible. The only difficulty arose from polarization effects when the electrodes were made of different metals.

The problem of making cable measurements with the sheath earthed has been ably dealt with by Dr. Brazier and Mr. Scott. The large error due to transformer capacity currents had been observed by us in developing a method for 3-phase measurements; but their method of eliminating this error by using a special transformer with shielded secondary seems much preferable to making two measurements. Dr. Brazier's observation on long lengths of cable is particularly interesting.

Of the two methods of measurement referred to by Mr. Riley and Mr. Brockbank the thermal wattmeter appears insensitive and unsuitable for use as a standard method, though it may be useful for routine purposes. The bridge method only differs from the Schering bridge in the method of obtaining phase-angle balance. Inductances are seldom perfectly astatic and for a standard method we prefer the condenser adjustment, which is not influenced by stray magnetic fields, and it can be as flexible and sensitive as the other. It is satisfactory to find that Mr. Riley's experience on measurements with different wave-forms agrees with our theory and limited experience. Our purpose was to point out that on bad wave-forms the different methods do in fact measure different quantities, and the work was done in order to obtain some idea of the relation between these quantities. If watt losses in the field be calculated from measured values of R.M.S. volts and R.M.S. amperes, using the power factor obtained with a sinusoidal supply, the figure calculated will be higher than the real losses, if the field supply be non-sinusoidal. If, however, the figure be calculated from a measurement of R.M.S. volts and the known capacity of the cable, the value obtained will be lower than the real losses.

A WIRELESS BROADCASTING TRANSMITTING STATION FOR DUAL PROGRAMME SERVICE.

By P. P. ECKERSLEY, Member, and N. ASHBRIDGE, B.Sc.

(*Paper received 4th March, and read before the* WIRELESS SECTION *7th May,* 1930.)

SUMMARY.

The B.B.C. Regional Scheme involves the construction of a number of twin wireless transmitting stations, each capable of radiating simultaneously two programmes on different wavelengths, and each at a power of 50 kW in the aerial. This paper describes the first of these twin transmitters, erected at Brookmans Park, Hertfordshire, to serve London and the Home Counties.

The paper deals with the considerations underlying the choice of sites for such broadcasting stations, the type of power supply adopted, and the factors contributing to reliability in operation, as well as with the wireless transmitters themselves. Detailed considerations underlying the design of such transmitters have been avoided in the anticipation that they will form the subject of a further paper; but, nevertheless, some information in regard to the essential and major points in their design is contained herein.

The paper deals further with the general station lay-out, the building and the auxiliary services, as well as with low-frequency apparatus for supplying modulation to the transmitter and apparatus for testing and monitoring purposes, etc.

Of particular interest is the use of high-tension direct-current machines at this station for the production of high-tension voltage for anode supply to the main power valves. The type of generator developed especially for this work is considered in some detail.

INTRODUCTION.

This paper describes a wireless broadcasting station, installed near London, designed to give two transmissions from virtually the same point on two different wavelengths. Thus a single building contains a power-supply equipment and two identical wireless broadcasting transmitters each arranged to supply modulated high-frequency energy of different frequency to two separate aerial systems.

The station is the first of the "twin" transmitting stations basic to the so-called "Regional Scheme" for British broadcasting. It is true that two different programmes have been radiated during the past two years from the Corporation's station at Daventry, but in this case the two-wavelengths service is given by the use of two separate transmitters in two different buildings a few hundred yards apart; moreover, the difference in carrier-wave frequency is larger.

The implications of the B.B.C.'s Regional Scheme are well known and it suffices to remark here that there will be 5 centres of dual-programme service. The 5 centres of transmission will be located in Scotland, North (Industrial) England, South-East England (based on London), the Midlands, and the South-West (to serve both the West and South Wales areas). Two are completed, Daventry for the Midlands and the station under discussion for London and South-East England.

CHOICE OF SITE.

The site for each of these twin-wavelength transmitters has to be chosen not only in terms of the regions and populations it has to serve, but also in relation to the distribution of the broadcasting service that it supplants.

The selection of the site for the new London station thus had to take into account the fact that, for several years, listeners in London and the neighbouring counties had been accustomed to take their service from a 2-kW station located in the heart of the West End. This location of the old single-wave-service London transmitter had accustomed listeners to a certain distribution of field strength to which they had automatically adapted themselves. Obviously, the measure of dislocation that occurs on changing over from an old to a new station is, to a number of listeners, the ratio of new to old field strength.

A site for the new London station had thus to be chosen on the periphery of the London area. The site, however, could not be so far away from the centre of London that the station erected upon it, albeit of greater power than the old, would give a weaker field strength over all London than the old, and not so near to the centre of London that it would produce intolerable "wipe out" to a great number of persons, owing to the presence of too great a field strength in densely populated areas.

These considerations determined the distance of the new site from the old. It remained to determine the direction of the new site in relation to the old. It would have been quite absurd to have chosen a site along the Thames estuary, eastwards, as much of the service area of the station would have lain over the North Sea; a southerly direction was chiefly debarred by the fact that civil aviation regulations prohibited the erection of masts on the top of the North Downs, which were about the right distance away. A western site would have given a distribution of field strength which would rob Essex and the Eastern counties of good service where strong field strength is required to overcome jamming from the transmissions from sea-going vessels, and, furthermore, would have produced quite unnecessarily strong service in an area already covered by Daventry (5XX and 5GB) transmissions. A northern location seemed, therefore, in all the circumstances to be the best. The northern site was furthermore recommended inasmuch as the existing telephone cables, essential for connecting the studio headquarters in London to the transmitter, were found to be most suitable in a northerly direction.

Description of Site.

The site finally chosen lies on the east side of the Great North Road a few miles on the London side of Hatfield. It is some 15 miles from the centre of London. Its name is derived from a large estate in the neighbourhood, Brookmans Park. The field which contains the station is 34 acres in extent and is, to all intents and purposes, perfectly flat. Flatness of site is of great advantage in laying out the aerial systems. It also allows the station to be built on one level and so produces a pleasing appearance, in addition to effecting considerable economy.

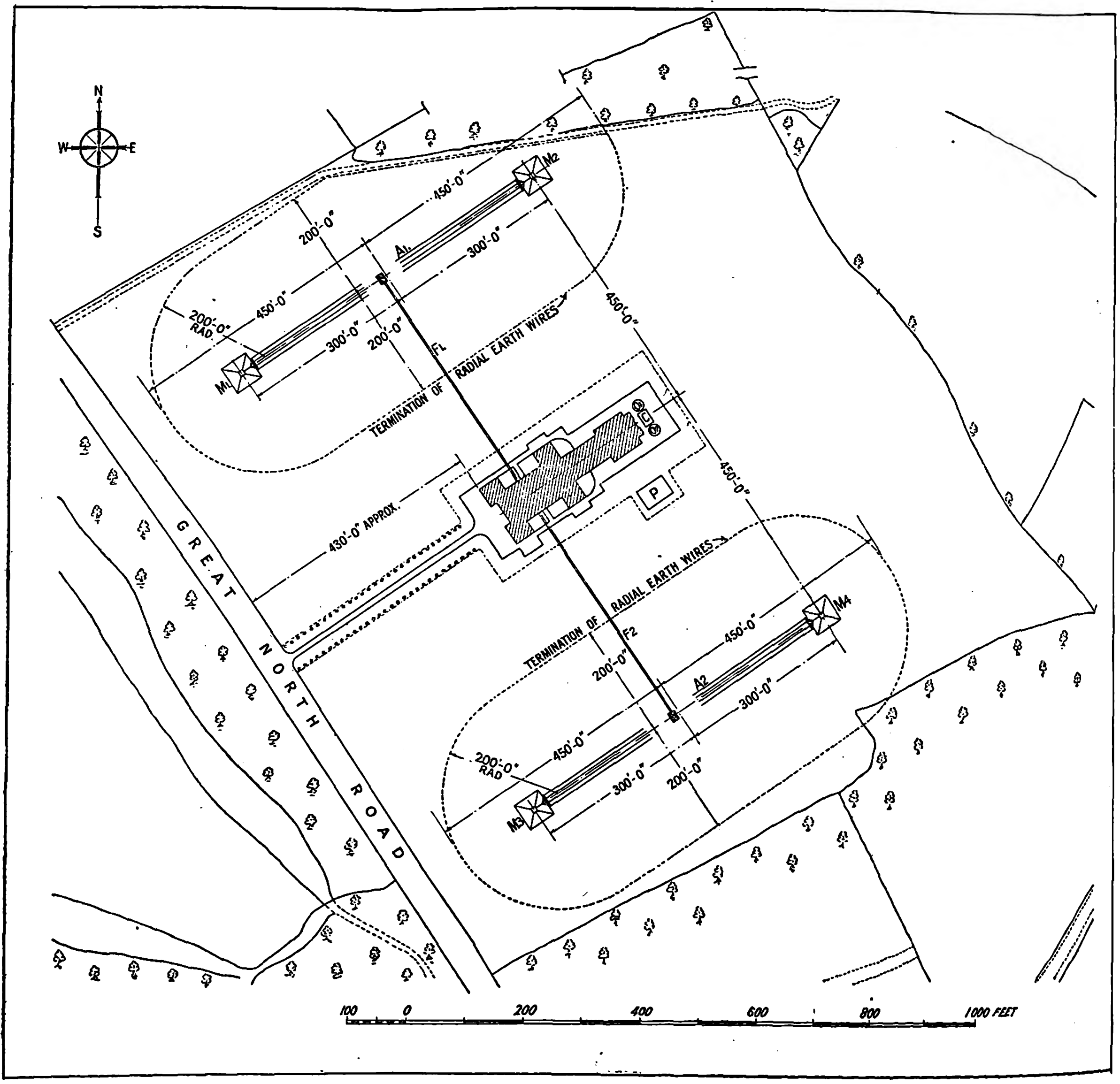

Fig. 1.—General lay-out of station. Block plan of site.

Telephone cables run close to the site; water, which is required at the maximum rate of 10 000 gallons a day, is available and is taken from the main supply.

Before purchase the site was tested for its electrical properties, as they have a bearing upon the aerial systems. Thus a 1-kW experimental mobile transmitter was erected on the selected site, in order to prove that the effective height of an aerial erected temporarily between 110-ft. masts was equal to that given by the theoretical assumption that the ground is perfectly conducting.* Certain sites give high earth losses which reduce the radiation efficiency of aerials erected upon them; it appeared from the experiments made that the site chosen behaved normally in this respect.

The experimental transmitter served the further useful purpose of giving a forecast of the expected field strength in and around the London area. Thus a motor-van containing field-strength measuring-apparatus travelled some 10 000 miles round the site and plotted the field-strength contours given by the temporarily erected mobile transmitter.

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* P. P. Eckersley, T. L. Eckersley and H. L. Kirke: "The Design of Transmitting Aerials for Broadcasting Stations," *Journal I.E.E.*, 1929, vol. 67, p. 507.

STATION LAY-OUT.

Power Supply.

It was thought advisable to install a self-contained generating plant and not to use the public supply mains. It is interesting to note that " shut-downs " of considerable duration at broadcasting stations have frequently been due to failure of the public supply mains. Moreover, it is possible to generate locally at approximately the same cost as, or in some cases a considerably lower cost than, that at which power can be bought. It is obvious that a programme may cost a great deal of money and time in preparation, and it may be of national importance. Failure to radiate the programme, due to lack of power or any other transmitter failure, is therefore a serious matter and it is particularly necessary to eliminate as far as possible all links which may involve long breakdowns. Further, it is desirable to be able to avoid fluctuations in supply voltage. Accordingly, for these two reasons Diesel-engine power units were chosen —generating direct current—so that a storage battery could be used. The battery provides a further factor of reliability in addition to compensating for variations in supply voltage.

General Plan.

The following is a general description of the station; the plant is described in greater detail in later sections.

The station building is so planned that there is a progressive evolution from the crude oil which feeds the Diesel engines (for the power supply) to the transmitters which supply the aerials with modulated high-frequency alternating currents. Thus (see Figs. 1 and 2) the oil tanks (O1 and O2) are located at the rear end of the building. These are sufficient to hold 3 months' supply of oil for the running of the station on full power on both transmitters. Between the oil tanks is the cooling tower (C). The power house contains four Diesel engines, each driving a d.c. generator. The output of the generators is floated across a 2 000-ampere-hour battery, contained in the battery room (B). The output of the power house is taken to switchboards W1 and W2 in the motor-generator room (M). In order to keep the noisy and vibration-making generation plant as far as possible away from the delicate machinery, and yet to maintain a covered communication way throughout the building for the use of the personnel, the battery room (B), packing space (Q), workshop (H) and store (K) are all interposed between the generating station and the motor-generator room. The motor-generator room contains machines which convert the 220-volt supply into the necessary forms for energizing the transmitters, which are located in the transmitter room (T). The output of the machines is led to the switchboard (W3), which is located in the transmitter room. This arrangement is adopted to facilitate operation and economize in personnel. The output from the two transmitters is passed through the two feeder lines (F1, F2) to the aerials (A1, A2). Each transmitter is capable of putting 50 kW into its associated aerial. The feeble low-frequency currents of modulation come from the distant studio in London via a cable line; this terminates in the control room (R2). The currents of modulation are there increased to a sufficient value to be injected into the modulating systems of each of the transmitters.

The valve-cooling arrangements comprise a grid of pipes (P), outside the building, through which the valve-cooling water passes. These stand in a concrete tank, and external cooling water from this tank is allowed to trickle over the outside of the pipes.

Building.

The building itself, which was erected by the Anglo-Scottish Construction Co., Ltd., under the supervision of the B.B.C.'s civil engineer, is, as far as the portions which contain the main technical equipment are concerned, of single-story construction. Many designs were considered in which galleries above the ground-level were to be erected in order to achieve an economy in building space. Calculations showed, however, that the total economic gain was fractional. It is desirable, furthermore, to ensure, as far as possible, freedom from extraneous noise in the transmitter room and so the separation of the machines and transmitters is further desirable. Silence in the transmitter room is of importance not only for the comfort of those operating the equipment, but also because the location of faults due to arcing and sparking of components of the apparatus is much facilitated if there is no extraneous noise. It might, however, have been possible to overcome noise interference by erecting the transmitter in an upper story. Here, again, there are disadvantages, inasmuch as the earthing of the transmitters would have to be made by relatively long earth leads, and it was feared that possible inductive effects between the two transmitters might be incurable. There is of necessity a large amount of ground available, and considerations of actual space are not therefore of paramount importance.

A departure from single-story construction is made in two instances, one where a vault (Y) below ground-level is arranged to contain certain subsidiary apparatus, and the other where the office block has a " first "-floor story. The object of this vault is two-fold. Firstly, it gives easy wiring runs from the machines in the motor-generator room (M) to the output switchboard (W3), and from this switchboard to the transmitters (T1, T2); and secondly it provides space for pumps, tanks, auxiliary batteries, etc. The extremely complicated wiring of the station practically necessitates the vault, because cables run in ducts would be difficult both to inspect and to install.

General Appearance.

An attempt has been made to dispel the illusion that any building connected with engineering is necessarily ugly. Extreme simplicity is the keynote of the architectural finish. Although there is no actual interior decoration in the usual sense of the word, nevertheless an attempt has been made to express in the colour scheme and general arrangement the essentially utilitarian principle of the whole lay-out. The walls of the big rooms are sprayed with white distemper over the common brick. The floors are of red tiles in the engine and

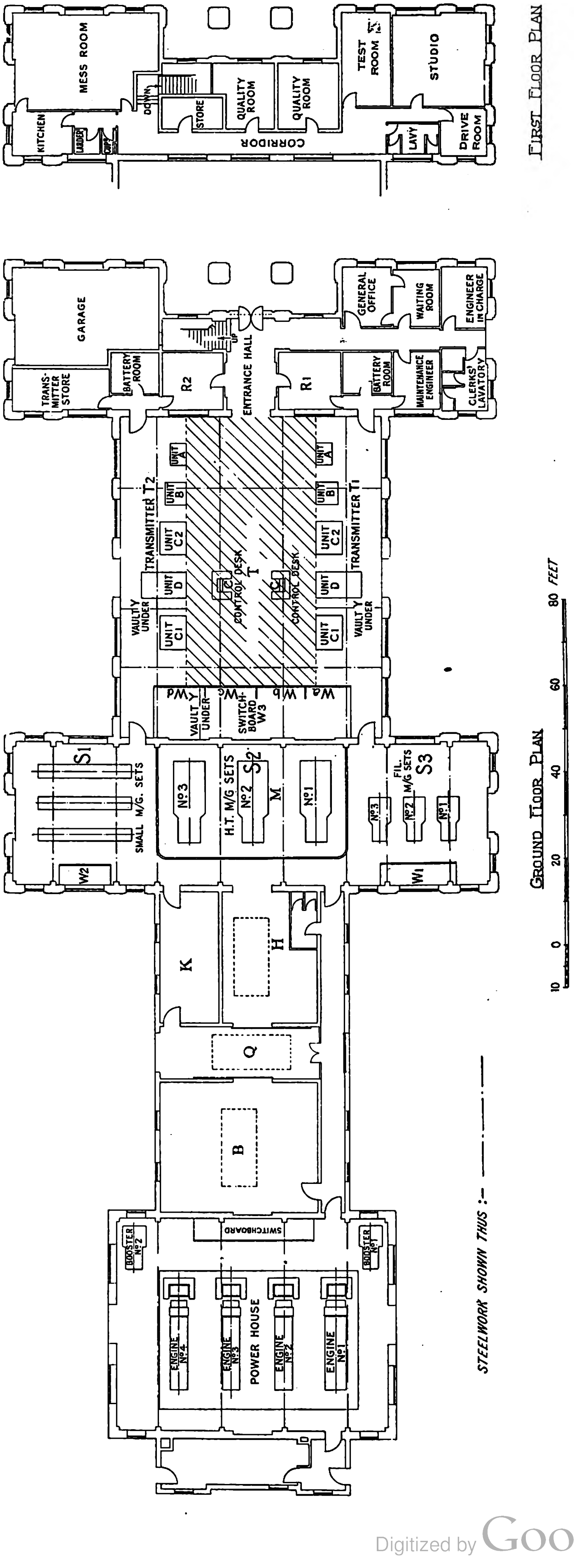

FIRST FLOOR PLAN
MESS ROOM
KITCHEN
LARDER
CUP'D
DOWN
STORE
QUALITY ROOM
QUALITY ROOM
CORRIDOR
TEST ROOM
STUDIO
LAVY
DRIVE ROOM
GROUND FLOOR PLAN
GARAGE
TRANS-MITTER STORE
BATTERY ROOM
R2
UP
ENTRANCE HALL
R1
BATTERY ROOM
GENERAL OFFICE
WAITING ROOM
ENGINEER IN CHARGE
MAINTENANCE ENGINEER
CLERKS' LAVATORY
TRANSMITTER T2
TRANSMITTER T1
UNIT A
UNIT B
UNIT C2
UNIT D
UNIT C1
CONTROL DESK
T
C
VAULT UNDER
Wa
Wb
Wc
Wd
VAULT UNDER
SWITCH-BOARD W3
S1
SMALL M/G. SETS
W2
S2
H.T. M/G SETS
No. 3
No. 2
No. 1
M
FIL. M/G SETS
S3
W1
K
H
Q
B
SWITCHBOARD
BOOSTER No. 2
BOOSTER No. 1
ENGINE No. 4
ENGINE No. 3
ENGINE No. 2
ENGINE No. 1
POWER HOUSE
STEELWORK SHOWN THUS :-
10
0
20
40
60
80 FEET

FIG. 2.—General lay-out of building.

motor-generator rooms, and of red rubber and oak in the transmitter room. Ceilings and office walls are rendered. Ceilings are white but the office-block walls and passages have a grey dado high enough to prevent their showing the dirt inevitably caused by people leaning or brushing against them.

The field on which the building stands is to be left as a grass field. The station, however, is surrounded by a gravel road with a hard core so that heavy transport can deliver loads at the appropriate doors or, in the case of oil supply, to the tanks.

POWER HOUSE.

Each transmitter is designed to give a carrier-wave energy of 50 kW to the aerial, with the transmitter so adjusted as to be capable of 100 per cent peak modulation without distortion. Although actually it was intended to inaugurate the service from this station with a power of about 30 kW to each aerial, the load on the power house, when each transmitter is giving 50 kW to the aerial, has been allowed for and this is approximately 500 kW. It is made up as follows:—

Input to the two main high-tension motor-generators, each absorbing 200 kW	400 kW approx.
Input to two main filament-lighting motor-generator sets, each taking 35 kW	70 kW approx.
Input to grid negative motor-generator sets and motor-generator sets for anode power to drive, separator and modulated amplifier stages on the transmitter ..	9 kW approx.
Motor-driven power-house auxiliaries and motor-driven pumps for valve water-cooler	10 kW approx.
Lighting, cooking, etc.	25 kW approx.
Total	514 kW approx.

Further details of the motor-generator sets mentioned above are given in a later section of the paper.

In order to generate the required power of approximately 500 kW it was decided to use three units, each capable of producing 200 kW. The advantage of using Diesel engines in preference to steam engines for generating power of this description under the conditions which obtain in practice are so obvious as to need no explanation. Actually, four Diesel engines were installed, coupled to d.c. shunt-wound generators supplied by the English Electric Co. and having a voltage range from 220 to 260, the working station voltage being 230. It is intended that only three engines shall run at the same time, the fourth being held in reserve. Fig. 2 shows the general lay-out of the power house.

The size of the power unit was carefully chosen because it allows two engines to be run at just under full load when each transmitter is delivering 30 kW to the aerial, at the same time allowing a margin of about 100 kW with three engines when the whole station is running at maximum load. The decision to use direct current in preference to alternating current was taken principally in order to make it possible to float a storage battery across the mains. This matter, however, is referred to more fully in connection with the storage battery itself.

When considering the type of crude-oil engine to be adopted, the question of vibration was looked upon as being of very considerable importance; first, from the point of view of its possible effect on the transmitters themselves; and, secondly, in view of the possibility of complaints from the owners of surrounding property, since the district is rapidly being developed for residential purposes. For this and other reasons a vertical 6-cylinder engine was eventually chosen capable of developing 50 h.p. per line at 300 r.p.m., i.e. a total brake horse-power of 300. These engines were built by Ruston and Hornsby, Ltd., and are of recent design. They employ so-called " solid injection " of the fuel, and are of the full Diesel trunk-piston type (" full Diesel" is intended here to indicate that no means of igniting the fuel is employed other than the heat generated by compression). Forced lubrication is fitted to all important points, with stream-line filters, integral with the engines, for the lubricating oil.

It is not proposed to give further details of the design of these engines, since they are a standard production intended for general industrial purposes, but the figures under actual working conditions for one commercial grade of fuel may be of interest.

Specific gravity of oil ..	0·915.
Calorific value of oil.. ..	19 200 B.Th.U. per lb.
Full-load consumption ..	0·422 lb. per b.h.p.-hour.
Half-load consumption ..	0·47 lb. per b.h.p.-hour.

Although the type of engine chosen creates comparatively little vibration, nevertheless it was considered necessary to take every precaution to ensure that no detectable vibration should reach the transmitters. With this object in view the engines were mounted on a special bed, constructed in the following way. The four engine units are mounted on a single block of concrete measuring 45 ft. 6 in. × 32 ft. × 6 ft. deep. This block weighs some 600 tons, and the concrete mixture was so specified that the weight should not be less than a fixed amount. The block rests on a raft, but is insulated from it by blocks of material known by the trade name of " Corosil." This material consists of cork mounted in iron frames and given a special treatment to ensure durability. Each frame is approximately 2 ft. 6 in. square, and the cork material is 2½ in. thick. The pressure on the cork is approximately 7·5 lb. per sq. in. Between the foundation block and the retaining walls of the raft there is an air space 3 in. wide which is closed by removable teak boards, fitted flush with the floor of the power house. The special foundations were designed by Christie and Grey, Ltd. Fig. 3 shows a section through the foundation block and raft. This arrangement has proved entirely effective in preventing any detectable vibration from reaching the transmitter; in fact there is no perceptible vibration even in the battery room, which adjoins the power house. The power-house accessories are on standard lines, and for this reason only a very brief description will be given.

Two external tanks, each capable of holding 75 tons, have been provided for the storage of fuel oil, the contents of the two tanks together being sufficient to run the whole plant at full load for three months, assuming the normal hours of working. A fuel-oil filter of the centrifugal type is installed for use in the event of the oil being found to contain water or solid impurities. The circulating water for the engines is cooled by means of an external cooling tower of standard design, and the make-up water is taken, so far as is possible, from a concrete pond which receives rain water from the roof of the whole building, the object being to supply soft water to prevent excessive deposit in the water jackets.

The exhaust system was carefully designed to give complete silence 100 yards from the building, and includes a waste-heat boiler capable of supplying sufficient heat by hot-water radiators to all rooms requiring artificial heating.

BATTERY AND SWITCHBOARD.

It has already been mentioned that a storage battery is floated across the main supply. This battery, which was supplied by the D.P. Battery Co., Ltd., has a capacity of 2 000 ampere-hours at the 10-hour rate of discharge, and its uses are as follows:—

(*a*) To take the load of one generating set in the event of the sudden failure of an engine or generator. To cover this requirement the battery is rated to give a discharge of 1 000 amperes for 1 hour when discharging to a voltage of 1·75 volts per cell.

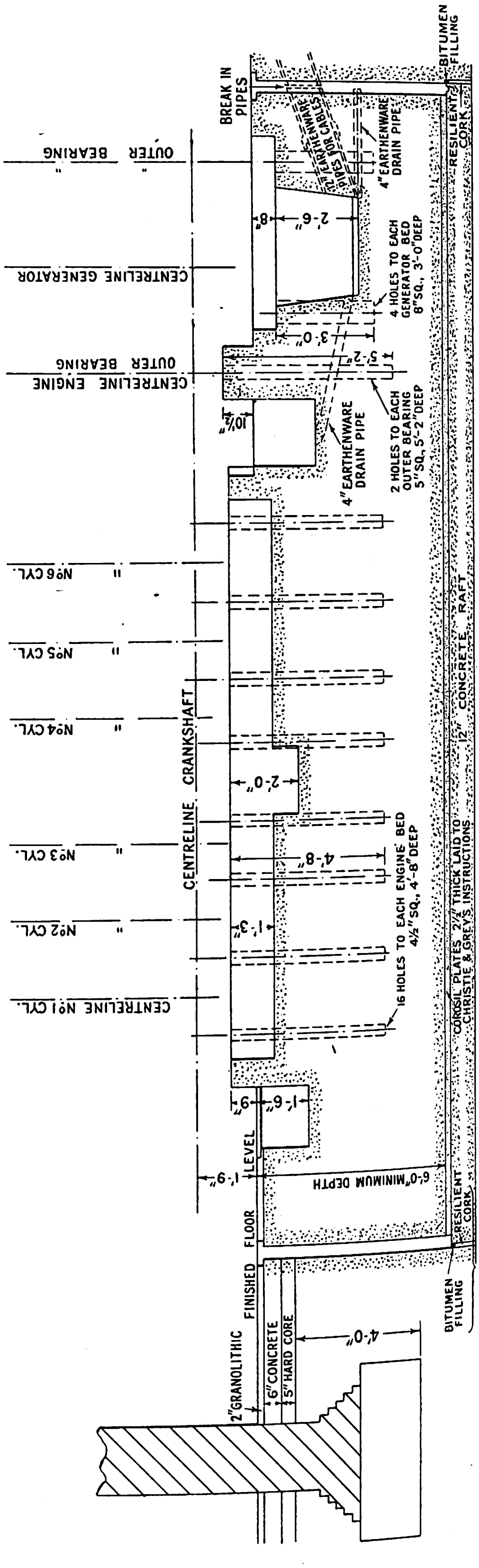
(*b*) To supply power for lighting, etc., and to run auxiliaries and workshop motors when no programme is being transmitted and the load is, therefore, comparatively very light.

(*c*) To assist in maintaining a constant voltage, especially when, for any reason, the load is rapidly varying. In general such occasions will be infrequent, but they arise when one transmitter is being run up while the other is taking the programme, or when some temporary trouble develops on a transmitter or machine.

Requirement (*b*) is sufficient to keep the battery in healthy condition without having recourse to trickle-charging or other special arrangement of this kind.

Two plain shunt-wound battery boosters (one of which acts as a reserve) are provided for battery charging and discharging, no end-cell connections being used. These boosters are hand-controlled by reversing potentiometer-type field regulators. It was not considered justifiable, from the point of view of expense, to install automatic reversible boosters, owing to the fact that the load is practically constant in normal circumstances. In the event of a sudden engine failure, which should, of course, be an infrequent occurrence, the attendant can readjust the voltage in a few seconds when the battery is called upon to take a large load, and the very temporary general drop in voltage will scarcely be detected by a listener.

The power-house switchboard, which was supplied by the English Electric Co., Ltd., is on standard lines and contains the following panels: 4 main generator panels; 2 booster motor panels; 1 battery panel; 2 main feeder


BITUMEN FILLING
BREAK IN PIPES
3" EARTHENWARE PIPES FOR CABLES
4" EARTHENWARE DRAIN PIPE
RESILIENT CORK
OUTER BEARING
2'-6"
8"
CENTRELINE GENERATOR
4 HOLES TO EACH GENERATOR BED 8"SQ., 3'-0" DEEP
3'-0"
3'-2"
OUTER BEARING
CENTRELINE ENGINE
10½"
4" EARTHENWARE DRAIN PIPE
2 HOLES TO EACH OUTER BEARING 5"SQ., 5'-2" DEEP
Nº6 CYL.
Nº5 CYL.
Nº4 CYL.
CENTRELINE CRANKSHAFT
12" CONCRETE RAFT
2'-0"
Nº3 CYL.
4'-8"
16 HOLES TO EACH ENGINE BED 4½"SQ., 4'-8" DEEP
Nº2 CYL.
1'-3"
CENTRELINE Nº1 CYL.
CORKSIL PLATES 2½" THICK LAID TO CHRISTIE & GREY'S INSTRUCTIONS
6"
1'-6"
1'-9"
6'-0" MINIMUM DEPTH
FINISHED FLOOR LEVEL
RESILIENT CORK
LAID TO CHRISTIE & GREY'S INSTRUCTIONS
BITUMEN FILLING
2" GRANOLITHIC
6" CONCRETE
5" HARD CORE
4'-0"

Section A–B

FIG. 3.—Section through engine foundation block and raft.

panels; 1 power auxiliary panel; 1 lighting panel; and 1 spare panel.

The main feeders running to the motor-generator room are so arranged that the supply to each transmitter can be kept separate and furnished, if necessary, by different generating sets. Thus if experimental work, such as valve-testing, is being carried out on one transmitter while the other transmitter is radiating a programme, one engine set can be isolated so as to supply the load for the test, obviating any risk of affecting the radiated programme by a short-circuit or other accident. This scheme of connections is also particularly useful in the event of some complicated breakdown of one of the transmitters, the cause of which is difficult to trace and which necessitates the frequent running-up of the set. Normally, however, the two sets of busbars and feeders are paralleled. The feeders themselves consist of bare 4 in. × 0·5 in. copper strips run on porcelain insulators along the roof of the passage leading to the motor-generator room.

MOTOR-GENERATOR ROOM.

Each transmitter when working on full load requires the following inputs:—

Supply	Volts	Amperes	kW
Main supply to anodes of all water-cooled valves ..	10 000	16	160
Filament-heating for all valves, water-cooled and air-cooled, except the master oscillator	22	1 100	24·2
Grid negative voltage for final power stage	200	4	0·8
Grid negative voltage for penultimate stage	2 000	0·2	0·4
Grid negative voltage for modulator, modulated amplifier and separator	500	0·5	0·25
Anode supply for the master oscillator	2 000	0·06	0·12
Anode supply for the modulator, modulated amplifier and separator	3 500	0·35	1·2

The above are the *actual* inputs for 50-kW working.

Fig. 2 shows the general lay-out of the motor-generator room. It contains three general allocations of space. S1 contains all the small-power machines for grid negative and small high-tension supply, etc. These are very small machines of the order of 1 kW each. They are mounted on pedestals 3 ft. from ground-level and surrounded by a stainless-steel guard which can be quickly removed. This arrangement facilitates the maintenance and repair work, in that the maintenance personnel need not undertake the necessary work in cramped positions. Space S2 is allocated to the high-tension d.c. generators, which take in power at 220 volts and deliver it to the transmitters at 10 000 to 12 000 volts. The remaining space S3 is taken up by the filament-lighting machines, which supply a very large current at a low voltage. The reliability of the machine-room supply is guaranteed in terms of three machines of every kind for two transmitters. Thus there is always a condition where two machines of each kind are working, leaving one spare to be put into service in case of breakdown.

MAIN HIGH-TENSION SUPPLY.

The switchboards controlling the motor side of the convertors are located at W1 and W2. W1 operates the high-tension machines and the filament machines, and W2 the small auxiliaries in the space S1.

The question of the best method of obtaining the main high-tension supply was discussed in a previous paper by one of the authors.* For reasons given in that paper it was decided to use motor-generators in preference to thermionic rectifiers, adopting as simple a design of motor-generator as possible, consistent with reliability. The machines adopted were developed to suit the requirements of this station by Mr. J. E. Calverley, of the English Electric Co. Their maximum output is 160 kW at 750 r.p.m., and the voltage range is 7 000 to 12 000, the machines being capable of giving the full 160 kW at any voltage between these limits. The lower limit of voltage was chosen to cover the possibility of the machines being obliged to work at a comparatively low voltage, on account of so-called "rocky point" effects in the water-cooled valves forming the final power stage of the transmitters. This trouble was somewhat persistent at the Daventry station (5GB) when the design of these machines was under consideration, and at that time the solution was not clear. It was intended to run these machines at approximately 10 000 volts, apart from this consideration, but at the same time it was considered that it might be desirable, at some later stage, to raise the working voltage to 12 000, since the higher voltage gives improved conditions on the transmitter from the point of view of efficiency and linearity of modulated output.

The driving motor is compound-wound, and the generators are separately excited from the station busbars, the fields of the two generators per set being permanently connected in series and controlled by one regulator.

The high-tension voltage is generated in two armatures, each having two separate windings in the same slots and two commutators. All four commutators are permanently connected in series. The voltage per commutator can be varied between 1 750 and 3 000 volts with the aid of the field rheostat so as to give the total high-tension voltage range required.

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* P. P. ECKERSLEY: "The Design and Distribution of Wireless Broadcasting Stations for a National Service," *Journal I.E.E.*, 1928, vol. 66, p. 501.

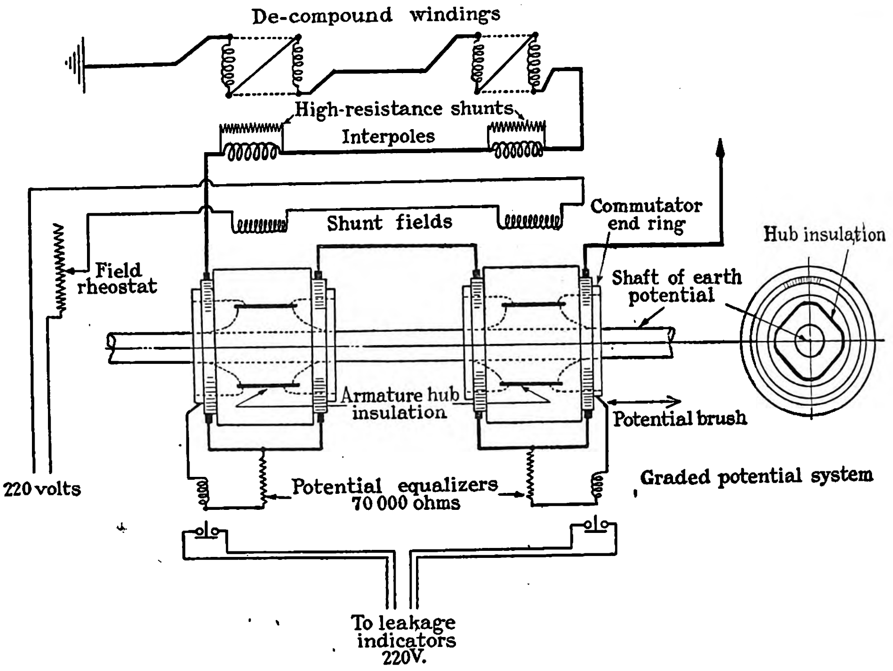
De-compound windings
High-resistance shunts
Interpoles
Shunt fields
Commutator end ring
Hub insulation
Field rheostat
Shaft of earth potential
Armature hub insulation
Potential brush
220 volts
Potential equalizers 70 000 ohms
Graded potential system
To leakage indicators 220V.

FIG. 4.—Insulation and distribution of dielectric stress in high-tension machines.

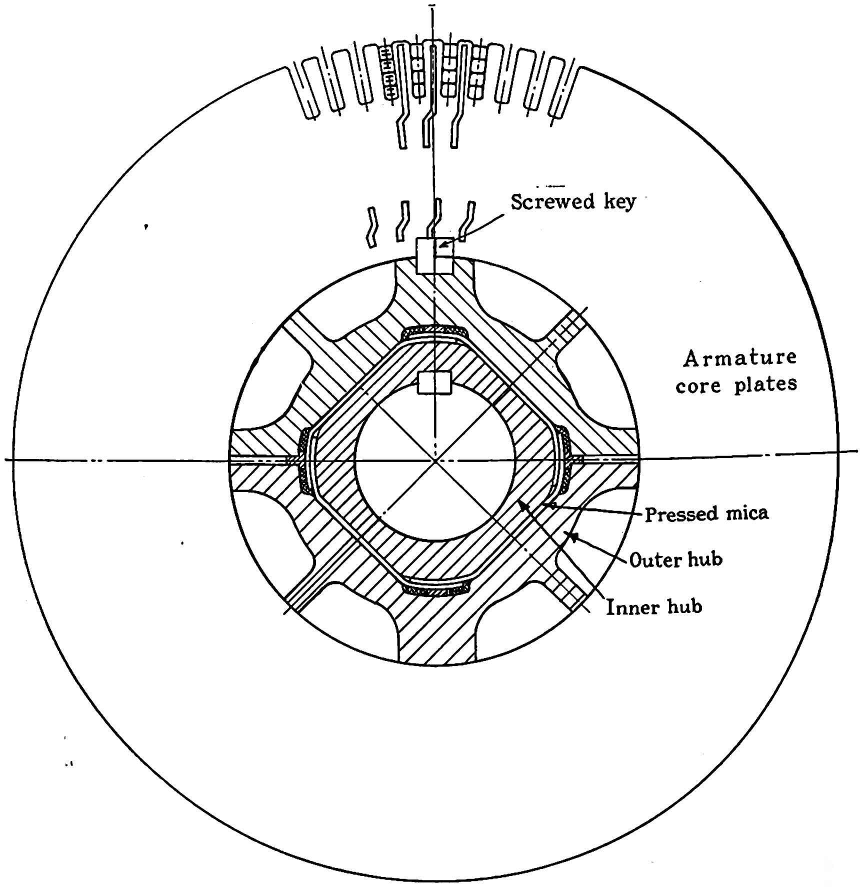
Screwed key
Armature core plates
Pressed mica
Outer hub
Inner hub

FIG. 5.—Insulation and distribution of dielectric stress in high-tension machines.

Each machine has four main poles and four commutation poles. The yokes and pedestals are split on the horizontal centre-line to facilitate erection.

The heaviest parts to be handled are the two high-tension armatures and shafts, each of which weighs 2·1 tons.

The shafts of all three armatures (one motor and two generators) in the set are rigidly coupled together and carried in four sleeve-bearings with oil-ring lubrication. Extra precautions were taken in the design of these bearings and pedestals to prevent creepage of oil along the shaft into the machine or on to the commutators. The armatures are mounted on very stiff shafts and were dynamically balanced to ensure smooth running and freedom from vibration.

The insulation scheme and distribution of the electric stress is probably the most interesting feature in the machines (see Fig. 4). Neither the couplings nor the foundations are insulated, the frames, shafts, bearings and bedplate being at earth potential. The English Electric Co.'s graded-potential system was adopted, the object of which is to remove the heavy electric stress from the slot insulation and apply this to a secondary layer of insulation built into the armature hub. The slot insulation consists of pressed mica 0·06 in. thick, and this is subject to a stress having a peak value of 3 000 volts twice per revolution, equivalent to an a.c. voltage of 2 120 at 24 cycles per sec. The stress on the slot insulation is identical in both armatures, though one is operating in series with the other, the system being earthed at the negative side.

The major insulation to earth is incorporated in the armature hub, and consists of pressed mica 0·125 in. thick. This mica is held between solid machined surfaces and projects beyond the armature hub to give a long creepage surface to earth. This layer of insulating material is made up of four overlapping sections moulded to shape and fitted round the inner hub, which is of square section with rounded corners (see Fig. 5). The armature hub in halves was assembled in position on the mica and secured by a shrink-ring at each end. To eliminate the possibility of films of air in any spaces between the mica and the steel, the moulded sections were given a good coating of insulating compound, and this was maintained in a fluid condition until the shrink-rings were in position and the hub complete. The insulating material in this position is very solid and is remote from any appreciable temperature variations. Each hub was tested to the shaft at 25 000 volts, 50 cycles, for one hour before the armature was wound.

The armature core with its hub carries also the commutator hubs, one at each end, so that the whole of the armature and commutators are well insulated from the shaft. The potential of these parts is maintained at its correct value relative to the armature windings by means of a potential equalizer. Two potential equalizers are provided for each pair of generators, one for each armature. They are totally enclosed and are mounted on the bedplate. The connections to the insulated armatures are made through a carbon brush running on an extension of one commutator and ring on each armature core. The potential equalizer maintains the potential of the armature core at a mid-value between the extreme potentials of the two commutators, and definitely determines the electric stress across the slot insulating material, the remaining voltage to earth being applied to the armature-hub insulating material.

The resistance in the potential-equalizer circuit is 70 000 ohms, which limits the fault current in the event of a breakdown of insulating material. If any current exists in this resistance owing to leakage or insulation breakdown, a relay connected in series will close two contacts on a low-potential circuit and operate the leakage-indicator gear.

All highly-inductive windings which are connected in the high-tension circuit, such as interpole coils and series windings, have reinforced insulating material on the end turns of each coil to safeguard them against breakdowns between turns due to surges or impulses. The interpole windings are provided with non-inductive shunting circuits to bypass any audio-frequency currents which may exist in the system.

The interpole coils and series coils are connected at the earth side of the armature, but are insulated for a high-pressure test of 5 000 volts (a.c.) owing to the fact that in certain circumstances higher voltages to earth than normal may exist.

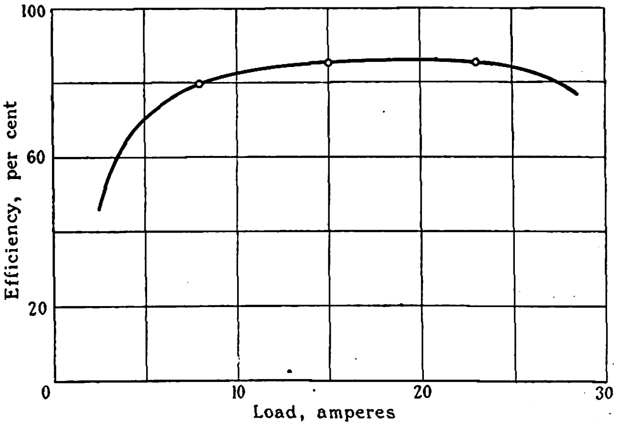

FIG. 6.—Overall efficiency of high-tension sets.

Insulation Tests.—The following high-pressure tests were carried out on the finished machines, using alternating potential from a 50-cycle circuit. All these tests were of 1-minute duration.

Armature windings to armature core ..	7 500 volts
Armature core to shaft	20 000 volts
Series and interpole windings to frame..	5 000 volts
Series winding to shunt winding ..	5 000 volts
Shunt winding to frame	2 500 volts
Potential equalizer and relay coil to bedplate	20 000 volts

Considering that the slot insulating material and the armature-hub insulating material are electrically in series, the total final test pressure between the armature windings and earth is equal to 27 500 volts (a.c.).

Efficiency and Temperature-rise.—The overall efficiency of these high-tension sets is shown in Fig. 6, from which it will be seen that the efficiency over the working range is from 85 to 86 per cent.

The machines have been designed to comply with B.S.S. No. 168—1923, as regards temperature-rise. The figures specified therein are not exceeded even if the maximum rated voltage of 12 000 and the maximum rated current of 23 amperes are taken together.

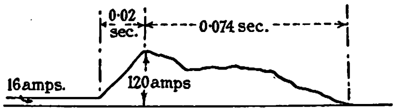

FIG. 7.—Oscillogram showing current when generator is short-circuited (with circuit breaker).

Voltage Characteristics.—Owing to the possibility of "rocky point" effects in the main transmitting valves, it was considered desirable to give the machines some form of inherent current-limiting characteristic, and for this reason the generators are heavily de-compounded with their own current. It was recognized that de-compounding could not be instantaneous in its action and prevent the first rush of current on a dead short-circuit, but as the smoothing system includes a high-value choke coil (5 henrys) in series with the machine, the rate of increase of current due to a short-circuit external to the choke and machine could be controlled and made sufficiently small to permit the de-compounding to keep pace with the current-rise.

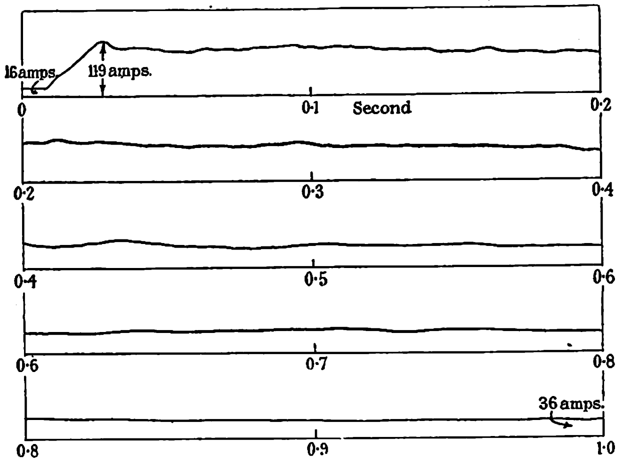

FIG. 8.—Oscillogram showing current when generator is short-circuited (without circuit breaker).

The total inductance of one pair of machines in a high-tension motor-generator set is about 1·1 henrys, and the oscillograms in Figs. 7 and 8 show that without the choke in circuit the initial rate of increase in current on short-circuit at the terminals is in the neighbourhood of 5 000 amperes per sec. The de-compounding winding has little effect at the instant of short-circuit, but after about 0·02 sec. (during which time the current is increased by about 100 amperes) the de-compounding becomes effective (Fig. 7).

With the 5-henry choke in circuit, the initial rate of increase of current is reduced to about 1 500 amperes per sec. and the current will not rise to more than about 35 amperes before the voltage begins to fall, due to the action of the series de-compounding windings. As this is the final short-circuit current, when the circulating current approaches this value it remains practically steady whilst the voltage falls to zero. This scheme has been found to be quite effective in service, and a short-circuit in the transmitter room does not cause any appreciable disturbance on the commutators of the motor-generator set.

On account of the wide range of current for which these machines are designed, the series windings on each pole are divided into two sections, and these can be connected for use on the higher current range so as to make two complete parallel circuits on each generator field. A further reason for this splitting of the series

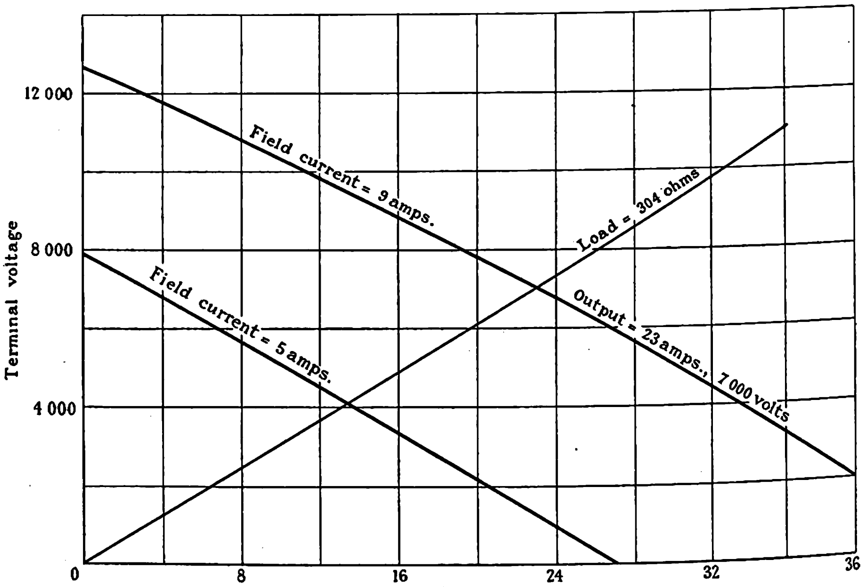

FIG. 9.—Load characteristics of high-tension machine with half de-compounding.

windings and putting half on each side of the shunt winding is to keep down to a low value the magnetic leakage between the shunt and series windings and to render the de-compounding windings quicker in their action.

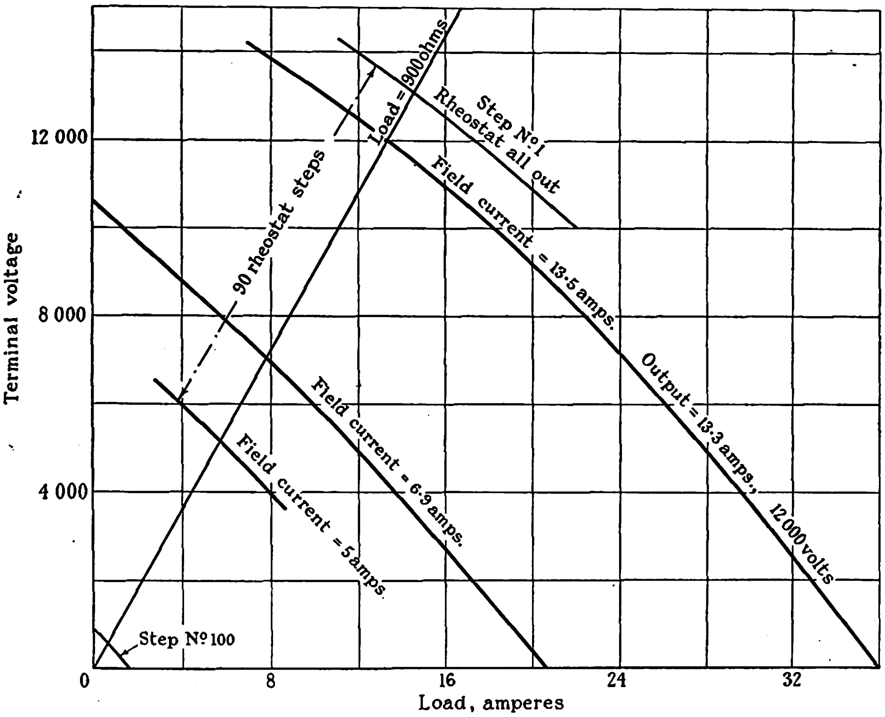

FIG. 10.—Load characteristics of high-tension machine with full de-compounding.

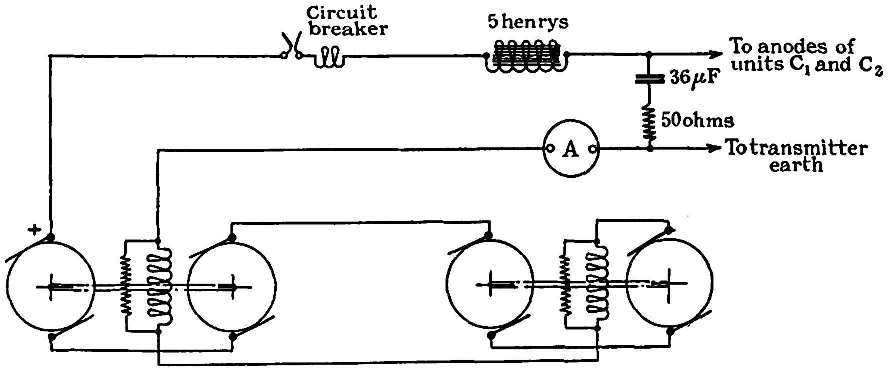

FIG. 11.—Diagram of connections of high-tension machine with smoothing set.

Links, provided on the lower portion of each magnet frame, permit of these sections being connected in series or in parallel to suit the current range required.

Figs. 9 and 10 show the characteristics of the machine with each arrangement of the connections. Fig. 10 illustrates the characteristics of the set with the de-compounding windings in series. This is a normal working condition for an output on the 9 000- to 12 000-volt range. It will be noted that the no-load voltage-rise is in the neighbourhood of 25 per cent, though this voltage-rise never occurs in practice because the machines always build up on load, and in the event of the circuit breaker operating it opens the shunt field circuit and eliminates the excitation.

The steady short-circuit current of the machine is about 36 amperes, and the curve shows how the voltage falls as the current increases. The load on these machines is practically a dead resistance load for any one adjustment of the transmitter, and under these conditions the field control is very precise and effective. Under the control of the field rheostat the machine will build up its voltage, following the straight line which is shown in the diagram to correspond to the resistance load of 900 ohms, which would absorb 13·3 amperes at 12 000 volts.

De-compounding curves for other values of the field current are also shown in Figs. 9 and 10. These all take the same shape and only differ in value with different values of the field current. Under these conditions the machine will build up along the straight line under the control of the field rheostat, and the increments of voltage per step of the rheostat are about 70 to 80 volts.

Short-circuit Characteristics.—Short-circuit tests were taken on these machines with and without the circuit breaker (see Figs. 7 and 8). The short-circuits were taken across the terminals of the machine. Fig. 7 shows the change and duration of the current with the circuit breaker in circuit. This curve was taken when the machine was delivering 16 amperes at 10 000 volts, and the maximum current recorded was about 121 amperes. This current commenced to decrease in 0·02 sec. owing to the de-compounding, and was interrupted by the circuit breaker, which brings the current to zero in about 0·095 sec. The circuit breaker is not of the special rapid type, since the impedance of the systems, together with the effect of the de-compounding, prevent any excessive current; it is, in fact, fitted with an adjustable time-lag device.

Fig. 8 shows a similar test without the circuit breaker in series. The wave is of similar shape, but instead of being interrupted by the circuit breaker the current is gradually brought down to its steady short-circuit value by the action of the de-compounding winding. The peak value of the current in this case is much the same as before, reaching its maximum value at 0·02 sec. from the instant of short-circuit. At this time the de-compounding winding becomes effective and gradually reduces the voltage and circulating current, until at the end of 0·95 sec. the current is steady at its short-circuit value.

Fig. 11 shows a diagram of connections of the machine with its associated smoothing circuit.

An oscillograph test was taken to determine the amount of the commutator ripple. It was specified that this should not exceed 1 per cent of the working voltage on either side of the mean, without the smoothing system in circuit. The ripple as actually measured in this way was approximately 0·08 per cent.

There are three of these machines installed, and each machine is enclosed by a separate iron grille the gates of which cannot be opened without closing down the machine. The main smoothing chokes, one for each machine, have a value of 5 henrys each, are oil-cooled, and are also mounted in these compartments.

Motor-Generators.

For Filament Heating.—These machines, which were also supplied by the English Electric Co., Ltd., are entirely straightforward and the only item in the specification which is in any way unusual is in connection with ripple. The maximum amount allowed was 1 per cent above or below the mean of the working voltage; the figure as measured by an oscillograph was approximately 0·5 per cent. As in the case of all the motor-generator sets for the various supplies to the transmitters, three machines were installed, one for each transmitter and one in reserve. The rating of the filament-heating motor-generator sets is as follows:—

Voltage range	15 to 30
Current	1 300 amperes
Speed	570 r.p.m.

The results of the tests were as follows:—

Efficiency	76 per cent
Highest temperature-rise	30 deg. F. (generator commutator)

For Anode Supplies to Separator, Modulator and Modulated Amplifier.—These machines were supplied by Messrs. Haslam and Newton, Ltd., and were given a specially liberal rating owing to the heavy duty required. The rating is:—

3 500 volts and 0·6 ampere; measured ripple 0·2 per cent.

The same maximum ripple was allowed as for the main h.t. machines, viz. 1 per cent.

For Master Oscillator High Tension.—These are rated at 2 000 volts and 200 mA; measured ripple 0·57 per cent.

For Grid Negative Supplies.—These are rated as follows:—

Main amplifier 250 volts, 4 amperes; measured ripple 0·5 per cent.

First power amplifier 2 000 volts, 200 mA; measured ripple 0·57 per cent.

Modulator and separator 500 volts, 500 mA; measured ripple 0·3 per cent.

TRANSMITTER-ROOM EQUIPMENT

Lay-out.

The transmitter room is 73 ft. 10 in. long, 60 ft. wide and 26 ft. high (see Fig. 2). The two transmitters T1 and T2 face one another, leaving a large space in the middle of the room. The switchboard is at right angles to both transmitters. The previously mentioned vault Y runs so that there is a corridor-shaped space below the transmitters and the switchboard. The height of the vault allows a man to walk upright, and the whole space is sufficient to take all wiring runs from machines to switchboard and from switchboard to transmitters. The main wiring was carried out by Drake and Gorham, Ltd. The vault contains, in addition, tanks, pipe runs, auxiliary batteries and pumps necessary for the valve-cooling plant.

Switchboard.

The switchboard on which the outputs of the machines are centralized and controlled before being passed on to the transmitters is divided into four partitions Wa, Wb, Wc, Wd. Wb and Wd deal with the output of the small auxiliary machines in space S1 (see Fig. 2) for grid negative, power supply for the drive, and so on. Wc contains the section for the output of the high-tension d.c. generators in space S2 (see Fig. 2). Wa deals with the output of the filament-supply machines, which are themselves located in the motor-generator room in space S3 (see Fig. 2).

It is obviously essential to arrange the switchboard in such a way that the output of any of the three machines in each group can be diverted to either of the two transmitters. The methods used are straightforward and do

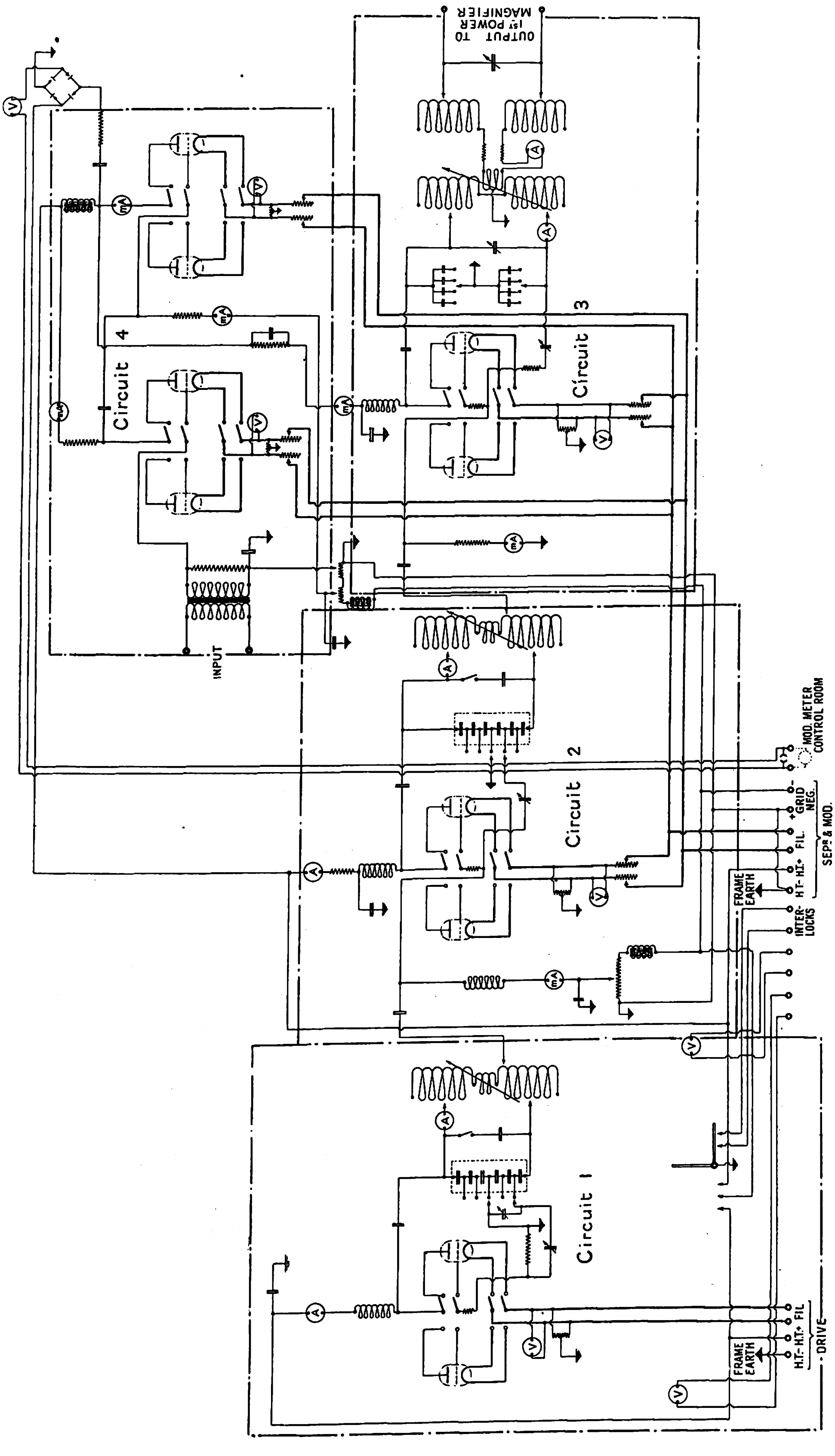
OUTPUT TO 1st POWER MAGNIFIER
Circuit 4
Circuit 3
Circuit 2
Circuit 1
INPUT
MOD. METER CONTROL ROOM
GRID NEG.
FIL.
H.T.+
H.T.-
SEPR & MOD. MAGR
FRAME EARTH
INTER-LOCKS
FIL.
H.T.+
H.T.-
FRAME EARTH
DRIVE
A
V
mA

FIG. 12.—Schematic diagram of unit A.

not merit description in a general paper. The arrangement of the high-tension switchgear which is found in the centre of the switchboard ensures absolute protection of the operating personnel, and none of the live parts comes in contact with the actual face of the switchboard. The instruments are recessed and are protected by a glass window flush with the face of the switchboard. The circuit breakers must of necessity be in such a position that, when they interrupt the current, the ensuing flame does not burn any part of the apparatus. To this end the breakers are placed above the centre part of the switchboard. The front magnetic shields of these breakers are at full positive potential and it is, therefore, necessary to protect them with an earthed expanded-metal screen so as to be absolutely certain that the personnel shall not come into contact with the live parts of the breakers, when carrying long pieces of conducting or semi-conducting material, etc. The smoothing condensers are installed behind the switchboard. The switchboard and doors cut off all access to the components at high tension.

TRANSMITTERS.

(*a*) *General Design.*—A previous paper * outlined the reasons for the adoption by the engineering branch of the B.B.C. of what is known as "low power" rather than "high power" modulation as the basic design for the transmitters themselves. Low-power modulation involves generating oscillations of the required high frequency, modulating them at comparatively low power and then magnifying the resultant by as many stages of high-frequency amplification as is necessary.

Each transmitter proper contains four units, as follows:—

The A unit contains all the circuits for producing modulated, relatively low-power oscillations, the fundamental or middle frequency being maintained sensibly constant even under conditions of maximum distortionless modulation.

The B unit increases the power of these modulated oscillations.

The C and D units comprise apparatus which increases the output of the B unit to the value required for radiation.

The A unit contains four separate shielded circuits, the drive, separator, modulated oscillation amplifier and modulator. A schematic diagram of the A unit is shown in Fig. 12. Circuit 1 is a conventional thermionic-valve oscillation generator. The frequency of oscillation of this circuit determines the frequency of the aerial carrier-wave current. To prevent frequency-change the drive circuit must work into a constant load. This condition is achieved by using a so-called "separator," circuit 2. The output of circuit 2 energizes circuit 3, the modulated oscillation generator. This latter acts to magnify the oscillations passed to it from the separator. The modulator (circuit 4) follows the conventional choke or Heising system, and modulates the intensity of these oscillations in sympathy with the low-frequency currents of modulation fed to it from the local control rooms.

The output from unit A is passed to unit B, which contains a push-pull connection of two water-cooled valves designed to magnify the modulated high-frequency currents fed to it from unit A. The output of unit B is passed on to the identical units C1 and C2. The latter contain banks of water-cooled valves, one unit taking one side of a push-pull circuit and the other the other side. Unit D contains a closed circuit consisting of inductance and capacity which is set into full-power oscillation by connection to the valves in units C1 and C2. Arrangements are made for neutrodyning the various circuits. Schematic diagrams of connections are shown in Figs. 13, 14 and 15.

It will be seen that the system comprises essentially a high-frequency amplifier which magnifies the modulated high-frequency currents generated in unit A. The output of the last stage is passed to the aerials via feeder lines.

It is not thought necessary to include a full description of the transmitter here, because otherwise the paper would be too long, and it is anticipated that a further paper will be written, but, the general lines having been indicated, it will perhaps be of interest to consider some salient points in more detail.

(*b*) *Construction.*—The transmitters were designed by the B.B.C. engineering branch, and were constructed by Marconi's Wireless Telegraph Co., Ltd. They are based on data obtained by the design and operation of an experimental station at the Corporation's transmitting centre at Daventry, familiar to listeners as station 5GB. The transmitters are thus the outcome of experience with an existing experimental "lash-up" which has been tested under conditions of service for over a year.

An attempt has been made throughout to design the apparatus so as to ensure absolute safety for the personnel operating the station. Thus each unit contains all its associated apparatus in an earthed aluminium screen, but where it is necessary to read instruments and keep the apparatus under observation, glass doors give this facility. The cases are so made that access to the apparatus is perfectly easy by opening the doors, but no door can be opened without automatically cutting off the power, as the door handle is connected to a switch which cuts off the supply when the handle is turned to allow the door to be opened. The closed metal construction has the further advantage of minimizing stray fields.

Great care has been taken to ensure that the components of the apparatus shall be sufficiently accessible, and, furthermore, to facilitate the quick change of faulty components these are in most cases not screwed down, but rest on spigots. Thus to remove a component it is only necessary to disconnect the various wires which run to it, lift it out and substitute a new one.

The essential circuits each contain a meter for registering the current or voltage essential to its operation. Thus, among other quantities measured, every valve grid and anode has a separate meter in order that the operating personnel may have continuous assurance that all the valves of the team are behaving identically.

Water-Cooling.—In the Daventry high-power long-wave station, designed five years ago, the insulation of the valve-cooling water, which must, of course, come in contact with the anodes, which are at several thousand volts above earth potential, is obtained by running it through a perforated plate somewhat similar to the rose of a watering can. This breaks up the water into fine drops and achieves practically perfect insulation. By allowing the water to run into the valve through a spray and go out from it also through a spray, sufficient insulation is achieved. There are, however, considerable maintenance troubles with such a system, and small particles of grit inevitably get into the water and are inclined to choke up the fine holes in the spraying plate. In the station being described a more conventional method of running the water into the valves through a coil of large rubber pipe, and forming an exit for the water in the same manner, has been adopted. There is, with this system, some direct-current loss due to conduction of current to earth via the water, and there is furthermore some loss due to high-frequency currents feeding into the pipes as a capacity to earth. However, neither trouble is serious. The actual valve-cooling water is fed into the valves by gravity from a roof tank. It passes, with rubber-pipe entrance and exit, over the valve anodes and thence to a tank in the vault, whence it is pumped through the cooler into the roof tank. The water which comes in contact with the valve anode is thus in a totally enclosed system, and this allows water having the correct degree of hardness to be used. The cooler itself consists of a bank of tubes mounted over an open concrete pond, water from which is sprayed over the outside of the pipes by means of a pump situated in the vault. The cooling system is so designed that the maximum temperature of the valve-cooling water leaving the valve jackets shall not exceed 110° F. under summer conditions. A separate bank of tubes is installed for each transmitter, but the external water system is common to both. This portion of the plant was supplied by Messrs. Rosser and Russell, Ltd. Instruments of the remote-indicating type give a continuous reading of rate of flow and temperature. Great care has been taken to ensure very good cooling of the valves, seeing that some trouble with valve flash-over was experienced on the experimental station. This latter point needs some further emphasis.

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* P. P. ECKERSLEY: "The Design and Distribution of Wireless Broadcasting Stations for a National Service," *Journal I.E.E.*, 1928, vol. 66, p. 501.

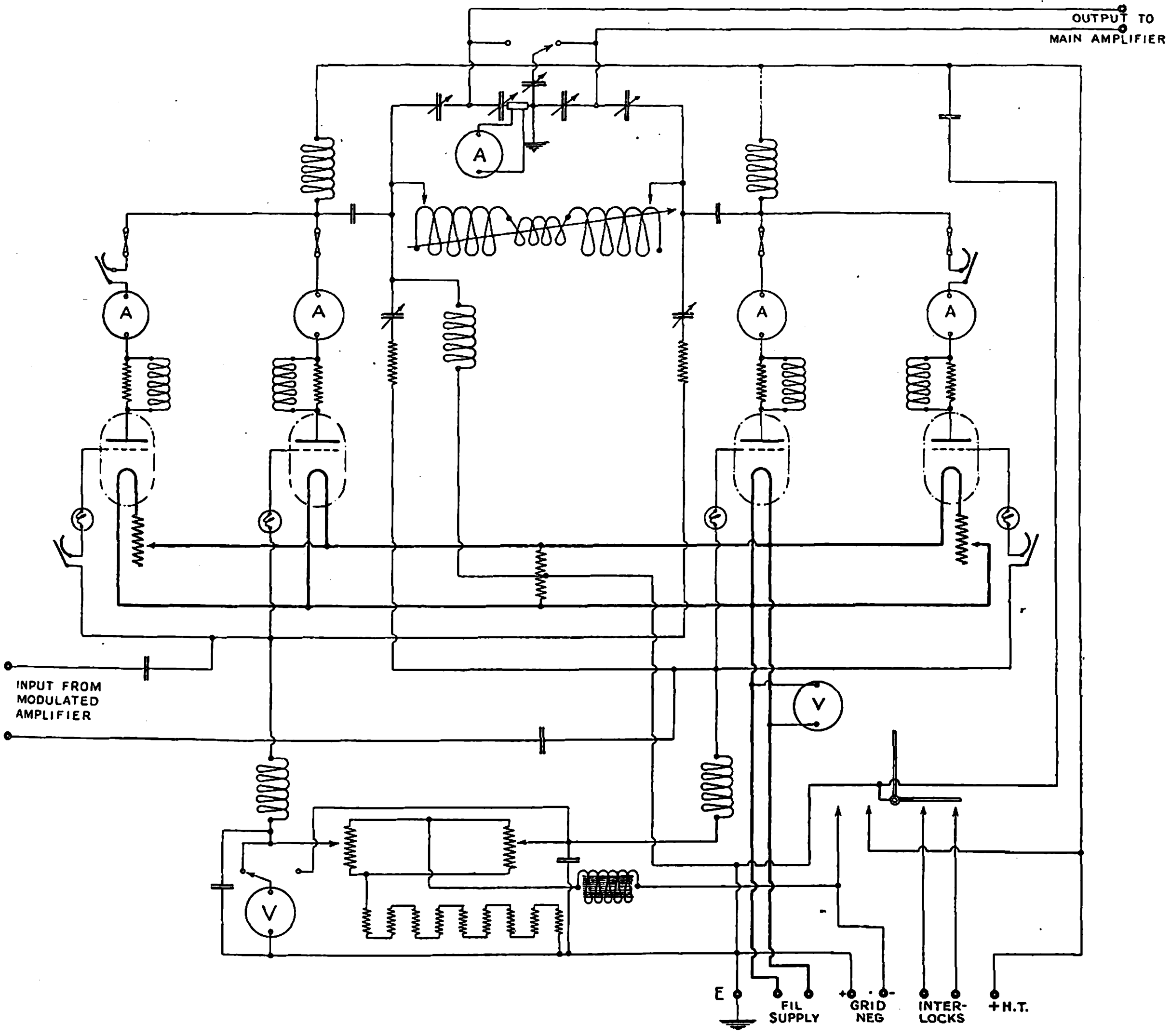

Fig. 13.—Schematic diagram of unit B.

Valve Flash-Over.—The chief difficulty met with at the experimental station was the frequent occurrence, soon after the set had been passed for service, of valve flash-over or "rocky point" effect. These flash-overs caused complete temporary shut-down of the station when d.c. generators were used, but did not cause such serious interruption when rectified alternating current was used; the latter naturally has a greater effect of limitation of current when valve flash-over occurs. While a full discussion is reserved for a further paper, it is interesting to note that the trouble was eventually cured, but there has been no opportunity to determine whether this was due to improvement in valve manufacture or to a rearrangement of the circuit. Originally the 5GB

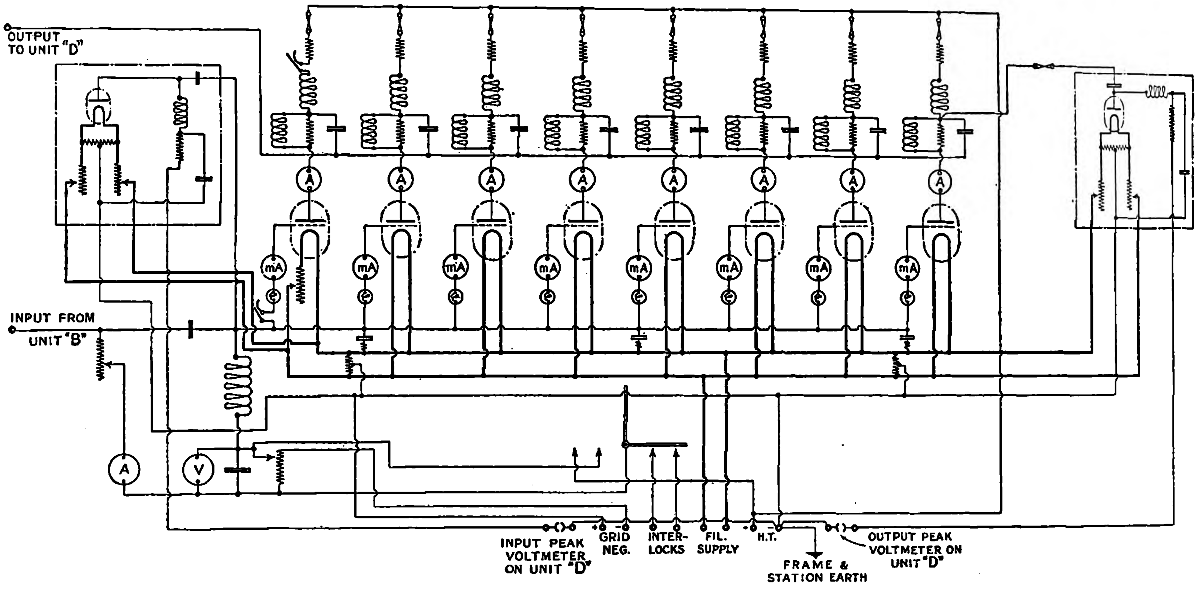
OUTPUT TO UNIT "D"
INPUT FROM UNIT "B"
A
V
mA
INPUT PEAK VOLTMETER ON UNIT "D"
GRID NEG.
INTER-LOCKS
FIL. SUPPLY
H.T.
FRAME & STATION EARTH
OUTPUT PEAK VOLTMETER ON UNIT "D"

Fig. 14.—Schematic diagram of units C1 and C2.

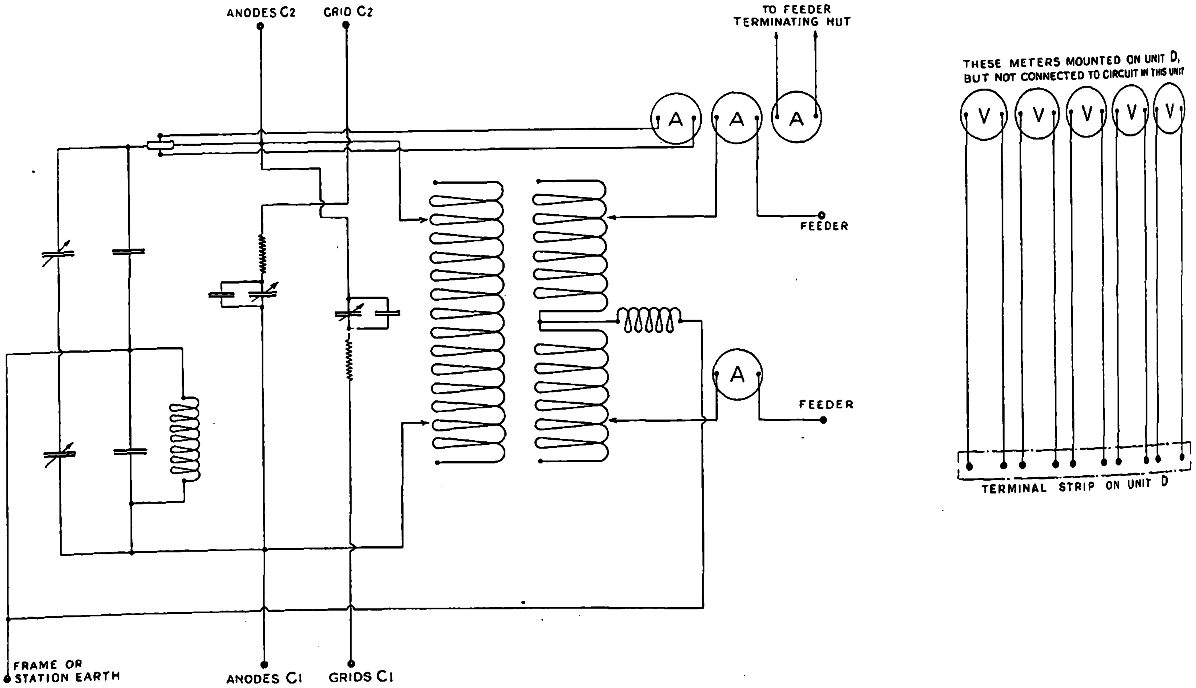
ANODES C2
GRID C2
TO FEEDER TERMINATING HUT
A
FEEDER
FEEDER
THESE METERS MOUNTED ON UNIT D, BUT NOT CONNECTED TO CIRCUIT IN THIS UNIT
V
TERMINAL STRIP ON UNIT D
FRAME OR STATION EARTH
ANODES C1
GRIDS C1

Fig. 15.—Schematic diagram of unit D.

circuit was conventional and worked on to the closed circuit in the usual "top feed" connection. It was noticed that flash-over occurred only when many valves were connected in parallel, and not on the penultimate stage where only two valves in parallel were used. The circuit was changed, therefore, to one in which each valve was fed individually through a separate air-cored choke and in which each valve anode contained a resistance. The object of individual feed was to try to arrange that each of the many valves energizing the last stage could not be influenced by the other valves. This appeared to have an influence in curing the trouble. The resistance was useful in checking incipient oscillations of much higher-frequency value than that which they were intended to magnify, and in minimizing the short-circuit current when valve flash-over occurred. It was finally decided to use a push-pull connection as well as individual valve-feed. Since this connection has been used no flash-overs have been experienced at the 5GB Daventry station, and the new transmitters at Brookmans Park appear to be perfectly stable. The interesting point to notice, however, is that the new circuits were used with new valves of better design (from the valve makers' point of view) and it is still undecided whether the new circuit or the new valves banished the trouble. There has been no opportunity, since 5GB is now a service station, to test the old circuit with the new valves or, much less, the old circuit with the old valves, since these are now either destroyed or in use on other work. The new transmitters, however, are designed not only with a circuit which is apparently stable, but also with every kind of precaution to minimize shut-down if and when "rocky points" occur (see former section of paper).

Quick Valve Replacement.—Great precautions have been taken to ensure reliability of performance. To this end, where there is one particular valve in a circuit which, if it failed, would put the rest of the apparatus out of action, arrangements have been made for throwing in a spare valve without cutting off the power from the particular unit. If, for instance, either one of the valves of unit B fails, the operator of the station can bring a new valve into operation in perhaps 15 seconds or less. To this end, a switch is mechanically arranged so that when the spare valve filament is brought up to full brightness by turning a handle operating a filament rheostat, a spring switch is released which connects the anode and grid of the spare valve. This operation does not, therefore, involve the necessity of cutting off power and water supply, taking out the faulty valve from its water jacket, substituting a new valve and switching on water and power again, as indeed has to be done with the older designs of equipment. The method of quick valve replacement is applied to all units. A carbon tetrachloride type of fuse in the anode circuit of each water-cooled valve serves to disconnect the valve which has become faulty, if indeed the fault has caused a short-circuit.

Measuring Instruments and Remote Control.—It is obviously necessary to ensure that the correct values of current and voltage are supplied to each component of the set, and continuous watch must be kept to ensure correct adjustment of supply voltages. Each transmitter has thus a remote-control table (see C, Fig. 2), and it is intended that the engineer shall sit at this table and keep a continuous watch on the various measuring instruments, which are located not only on the set but also immediately under his eyes on the table itself. Variations are taken care of by handles on the control table which regulate the voltage of supply by field-excitation regulation of the machines concerned. The quantities under direct control of the operating engineer and controlled by handles on the control table are filament voltage and high-tension supply voltage; other quantities also liable to variation can be controlled from the main output switchboard. Controls are also provided for tuning and adjustments on the units themselves.

The transmitter is theoretically capable of 100 per cent distortionless modulation, but distortion must inevitably occur when the input modulation exceeds this quantity. Voltmeters are connected in such a way that the operating personnel can, at any moment, see the amount of modulation. These meters are calibrated with instruments in the local control rooms, so that the general level of the ingoing modulation current can to some extent be regulated by local personnel. (The final authority of control is, however, given to the controlling engineer in the control room local to the studio, and the transmitting personnel, although they are given facilities for altering the degree of modulation, are under orders to make this general rather than momentary.)

Efficiency of Output Stage.—The main power valves are allowed to be operated with grid current, and precautions must therefore be taken against the occurrence of distortion due to variable loads on the input. Great loss of efficiency would occur if the positive grid region were not used. The effect of grid current is overcome by shunting a resistance from grid to filament of the power valves, of such a value that it is small compared with the effective resistance of grid to filament. In the static case, i.e. before modulation, the efficiency of the last stage is 28 per cent. This efficiency increases and decreases with modulation.

Earthing.—The earthing of the transmitter is to a grid of wires which were buried in the ground when the foundations of the building were being laid. There is thus what is called a "general station earth" which is separate for each transmitter. Great importance attaches to the symmetry of the earthing arrangements of the high-frequency units, and great care has been taken to avoid unequal earth paths. The high-frequency earths of the radiating systems are discussed later in the paper.

Feeder Lines.—The high-frequency feeder lines are connected to a high-frequency transformer circuit, the primary of which is formed by the inductance of the closed circuit in unit D, while the secondary is connected to the feeder lines. The feeder line terminates in the transformer house.

Aerial Systems.—The masts (M1, M2, M3 and M4) were supplied by the Foundation Co., Ltd. As will be seen from the general lay-out plan in Fig. 1, they are placed as far as possible from each other and from the building. The designers of the station were faced with the necessity of using relatively short masts. The Air Ministry considered that, in view of the amount of flying that takes place round the area, it would be dangerous to build masts of greater height than 200 ft. With such dimensions the problem is best solved by erecting four masts and placing them, as mentioned before, at the maximum possible distance one from another. Masts M1 and M2 support one aerial, and masts M3 and M4 support the other. A distance of 900 ft. separates one aerial from another. The object of this large separation is to ensure that there shall be no heavy induced currents in one aerial system from the other, and to try to arrange that the induced currents in any mast from the aerial it supports shall be so small as to produce little distortion of the horizontal polar diagram. The masts are insulated from the ground chiefly to give such a flexibility of adjustment that the mast can either be earthed or insulated, depending upon the wavelength used and the amount of distortion of the polar diagram found in practice. It is of interest to note that tests undertaken on specimen porcelain insulators, such as are used on the masts, showed that they were easily capable of withstanding a high-frequency voltage of 10 kV at 1 000 kilocycles per sec. without undue heating. When sprayed either with distilled or " hard " mains water no brushing was apparent. In practice very thin lead washers are fitted between the porcelains and between the mast foot and the end insulators, in order to obtain as intimate and evenly distributed a contact as possible. This was done to avoid local heating, which was observed on test if intimate contact between the metal and the porcelain and between each pair of insulators was not ensured. The technique of distant mast spacing naturally involves the use of a feeder line to conduct the high-frequency energy from the transmitter to the appropriate aerial.

Earth Systems.—A separate high-frequency earth system is arranged symmetrically under each aerial. Each earth consists of a number of copper wires radiating out from each feeder hut—one every 10°—the wires being buried about 9 in. below the surface and of such length that the earth system stretches out to about ¼ wavelength beyond the dimensions of the aerial (see Fig. 1). The wires do not terminate in plates.

OFFICE BLOCK.

The office block (Fig. 2) contains the two control rooms, with their associated battery rooms, offices and rooms for subsidiary apparatus. The offices comprise a general office, an office for the engineer-in-charge, and an office for the maintenance engineers. The ground floor is completed by a garage, waiting-room, hall and lavatories. The upper story comprises a staff mess-room to which are attached a larder and kitchen, and two listening rooms where the quality of the transmission can be checked on loud-speakers. A gallery for access to rooms on the upper story overlooks the transmitter room and gets borrowed light therefrom. The upper story also contains a test room, a studio, and a small room to be used for tuning-fork gear. A detailed description of the above follows.

LISTENING ROOMS.

Two rooms have been set aside for routine quality-checking by loud-speakers and they are intended primarily for use by the engineer-in-charge of a shift. It was considered necessary to provide two such rooms to enable simultaneous observations of the quality of each transmitter to be made by two listeners under similar conditions. There are, in fact, numerous occasions on which it is desirable to use both these rooms at the same time, and for this reason it was not considered advisable to provide only one. The equipment of each room consists of a loud-speaker which normally takes its input from the check receiver, but arrangements have been made to enable comprehensive checking also to be carried out, i.e. the input to the loud-speaker can be taken from (*a*) the B amplifier output, or (*b*) the check receiver output.

TEST ROOM.

A small room has been equipped with the necessary apparatus for taking definite measurements of the performance of either of the two transmitters. The intention is that such measurements shall be made once a week, or more often if necessary. The apparatus contained in this room is also used when any alteration has been made to a transmitter, or when the quality is considered below standard for some indefinable reason, or when special experimental work is in progress. The equipment consists of the following:—

(*a*) Cathode-ray oscillograph, used for checking the degree of modulation which the transmitter will take without distortion, and particularly for observing the linearity with a varying degree of modulation.

(*b*) A constant-amplitude variable-frequency valve oscillator with associated amplifiers, for measuring the frequency characteristics of the lines, amplifiers, etc.

(*c*) Comprehensive loud-speaker checking can also be carried out in this room, so that measurements can be taken simultaneously with observations by ear.

Permanent wiring has been installed between both control rooms and the test room, so that these operations can be carried out without disturbing the apparatus used for the routine transmission of programmes. Running from each transmitter to the test room there are also three screened leads which can be coupled to various points in the main transmitter circuit.

CONTROL ROOM.

Two rooms are provided to house the necessary amplifiers, check receiver and switchgear for controlling and checking the audio-frequency input to the transmitters. Since most of the apparatus has been developed by the B.B.C. specially for use at the Regional transmitting stations, it is proposed to describe it in some detail. Each control room is normally employed in conjunction with the transmitter adjacent to it (see Fig. 2, ground-floor building). Should the necessity arise, however, the control of each programme may be carried out from either position. In order to minimize, as far as possible, trouble from high-frequency currents which might be induced in various parts of the input equipment by the transmitters, the control rooms are screened with copper gauze built into the floor, ceiling and walls, the whole being efficiently bonded and earthed.

In each room the actual control position consists of a small mahogany desk upon which are mounted the volume-control potentiometers, monitoring meters, operating keys, etc., all leads to the desk being laid on an overhead cable rack running from the amplifier racks. Upon the latter are mounted the checking apparatus, the " A " and " B " amplifiers, etc., and, in the case of No. 2 control room, the cable terminating and testing equipment. An " A " amplifier is inserted between the " B " amplifier and the microphone when the studio is in use. The output of a " B " amplifier is connected to the input of the transmitter, while its input is derived either from the cable line to Savoy Hill or the output of an " A " amplifier.

There are two battery rooms, one adjoining each control room, that adjacent to No. 1 control room containing the anode-supply batteries and the other the filament batteries with their charging generators.

CABLE CIRCUITS.

There are five cable circuits to Savoy Hill, of which four are unloaded and suitable for music transmission, whilst the fifth is lightly loaded and is intended mainly for general communication purposes. The lines are terminated on " U " links in No. 2 control room, from which point the circuits are brought via line fuses to screened repeating coils, the latter being essential in preserving accurate capacity balance between cable and earth.

Distribution of Cable Circuits.—The secondaries of the repeating coils are brought to connection strips at the top of the test rack, at which point the actual distribution of the circuits takes place. Double jumpers connect each music line to two sets of break jacks, upon which terminates the internal wiring from the respective control desks, the main purpose of the jacks being to enable a line to be isolated from either desk should a local fault occur.

On the desks each line is common to two 3-position keys, and a " busy " lamp associated with the line in question lights on each desk as soon as one of the keys in either control room is moved from a central position and a line thus occupied.

The functions of the two keys are:—

(1) To connect a line to one or other of the " B " amplifier inputs (there are two sets of amplifiers in each control room); or

(2) To connect a line either to the break-jack field on the test rack in No. 2 control room or to the desk control telephone common for communication purposes.

With regard to the fifth line, a jumper brings it to a break jack, from which connection is made to a key on No. 2 control desk. This key, when in the normal position, connects the line through to the office, and when in the " off normal " position brings the line to both control desks, where it can be utilized in the same manner as the other lines. A " busy " lamp glows on each desk as soon as this line is occupied.

Communication with Savoy Hill.—During transmission one line is employed on each desk for communication purposes, and should this or one of the music lines fail, two courses are open, one being to utilize the office line (No. 5) and the other to share the remaining control line between both control desks. Obviously, wherever possible, the office line is used for communication and not for transmission purposes, owing to its comparatively bad frequency characteristic.

Each control position is provided with a ringing machine and a hand microphone-telephone set, the latter hanging conveniently at the side of the desk.

AMPLIFIERS.

Each control room is provided with a single " A " and two " B " amplifiers, the former being for use in connection with the local studio equipment as indicated above.

The amplifiers are mounted on the apparatus rack, their feed meters and the microphone current meter being fitted in a panel above them, whilst the " B " amplifier control potentiometers are placed in a convenient position on the control desks.

For test purposes both inputs and outputs of all amplifiers are terminated on break jacks, a strip of which is mounted on each amplifier rack. The amplifier filament circuits are completed by means of keys, placed within reach of the control engineer, on the rack just above the amplifiers themselves. H.T. and L.T. fuses are connected in each circuit.

CHECKING RECEIVER.

Each control room is provided with complete equipment for checking by wireless reception.

The performance for which the receiver was designed is as follows:—

Selectivity.—The receiver is to be capable of completely cutting out signals of equal strength separated by 50 kilocycles per sec. from the frequency to which the receiver is tuned, the selectivity to be such that there is no audible trace of the interfering signal.

Audio-Frequency Response.—The overall frequency-response characteristic of the receiver should be flat from 20 to 10 000 cycles per sec. within $\pm\ 0\cdot5$ decibel.

MONITORING ARRANGEMENTS.

(*a*) *Visual.*—Three meters are available for visual monitoring at each control desk, these being the modulation meter, the slide-back galvanometer and the speech-choke voltmeter. The latter is operated in series with that joined across the speech choke in the anode circuit of the modulated magnifier stage of the transmitter, and is calibrated accordingly. As a general rule this voltmeter is used in preference to the other meters, as it gives the engineer more direct check over the performance of the transmitter.

Slide-Backs.—Each control room is fitted with a standard slide-back unit, incorporating two separate instruments. These are each connected permanently across one of the " B " amplifiers, separate meters being mounted on the control desks.

A slide-back unit consists of a triode valve with a negative grid-potential, the low-frequency input to which can be adjusted accurately by means of a potentiometer. A sensitive d.c. milliammeter is connected in the plate circuit to indicate when anode current is flowing. The grid and anode potentials of the slide-back valve are set, and the input potentiometer is so adjusted that anode current flows only when the transmitter is receiving its maximum audio-frequency input.

(*b*) *Aural.*—Loud-speakers, operated by the comprehensive checking amplifier, are available for programme checking in both the quality rooms and the control rooms, although routine checking is carried out by means of headphones only in the latter. Jacks for the headphones are fitted at each transmitter control desk and in both control rooms, so that, if required, both programmes may be heard by the engineer on duty.

In order that telephonic communication may be carried out without interruption when the loud-speaker is in use, a pair of contacts from the desk telephone speak-ring key are arranged to operate a relay which breaks the loud-speaker circuit when the key is in the "speak" position.

The loud-speaker amplifier is not used for routine monitoring, but feeds loud-speakers in the test room, engineer-in-charge's office, mess room and waiting room, etc. Two lines are run to each of these points, one from each checking equipment, and a pair of jacks is provided to enable a choice of programmes to be made.

Test Rack.—As previously stated, any of the five circuits from Savoy Hill may be brought to the break-jack field on the test rack in No. 2 control room, by throwing a key on one or other of the control desks. Similarly, all amplifiers, etc., are terminated on break jacks, and they may thus be utilized for test or tested themselves by connecting them to the break-jack field by means of double-ended cords. Tie lines are brought from the jack field in No. 1 control room to that in No. 2, in order that the apparatus in the former may be available for use in the test bay.

Break Jacks.—All break jacks employed on the apparatus are of the double type, i.e. they consist of two 3-point jacks (tip, inner and sleeve) mounted one above the other.

The plugs used in connection with these jacks are serrated on one side of the grip, in order that polarity may be traced when they are used on a double-ended cord.

APPARATUS FOR MAINTAINING ACCURACY OF RADIATED CARRIER FREQUENCY.

A room has been set apart for apparatus for maintaining a specially high degree of constancy of the carrier wave of one of the transmitters. This has been done to cover the possibility of working one of the transmitters on the same radio frequency as one or more other B.B.C. stations. The system used at present for several of the smaller transmitters working on a single frequency depends on a thermostatically controlled tuning-fork, which produces a constant frequency of the order of 1 000 cycles per sec. This frequency is then multiplied by frequency-doubling amplifiers until the required radio frequency is obtained.* It is possible that such apparatus may also be installed at Brookmans Park for the purpose of emitting a standard frequency of declared accuracy, which would be of the order of 5 parts in a million, assuming the tuning-fork method of drive. Working the station as it is at present, i.e. relying only on the master oscillator, which is a D.E.T.2 valve working at a power level of about 200 watts, provided with filament heating from a battery and a separate motor-generator for the anode supply, the accuracy is of the order of 300 cycles over a period of two or three days for a carrier-wave frequency of 1 148 kilocycles per sec.

STUDIO.

A small studio has been provided in order to enable tests to be carried out locally, and for use in emergency. The walls are treated in the normal manner in order to give satisfactory results acoustically. Gramophone apparatus has been installed in addition to the usual microphone equipment.

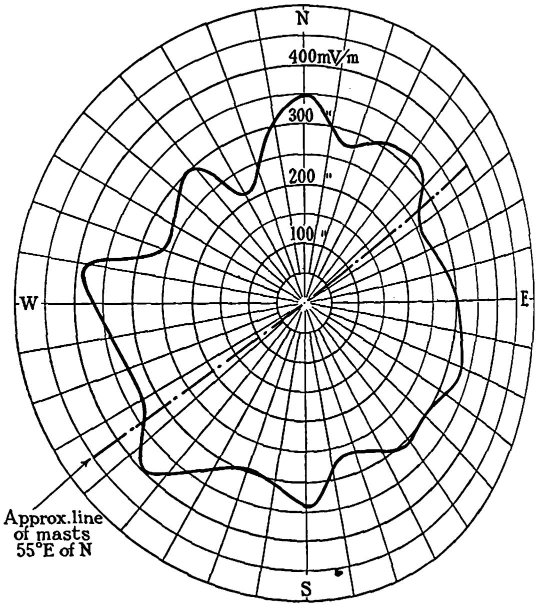

FIG. 16.—Polar diagram of 356-m transmitter, with approximately 30 kW in the aerial.

ALARM SYSTEM.

In order to summon the engineer-in-charge of a shift to any part of the building where assistance may be required, a system of coloured signal lights has been installed in several positions, such as the transmitter hall, power house, control rooms, etc. One particular colour is associated with each point, for instance a red lamp may indicate the power house, a blue lamp the transmitter hall, etc. When assistance is required, the attendant presses a button on the wall and a lamp having the colour allotted to that particular room lights up in all the other rooms where the shift engineer is likely to be, a bell ringing in each room at the same time in order to attract his attention to the lamp. The engineer can then proceed straight to the room indicated. This system, together with the internal telephone system, was installed by Ericsson Telephones, Ltd.

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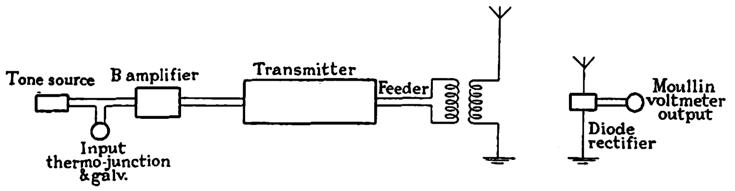
* P. P. ECKERSLEY and A. B. HOWE: "The Operation of Several Broadcasting Stations on the same Wavelength," *Journal I.E.E.*, 1929, vol. 67, p. 772.

GENERAL PERFORMANCE OF THE STATION.

The effect on the listening public of the change-over from a low-power station situated in the centre of London, to a comparatively high-power station approximately 15 miles due north of London, has already been discussed in an earlier section of the paper. This concerns, of course, the transmitter which is tuned to a frequency of 842 kilocycles per sec. (356·3 m). The input to the high-frequency feeder lines in this case is approximately 30 kW, and the polar diagram of field strength for this power, when taken at a distance of 5 km from the station, is shown in Fig. 16. It must be realized that polar diagrams express a mean of field strength, and that idiosyncrasies of particular localities produce large variations from this mean.



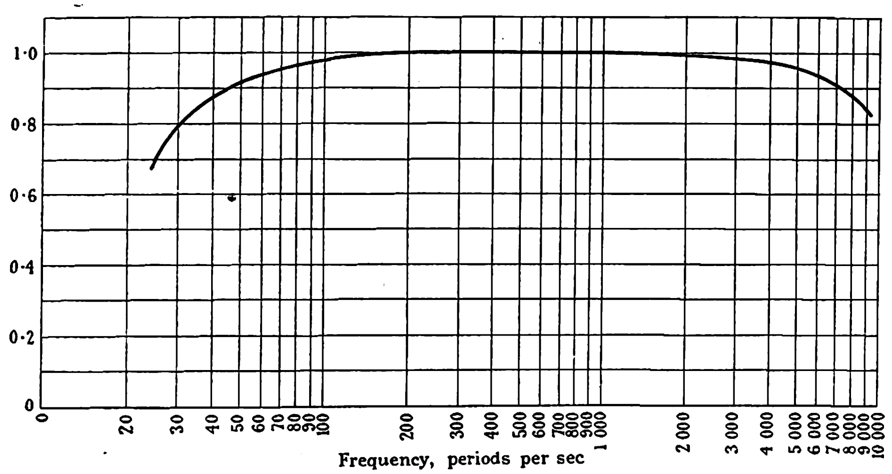


FIG. 17.—Overall response curve of 356-m transmission.

Fig. 17 gives the overall frequency-response curve including the "B" amplifier, transmitter and aerial. The response of the transmitter to varying amplitudes of audio-frequency input at a given frequency is sensibly flat up to 100 per cent modulation. The frequency of 842 kilocycles per sec. (356·3 m) is transmitted on the north masts, which are insulated at the base. The effect of the masts under these conditions is negligible at this frequency. As will be seen from Fig. 1, the two aerials are parallel and the distance between the line of each aerial is 900 ft. At this distance the effect of the masts of one transmitter on the other is also practically negligible, whether they are earthed or unearthed. This fact is apparently due to the distance alone, because the effect on either transmitter of earthing or unearthing the masts of the other transmitter is very small, while the effect of earthing or unearthing the masts in use for either transmitter is very considerable. In the case of the 1 148 kilocycle-per-sec. (261·4 m) transmitter the polar diagram can be varied by different methods of earthing the masts, and work on this problem is still proceeding, but the conditions of working at the time of writing the paper are shown in Fig. 18. The power supplied to the aerial system has since been raised to 45 kW.

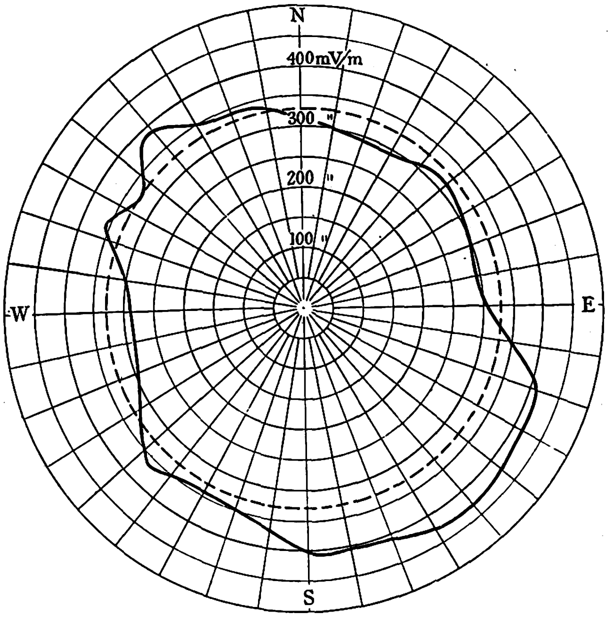


FIG. 18.—Polar diagram of 261-m transmitter with approximately 30 kW in the aerial.

Observations of variations of frequency of the carrier wave due to modulation (frequency modulation), made both in the static and dynamic conditions, indicate that this was so small that it was extremely difficult to obtain any definite figure.

No difficulties of an interesting nature were encountered when testing the station in the preliminary stages, although the transmitters had not been tested as complete units at the makers' works. Certain minor defects and omissions of little importance showed themselves, but in no case was any major alteration made.

It had been anticipated during the design stage that some difficulty would be experienced from "cross-talk" between the two programmes. There was, of course, the possibility that there might be some mutual high-frequency effect between the two transmitters themselves and between the feeder lines and aerial systems, but this effect was found to be absent to a rather remarkable extent. When the transmission from one aerial was unmodulated and a pair of telephones was connected across the check receiver at a point where the power level was suitable for a loud-speaker, no trace of the modulated radiation from the other transmitter could be heard. This was carried out with the control-room apparatus disconnected from the transmitter under test. This test is, of course, extremely drastic because no practical listening could be carried out under equivalent conditions. However, when one transmitter was radiating a programme and the other was emitting an unmodulated carrier, but with the input apparatus fully energized, distinct cross-talk was audible. This was found to be due to the fact that two earths had been provided for each control room, on the principle of a "silent" and "noisy" earth. The filaments of the amplifier valves were connected to the "silent" earth, and the amplifier screening-boxes and the gauze screen enclosing the whole control room were connected to the "noisy" earth. This scheme of connections resulted in a pick-up of the modulated high frequency from the other transmitter, which found its way through the amplifier to the transmitter, becoming sufficiently rectified on the way to produce an audio-frequency component of the unwanted programme. This was rectified very simply by using a common earth for all apparatus in the control room, no other effects being introduced by this altered method of connection.

CONCLUSION.

The authors' thanks are due first of all to the Governors of the British Broadcasting Corporation, for permission to publish this paper, and to the following members of the B.B.C. staff, who have made considerable contributions to the design and construction of the station itself: Mr. H. Bishop, the assistant chief engineer; Mr. H. L. Kirke, head of the research department, and his assistant, Mr. T. C. Macnamara; Mr. M. T. Tudsbery, the civil engineer; and Mr. B. N. MacLarty, head of the installation section. Finally, thanks are due to Mr. L. W. Hayes, for assistance in correcting diagrams and proofs, and to Mr. J. E. Calverley, of the English Electric Co., for supplying information in connection with the large high-tension motor-generators.

DISCUSSION BEFORE THE WIRELESS SECTION, 7TH MAY, 1930.

Col. A. S. Angwin: I am very interested in the essential differences between this, the most modern wireless station for broadcasting, and the general practice in radio-telephony stations for commercial point-to-point working. One of the most striking features of the new station is the finality which presents itself in the lay-out. It is obvious that the authors are not contemplating turning their twin transmitters into triple transmitters at any very early date; neither are they likely to embark on a competition with European broadcasting stations in augmenting the power of the station. The ground space is adequately filled and they have presented a complete lay-out sufficient for the immediate problem, without provision for expansion in the future. I think that this limit to the possible expansion must have largely influenced the authors in deciding whether to take power from outside or to use a self-contained system. For a station of this power (500 kW) and with the very good running load-factor, the conditions are undoubtedly as favourable as they could be for a self-contained power system, but the statement actually made by the authors in dealing with the question of their choice: "Moreover, it is possible to generate locally at approximately the same cost as, or in some cases a considerably lower cost than, that at which power can be bought," merits some attention. The authors' contention does not agree with our experience for power supply to commercial radio stations. From the remarks which Captain Eckersley made in presenting the paper, I gather that cost was not the main consideration. If power of the order of 500 kW can be generated locally more economically than it can be bought in such a location as London, close to a power supply, it does not reflect favourably on the scheme for the adequate supply of power at a reasonable cost which is at present covering the country. With regard to the factor of breakdown, the authors state: "It is interesting to note that 'shut-downs' of considerable duration at broadcasting stations have frequently been due to failure of the public supply mains." This seems to be a grave reflection on the reliability of a public supply. I think that, in spite of the fact that provision has been made for a complete spare Diesel engine and generator, the other sources of trouble common to the motor-generator plant are in themselves as likely to cause interruption as anything that might normally be expected from a well-regulated outside power system. It is interesting to note that the designers have stood their ground and have provided for a high-tension d.c. supply rather than a rectified a.c. supply. It is obvious, however, that consideration of the trouble which they have experienced was ever present with them when the station was designed, and precautionary measures have been necessary, such as the addition of chokes and resistances in the anode supply to the valves. The device of adding a resistance at each anode feed is, it seems to me, essentially a compromise. It is clear that much work remains to be done on the problem of connecting a high-tension d.c. supply from a motor-generator direct to water-cooled valves such as those at present in use. The insertion of a resistance of the high order of 500 ohms directly in the feed circuit seems rather like throwing away the efficiency which is striven for by the use of high-tension d.c. generators. I have made a small calculation which shows that a resistance of 500 ohms dissipates about 0·5 kW of energy in the anode supply to each valve. Taking the cost of power as 1d. per unit, this is ½d. per hour per valve. I estimate that the valves themselves are costing 3½d. per valve per hour to run. From this, it seems that unless an increase in the life of the valve of the order of 14 per cent is secured it is a very uneconomic means of providing for a lengthening of valve life. I presume that the station has not been running long enough for any figures to be available as to what order of life is being obtained from the valves, but it is of importance to consider how much one can afford to waste by adding resistance in the anode circuit of a valve in order to improve the life of the latter. There are other considerations which have doubtless carried weight with the designers, such as greater security from temporary breakdown. It is stated on page 1168 that the present accuracy of frequency is of the order of 300 cycles per sec. in 1 148 kilocycles per sec. I congratulate the designers on having at once obtained a tolerance which was suggested at the last C.C.I.R. Conference. This is done by the use of a master oscillator. The C.C.I.R. has also recommended that within a short time this limit of tolerance of a broadcasting station should be brought down to 50 cycles. It would be interesting if the authors could give some indication of how they hope to achieve this, whether by means of a master oscillator or by the use of a tuning fork. A photograph of the high-frequency transmission line has been shown on the screen and it is briefly mentioned in the paper. Some details of the actual type of line employed would be of great interest. I should also welcome further information regarding the methods which the authors have adopted for altering the shape of the polar diagram (Fig. 18). I infer that there is more involved than merely insulating or earthing the masts; presumably something in the nature of a tuned circuit is interposed between mast and earth.

Mr. J. E. Calverley: I should like to refer to the high-tension machines used in the station. The firm with which I am associated has been manufacturing high-tension machines for over 20 years. The first were built about 1907 and were of 50-kW capacity at 5 000 volts. They had air-insulated commutators, and insulated foundations and couplings. The present machines have been developed in the course of time from those original sets. In the meantime, about 20 different sets have been built for voltages of 10 000 and over. The first machines were used for telegraphy, and four were connected in series to give 20 000 volts. To prevent large variations of load on the generators a battery of 10 000 cells was used in parallel. There was an air of experiment throughout, but in the present station there is apparently nothing experimental at all. The machines are normal, the lay-out is normal, the cables are taken in an orderly manner in ducts and there is little to distinguish the station from one running at 500 volts d.c. This very real progress is the more evident by reason of its unobtrusiveness. The first point upon which a designer would seize when designing the high-tension machine is the apparent advantage offered by 2-pole windings with wide spacing from brush to brush. The machines adopted by the authors are of the 4-pole type, and only when one is building a 2-pole machine is its weakness apparent. The insulation to earth and between conductors of the long end-windings is a difficult matter with 2-pole machines. In d.c. machines, where the slot pitch is limited by commutating conditions, the maximum thickness of insulation is probably in the neighbourhood of 0·1 in., and with 10 000 volts to earth the stress on the slot insulation is then 100 000 volts per inch, which is too high for continuous operation. For this reason it is usual to insulate the machines from earth, but this has its disadvantages, being expensive and dangerous and necessitating insulating couplings. It is quite a definite step forward to take such precautions that the insulation stresses are graded throughout from positive to earth in such a way that the stresses are normal and, further, that they are so controlled that no undue stress can arise in any part, even in the case of accidents. I should be interested to know how extensive a development of high-tension machines will be required during the next few years. What outputs and voltages will be required? It is difficult to design machines for wireless experts owing to their constant new demands, but the limit of size for this class of machine does not seem to be in sight. It will be safe to make much larger machines than have been built up to the present. In view of the general popularity of rectifiers, I think that much credit is due to the engineers of the B.B.C. for adopting d.c. machines with their higher efficiencies and greater robustness.

Mr. E. H. Shaughnessy: I am interested to see that the B.B.C. have taken up the closed water-cooled system. I believe that the first closed system was installed at the Rugby radio station, where we used distilled water. I am also glad to note that the authors have adopted the practice which we favoured at Rugby of using d.c. machines for the high-tension supply to the valves. At Rugby we have d.c. machines made by the British Thomson-Houston Co., each unit of which is of 250 kW, has only one commutator and gives 3 000 volts, so that with two machines we develop a pressure of 6 000 to 7 000 volts for the high-tension supply. These have now been running satisfactorily for some years. I congratulate the engineers of the B.B.C. on the performance of the Brookmans Park stations. The reception that we obtain in South London is quite as good from the new station as it was from the old 2LO. On Sunday last, however, I was listening to some very quiet music, by Wagner I think, on the National programme, when I heard a religious service which was being broadcast on the same wavelength, and which was also being radiated from the second Brookmans Park transmitter. On testing my receiver I found that nothing was wrong with it. I should be interested to know whether this overhearing was due to the land lines, some coupling in the station at Brookmans Park, or the arrangement at Savoy Hill.

Mr. P. K. Turner: The new station has a good audio-frequency response curve—far better than that of any other broadcasting station I have seen. In connection with the possibility of good reception from the station, I notice that it is so designed that it can be modulated up to 100 per cent without distortion. I do not know quite what this means. Can the authors give figures showing what they regard as the mean and the peak modulation percentages of the transmitter? I would ask them not to make these figures too high, as although there is everything to be said, from certain aspects, for pushing up the modulation, it rapidly becomes almost impossible to rectify this in the receiver without undue distortion. It is quite easy to rectify matter which is modulated 60 per cent, but with modulations of 80 or 90 per cent it becomes increasingly difficult to rectify without bad wave-form distortion.

Captain P. P. Eckersley and **Mr. N. Ashbridge** (*in reply*): Colonel Angwin questions *inter alia* whether more allowance should have been made in the general design of the station for future extensions. The existing plant allows for an output from each transmitter of 50 kW, although it was intended to operate them with an output of 30 kW. The latter power was actually used when the station was opened, but in the case of the transmitter using a frequency of 1 148 kilocycles per sec. (261·3 m) the power has since been raised to 45 kW in order to minimize, as far as is possible, the effects of local shielding, which are somewhat severe in certain districts on this comparatively high frequency. We doubt whether a large increase in power over and above 50 kW to the aerial is justifiable economically, for transmitters using these frequencies when considered in relation to the increased performance obtained. With regard to the question of a large-scale extension, such as the installation of a complete additional transmitter, sufficient land is in fact available.

Colonel Angwin has expressed surprise that it should be possible to generate electric power locally at a price comparable with that charged by a public supply company. In this connection it has to be remembered that the nature of the load is very advantageous, and with Diesel engines operating at their optimum load the cost of generation should be low. In comparing the two possible methods of providing power, account must be taken, firstly, of the fact that the provision of some proportion of stand-by generating plant was considered to be essential on account of the prime necessity of continuous service; and, secondly, of the cost of cables and substation plant. With regard to the question of the relative reliability of a public supply as compared with local generation, it is not really a comparison of the reliability of one generating station with another, because in our experience the failures of public supplies have almost invariably been due to the mains and not to the generating stations. It is true that failures elsewhere in the station are likely to be more frequent than supply failures, but the breakdown of a single component cannot be compared with the complete failure of supply, which entirely puts out of action both transmitters, together with all auxiliary plant such as motor-generator sets, water pumps, etc. Apart, therefore, from the duration of the actual mains' failure, some additional time is lost in restarting the whole station.

We agree that the insertion of a 500-ohm resistance in the anode supply lead to each main power valve is a compromise, but it is hoped that with improved valves this may not be necessary in future. It is done at present more to minimize the effect of an unstable valve than to lengthen the life of the valves, although to an extent the latter is an additional advantage.

Colonel Angwin inquires what steps could be taken to increase the constancy of the carrier frequency, should this become necessary. It is probable that a thermostatically controlled tuning-fork will be used, but the possibility of a "crystal " drive will not be overlooked. The whole question is actually bound up with the ultimate object in view; for instance, whether constancy is most desired, and whether absolute accuracy is necessary in addition, and so on. It should be explained that the stability of carrier frequency of 300 cycles per sec. in 1 148 kilocycles per sec. mentioned in the paper is obtained without any day-to-day readjustment of the drive circuit of the transmitter. This figure is reduced in practice to a variation of about 100 cycles per sec. by an occasional slight re-adjustment of the drive to take account of temperature variations, the amount of re-adjustment necessary being indicated by a wavemeter of the type designed by the Union Internationale de Radiodiffusion.

The feeder lines are composed of 19/·044 phosphor-bronze wire, supported on tubular posts 13 ft. high. The insulators are of standard pattern, and were tested at 7 000 volts, 1 200 kilocycles per sec., for 4 hours. There is nothing unusual in the construction of these feeder lines, and similar feeders have been erected elsewhere in the B.B.C. system. Data as to how the shape of the polar diagram was corrected are not yet available for publication. It is probable, however, that they will be contained in a future paper.

Mr. Calverley inquires what outputs and voltages are likely to be required for high-tension d.c. motor-generator sets in the future. We do not consider that it is possible at the moment to estimate the future requirements of designers of broadcasting stations. There are, of course, alternative methods of producing the necessary high-tension direct current for wireless transmitters, and it is difficult to say which will ultimately gain the most favour for all types of radio stations. Speaking of broadcasting, it would appear that with a self-contained plant high-tension d.c. generation is most economical and flexible. If, however, a.c. mains supply is used, it is possible that the mercury-arc rectifier would show substantial economies over any other system. From the point of view, however, of the particular station under discussion, the mercury-arc rectifier is not considered to be superior to d.c. generation, and, therefore, there seems to be an important application for the method adopted by the Corporation.

Mr. Shaughnessy refers to cross-talk which occurred on a certain occasion between the two programmes radiated from Brookmans Park. It is true that cross-talk has occurred on occasions, but in most instances this has not been due to the transmitting station itself. There has been cross-talk between external telephone lines as well as in the control room at Savoy Hill, but in both cases steps are being taken by the Post Office and the B.B.C. respectively to reduce the number of occasions on which it occurs.

In reply to Mr. Turner, whilst it is true that the paper states that the transmitters are capable of being modulated linearly to the extent of 100 per cent it does not mean that the transmitters are necessarily run under these conditions. It is not possible to give a definite figure for the average modulation of a transmitter, because this varies with every type of programme. The maximum peak modulation normally reaches about 80 per cent, and the average is very roughly in the neighbourhood of 20 per cent, but, as already mentioned, the latter figure cannot be stated with accuracy.

DISCUSSION ON

"THE DEVELOPMENT OF A PRECISION AMMETER FOR VERY HIGH FREQUENCIES." *

Mr. W. F. Dunton (*communicated*): In Section (2) of the paper the author quotes a well-known but incorrect formula for the electromagnetic force between parallel conductors. The correct formula, first published by me in 1927, is now widely known among electrical engineers on the Continent. If two straight parallel conductors, each s cm long, have a direct current of I amperes uniformly distributed over their circular cross-sections, and if the distance between their axes is a cm, the force (in pounds) with which these conductors tend to attract or repel each other (according to whether the currents are similarly or oppositely directed) is not $4 \cdot 5\,(I/10\,000)^2 s/a$ but $4 \cdot 5 (I/10\,000)^2 \left\{ \sqrt{\left[(s/a)^2 + 1 - 1 \right]} \right\}$. Mr. Moullin says that the force is given by the first of these expressions when the conductors are "long"; but he does not give any idea as to the length which he has in mind, and he does not give any formula for other lengths. The second expression will, however, give the actual force in all cases and, to an engineer with a slide rule, is almost as convenient as the first. In a circuit breaker $(s/a)^2$ is frequently less than $\frac{1}{4}$, and in such cases the last factor in the second expression is approximately $\frac{1}{2}(s/a)^2$. The results given by the first expression are then $2a/s$ times what they ought to be. But a/s is frequently greater than 3, and the results obtained with the first expression are then more than six times what they ought to be, no matter how long the conductors may be. On the other hand, if $(s/a)^2$ is much greater than 1, the last factor in the second expression becomes approximately $(s/a - 1)$. Therefore, even where the length of each conductor is many times the diameter while the distance between their axes is only a few times the diameter of either conductor, the first expression would be improved by substituting $(s/a - 1)$ for s/a, a change which obviously does not make the formula less convenient. A detailed proof of the formula will be found in the *Journal of Scientific Instruments* dated November 1927, and in the *Revue Générale de l'Électricité* dated 12th May, 1928.

Mr. E. B. Moullin (*in reply*): The expression $F = 2I^2D$ per unit length is of course the limiting value which is approached when the length of the conductors is very great compared with their distance apart. In lines 20 and 24 of page 548 the length is given as 10 cm, and at the bottom of the second column of that page, and at the top of the second column of page 550, the value of D is found to be $1 \cdot 11$ cm for one instrument and $0 \cdot 87$ cm for the other. The length of the conductors is therefore about 10 times the distance between their centres. The approximate form of Mr. Dunton's formula, namely $F = 2I^2(s/D - 1)$, is a very useful and convenient abbreviation of the correct expression for the force between wires of finite length. It shows that the force in these instruments is about 10 per cent less than is given by $F = 2I^2/D$ per unit length. This deficit produces no real error, because the instrument is calibrated from another ammeter and not from the measured value of the force. It has also a small effect on the correction factors, but the effect is of the second order of magnitude. The total correction factor for proximity is about 4 per cent; over a small portion of the length this factor will be perhaps a little less than 4 per cent and so the total factor will be reduced by a very small amount, certainly less than 10 per cent. But the factor itself is small, so the correction to the correction is negligible and quite outside the accuracy of reading. The effect will be more pronounced in the correction factor for the screen tube and this is implicit in the statement near the bottom of page 550. The screen factor can, however, be measured and we need not rely on calculated values; thus it is found to be $6 \cdot 6$ per cent when the calculated value was 8 per cent. The effect of the finite length of the cylinders has been fully appreciated, but it has no measurable effect on the accuracy of the instrument, because the calibration is made from another ammeter. The "effect of irregularities at the ends of the system" was also dealt with in section (8) on page 67 of vol. 121 (1928) of the *Proceedings of the Royal Society*.

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* Paper by Mr. E. B. Moullin (see page 544.)

GENERAL FORMULÆ FOR THE RADIATION DISTRIBUTION OF ANTENNA SYSTEMS.*

By R. M. WILMOTTE, M.A., Associate Member.

[From the National Physical Laboratory.]

(*Paper first received* 12*th September*, 1929, *and in final form* 27*th February*, 1930.)

SUMMARY.

Formulæ are given for the distribution of radiation in different directions. The paper is divided into the following sections:—

(1) Introduction.
(2) Antenna elements.
(3) Polarization.
(4) Current distribution.
(5) Effect of image in the ground.
(6) A straight wire inclined at any angle.
(7) A system of similar antennæ spaced in any given manner.
(8) A system of antennæ uniformly distributed around the circumference of a circle.

A number of special cases are deduced from these general formulæ, and curves are given to facilitate computation.

(1) INTRODUCTION.

It was considered that it might be of value to combine in one paper some general formulæ for the distribution of radiation from antennæ in various directions as far as present theories permit. These theories are not yet rigorously established and much experimental confirmation is still required. Many special cases of radiation from antenna systems have already been worked out by a number of authors. These, as far as they are known to the present author, are given in the Bibliography [items (1) to (10)]. Most of the formulæ are special cases of those given below, but special credit should be given to Abraham,† who initiated the principle of representing an antenna by a series of doublets, and to Pierce,‡ who first extended it.

In employing the formulæ given below it must be remembered that all the conducting currents must be taken into account. The presence of masts, stays and even underground conductors may affect the radiation distribution of an antenna system to a very considerable extent, owing to the currents induced in these conductors from the main antenna system. The extent to which this may occur is strikingly shown when an attempt is made to screen a portion of an antenna. Smith-Rose and Barfield § published some interesting results on this subject. They found that, on long waves, practically no effect on the signal strength was produced when the vertical portion of an inverted "L" antenna was surrounded by a metal screen. Evidently the currents induced in the screen induced in the horizontal portion an e.m.f. roughly equal to that which would have been induced in the vertical portion of the antenna had the screen not been there. Removal of the horizontal portion reduced the signal practically to zero. If such is the case it is to be expected that considerable alterations in the radiation distribution may be expected to be produced by any neighbouring conductor. It is probable that the result obtained by many workers, that a horizontally polarized ray on the ground is always rapidly rotated into a vertically polarized ray, is largely due to this effect. The horizontally polarized ray is so rapidly attenuated compared with the vertically polarized ray that its strength at any reasonable distance is negligible and the signal received is produced by vertical conductors in the neighbourhood of the transmitting system. This may also be produced by groups of horizontal and vertical conductors sufficiently close to the transmitter for the currents induced in the horizontal members to induce sufficient current in the vertical members to enable a definite signal to be received on a vertical antenna at a reasonable distance.

Many of the formulæ given below are very cumbersome. For computation purposes the curves given in Figs. 4 to 9 and 12 and 13 will be found useful.

Before embarking on the analysis it may be of interest to consider what is exactly meant by "radiation distribution." The property of the antenna system which this term is intended to convey quantitatively is the variation of field strength in different directions when the attenuation is neglected. In this connection there are two terms which are commonly used but have no rigorous meaning and largely overlap one another. They are "polar diagram" and "effective height." Effective height is a factor which, when suitably applied in Hertz's radiation formulæ, gives the field strength. A single number as a representation of this property is meaningless when applied to a directive system. Often there is no ambiguity in its meaning, but a combination of this with the polar diagram, which itself purports to give the variation of field strength with direction, would be more rigorously correct. This then would be a function of angular directions which, when applied, as explained below, in Hertz's equations, gives the signal strength in various directions when the attenuation is neglected. This factor may for convenience be called the "radiation distribution of the antenna system."

This function should give not only the strength of the field but also its direction and phase. A convenient method of expressing this is by means of two functions, one for each of the components of the electric field, these two components being perpendicular to the direction of propagation. The radiation distribution will, therefore, consist of two functions containing direction (relative to the antenna) and phase as variables. The field at a point P having polar co-ordinates $(r,\ \theta,\ \phi)$, where θ is the vertical angle, ϕ the horizontal angle (see Fig. 1) and r the distance, is large compared with the dimensions of the antenna system, is given by

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* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† See Bibliography, (1). ‡ *Ibid.*, (2). § *Ibid.*, (11).

$$E_\theta = \frac{60\pi I}{\lambda r}\Big[f_\theta \cos \omega\big\{t - (r'/c)\big\} - f'_\theta \sin \omega\big\{t - (r'/c)\big\}\Big] \text{ volts per metre} \quad . \quad (1)$$

$$E_\phi = \frac{60\pi I}{\lambda r}\Big[f_\phi \cos \omega\big\{t - (r'/c)\big\} - f'_\phi \sin \omega\big\{t - (r'/c)\big\}\Big] \text{ volts per metre} \quad . \quad (2)$$

where E_θ is the longitudinal and E_ϕ the latitudinal component of the electric field, λ (metres) is the wavelength, c (metres per sec.) the velocity of light, ω is 2π × frequency, and r' (metres) is the equivalent distance, as explained in a previous paper by McPetrie and the author.*

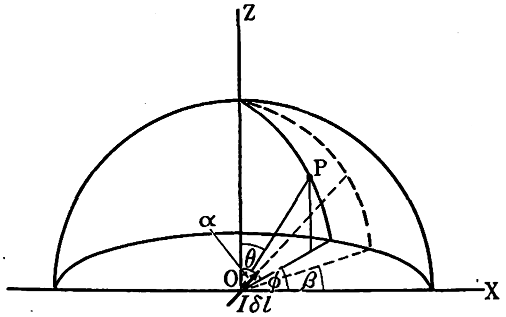

FIG. 1.

The radial component is not given, as the distances are usually so large as to make this negligibly small. These equations give the field strength in any direction when there flows in the antenna current of value $I \sin \omega t$ amperes. As this current is not the same in all parts of the antenna system it is essential to state the point where it is measured. The functions f_θ, f'_θ, f_ϕ, f'_ϕ are all functions of direction and represent the radiation distribution. It will be convenient to write the radiation distribution in the form

$$(f_\theta + jf'_\theta); \quad (f_\phi + jf'_\phi).$$

(2) RADIATION DISTRIBUTION OF ANTENNA ELEMENTS.

(*a*) *Straight Element of Wire.*

The variation of field strength around an element of straight wire is sinusoidal and symmetrical about the axis of the wire. It is, therefore, possible to resolve the element of wire into components as though it were a vector. Consider an element of wire in free space of lengths δl metres situated at the origin in the plane $\phi = 0$ and making an angle a with the axis OZ (Fig. 1). Suppose it carries a current $I \sin \omega t$ amperes. The field in the plane $\phi = 0$ will be given by

$$E_\theta = \frac{60\pi}{\lambda r} I\delta l \sin(\theta - a) \cos \omega\big\{t - (r'/c)\big\} \text{ volts per metre}$$

and $$E_\phi = 0.$$

These formulæ do not take account of the image in the ground.

In order to find the field at the point P (Fig. 1) having co-ordinates $(r,\ \theta,\ \phi)$ from a similar wire element but in a plane making an angle β with the plane XOZ, the element can be resolved in and perpendicular to the plane POZ. It can then be readily shown that

$$f_\theta + jf'_\theta = \big[\cos a \sin \theta - \sin a \cos \theta \cos(\phi - \beta)\big]\delta l \quad (3)$$

and $$f_\phi + jf'_\phi = -\sin a \sin(\phi - \beta)\delta l \quad . \quad . \quad (4)$$

(*b*) *Element of Coil.*

A straight element of wire is not the only form of antenna which can be represented by a line and treated as a vector. The field from a coil has also cylindrical symmetry and varies sinusoidally with the angular direction relative to that axis. It is, therefore, possible to represent a small coil by means of a vector perpendicular to the plane of the coil and passing through its centre. It is necessary to use some arbitrary convention regarding the direction of this vector, and the author suggests that, by analogy with other conventions of signs, the right-handed screw rule should be used as explained by Fig. 2. There is an important difference between the vector representation for a straight wire and for a coil. From a straight wire the direction of the electric field is in the plane containing the vector representing the element of wire and the direction of propagation considered, while for a coil it is perpendicular to this plane. Such a representative vector can be resolved into components as desired and, by reasoning similar to that followed in the case of elements of straight wire, the following results can be obtained for a coil represented by the arrow in Fig. 1.

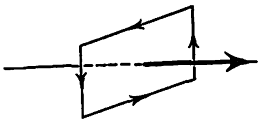

FIG. 2.

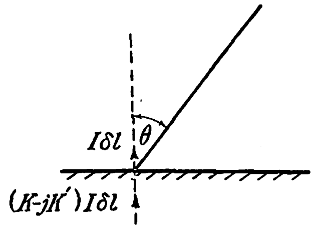

FIG. 3.

If δA represents the area-turns of the coil in square metres, and the current is $I \sin \omega t$ amperes, then the field in the plane $\phi = 0$ will be given by

$$E_\theta = 0$$

$$E_\phi = -\frac{120\pi^2}{\lambda^2 r} I\delta A \sin(\theta - a) \sin \omega\Big(t - \frac{r'}{c}\Big) \text{ volts per metre}$$

As before, these formulæ do not take account of the image in the ground.

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* See Bibliography, (12).

Hence, from the field at any point P, we shall have

$$f_\theta + jf'_\theta = j\frac{2\pi}{\lambda}\sin\alpha\sin(\phi-\beta)\delta A \quad . \quad . \quad (5)$$

and

$$f_\phi + jf'_\phi = j\frac{2\pi}{\lambda}[\cos\alpha\sin\theta - \sin\alpha\cos\theta\cos(\phi-\beta)]\delta A \quad (6)$$

It follows that any result which applies to a given distribution of vectors representing elements of straight wires will also apply to an identical distribution of vectors representing elementary coils, if we write $-E_\theta$ for E_ϕ, E_ϕ for E_θ, $2\pi I\delta A/\lambda$ for $I\delta l$ and advance the field by 90°.

(*c*) *Special Cases.*

The above formulæ are seldom required in their complete form. The following are the more usual:

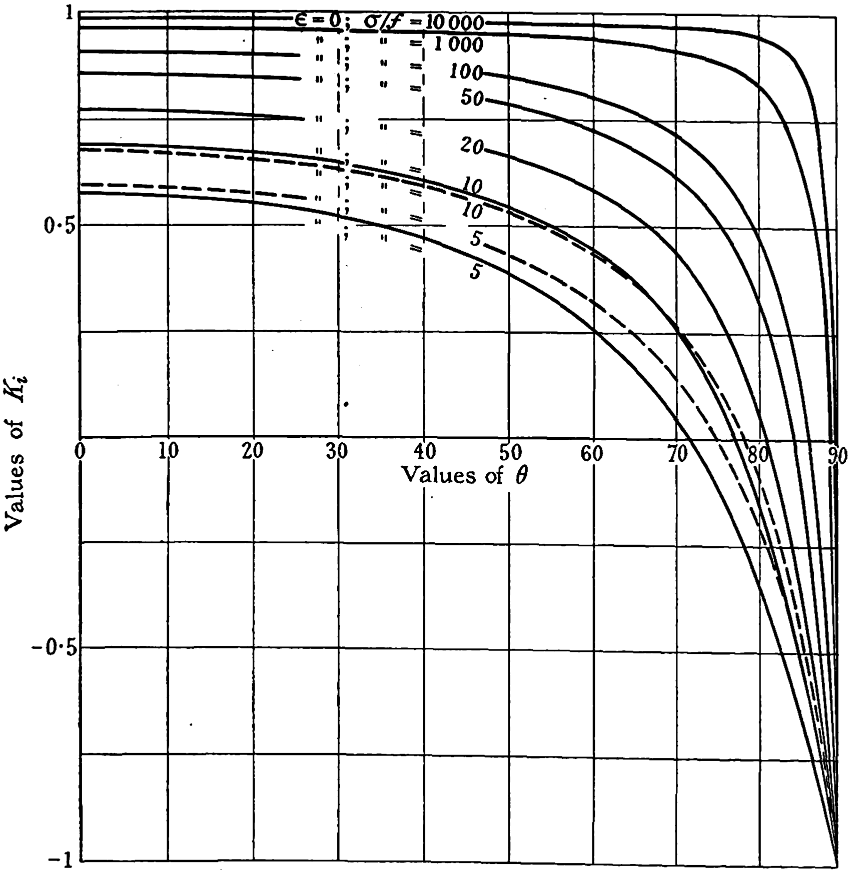

FIG. 4.

$$K_i = \frac{(\varepsilon^2 + 4\sigma^2/f^2)\cos^2\theta - (c^2 + d^2)}{(\varepsilon^2 + 4\sigma^2/f^2)\cos^2\theta + (e^2 + d^2) + 2\cos\theta\,(\varepsilon e + 2d\sigma/f)}$$

where $c^2 = \frac{1}{2}\left[(\varepsilon - \sin^2\theta) + \sqrt{\{(\varepsilon - \sin^2\theta)^2 + 4\sigma^2/f^2\}}\right]$

$d^2 = \frac{1}{2}\left[(-\varepsilon - \sin^2\theta) + \sqrt{\{(\varepsilon - \sin^2\theta)^2 - 4\sigma^2/f^2\}}\right]$

When $\varepsilon = 0$

$$K_i = \frac{2(\sigma/f)\cos^2\theta - 1}{2(\sigma/f)\cos^2\theta + 2\sqrt{\{(\sigma/f\cos\theta) + 1\}}}$$

(i) Vertical wire:—

$$f_\theta + jf'_\theta = \sin\theta\delta l; \quad f_\phi + jf'_\phi = 0 \quad . \quad . \quad (7)$$

(ii) Horizontal wire parallel to X axis:—

$$f_\theta + jf'_\theta = -\cos\theta\cos\phi\delta l; \quad f_\phi + jf'_\phi = -\sin\phi\delta l \quad (8)$$

(iii) Horizontal wire parallel to Y axis:—

$$f_\theta + jf'_\theta = -\cos\theta\sin\phi\delta l; \quad f_\phi + jf'_\phi = \cos\phi\delta l \quad (9)$$

(iv) Vertical coil. Vector parallel to X axis:—

$$f_\theta + jf'_\theta = \frac{j2\pi}{\lambda}\sin\phi\delta A; \; f_\phi + jf'_\phi = -\frac{j2\pi}{\lambda}\cos\theta\cos\phi\delta A \quad (10)$$

(v) Vertical coil. Vector parallel to Y axis:—

$$f_\theta + jf'_\theta = -j\frac{2\pi}{\lambda}\cos\phi\delta A;$$

$$f_\phi + jf'_\phi = -j\frac{2\pi}{\lambda}\cos\theta\sin\phi\delta A \quad . \quad (11)$$

(vi) Horizontal coil. Vector parallel to Z axis:—

$$f_\theta + jf'_\theta = 0; \quad f_\phi + jf'_\phi = j\frac{2\pi}{\lambda}\sin\theta\delta A \quad . \qquad (12)$$

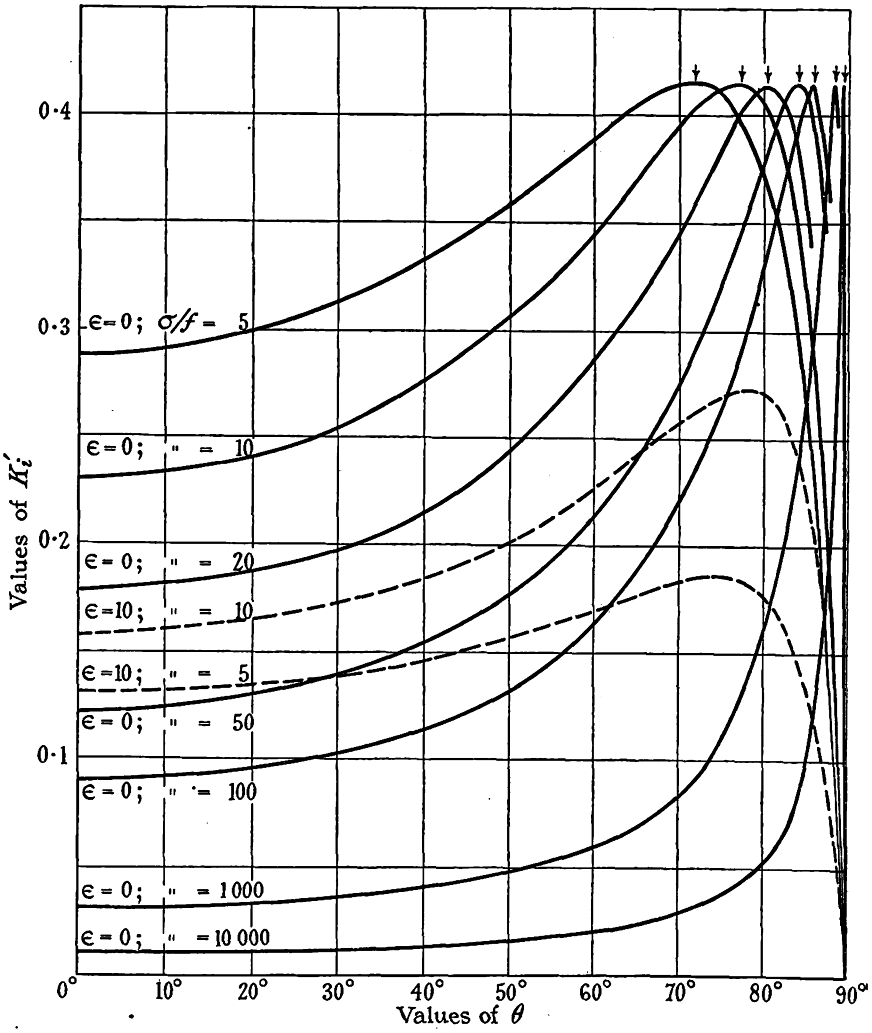

FIG. 5.

$$K_i = \frac{2\cos\theta(2c\sigma/f - \varepsilon d)}{(\varepsilon^2 + 4\sigma^2/f^2)\cos^2\theta + (c^2 + d^2) + 2\cos\theta(\varepsilon c + 2d\sigma/f)}$$

where $c^2 = \frac{1}{2}\left[(\varepsilon\sin^2\theta) + \sqrt{\{(\varepsilon - \sin^2\theta)^2 + 4\sigma^2 f^2\}}\right]$

$d^2 = \frac{1}{2}\left[-(\varepsilon - \sin^2\theta) + \sqrt{\{(\varepsilon - \sin^2\theta)^2 + 4\sigma^2/f^2\}}\right]$

When $\varepsilon = 0$

$$K'_i = \frac{2\sqrt{(\sigma/f)}\cos\theta}{2(\sigma/f)\cos^2\theta + 2\sqrt{(\sigma/f)}\cos\theta + 1}$$

giving maximum of $K'_i = 0{\cdot}414$ when $\cos\theta = \sqrt{(f/2\sigma)}$

(3) POLARIZATION.

The propagation of electromagnetic waves in or on the surface of an absorbing medium depends considerably on the polarization of the waves. In equations (1) and (2) E_θ is usually known as the vertically polarized component and E_ϕ as the horizontally polarized component.

A vertical current element can only produce vertically polarized components, but a horizontal current element may produce either and usually produces a combination of both. This is readily seen from equations (7), (8) and (9). A horizontal element will only produce purely horizontally polarized waves in a plane perpendicular to the plane in which the element lies, while it will produce purely vertically polarized waves in the plane in which it lies. In any other plane it will produce a combination of horizontally and vertically polarized waves.

(4) Current Distribution.

(a) Case of a Uniform Wire.

On the assumption of uniformly distributed inductance and capacity and negligible resistance it can readily be shown that the current distribution along a simple straight-wire antenna should be sinusoidal. That is, if the origin is taken to be the open end of the antenna, the current at a distance x from it will be

$$I \sin\left(\frac{2\pi x}{\lambda}\right) \quad . \quad . \quad . \quad . \quad . \quad (13)$$

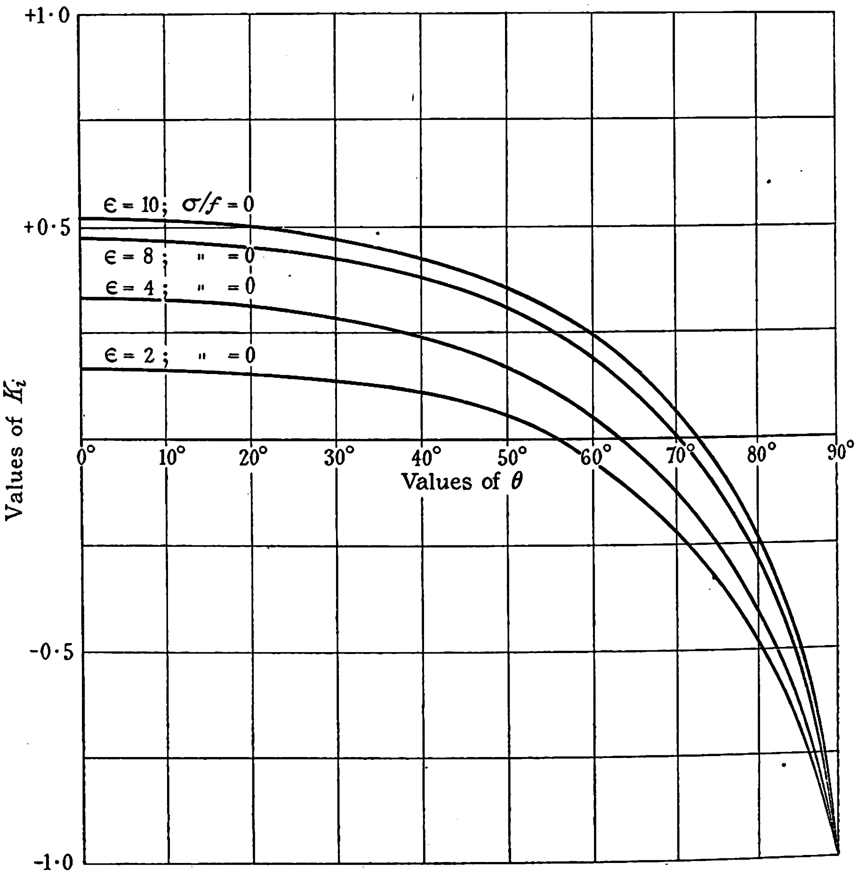

FIG. 6.

When $\sigma/f = 0$

$$K_i = \frac{\varepsilon \cos\theta - \sqrt{(\varepsilon - \sin^2\theta)}}{\varepsilon \cos\theta + \sqrt{(\varepsilon - \sin^2\theta)}}$$

$$K_i' = 0$$

This simple sinusoidal law of distribution of current was proved experimentally by the author * to hold with sufficient accuracy, except for local end-effects, for lengths up to $\frac{3}{4}\lambda$, and there is no reason to suppose that it will fail, except possibly when the total is very many wavelengths long.

In applying this formula it is necessary to be particularly careful, when there are discontinuities in the antenna such as multiple branches, a change in the diameter of the wire, lumped inductances, etc. On the simple theory, the voltage and current at any point distant x from the end of a length of uniform wire can be written in the form

$$v = jIa \cos\frac{2\pi}{\lambda}(x + b) \quad . \quad . \quad . \quad (14)$$

and

$$i = I \sin\frac{2\pi}{\lambda}(x + b) \quad . \quad . \quad . \quad . \quad (15)$$

In these equations I depends on the amplitude of the current, while b depends on the type of impedance connected at the end of the wire from which the distance x is measured. (This impedance is generally of the form of one or several lengths of wire.) a is a constant depending on the distributed constants of the wire and is equal to $\sqrt{(L/C)}$, where L is the self-inductance per unit length and C the capacity per unit length. We may write

$$a = \sqrt{(L/C)} = \frac{1}{cC} = cL \quad . \quad . \quad . \quad (16)$$

since c, the velocity of light, is very nearly equal to $1/\sqrt{(LC)}$.

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* See Bibliography, (13).

It will be noted that b has the dimensions of a length, so that the impedance at the end of the wire may be represented by a length so far as the current and potential along the wire are concerned. When there is no impedance at the end of the wire, that is when that end is open, $b = 0$. It will be shown that any discontinuity can be represented, as far as the current distribution is concerned, by a loss or a gain of length of the wire at the point of discontinuity, together with a change in amplitude of the current.

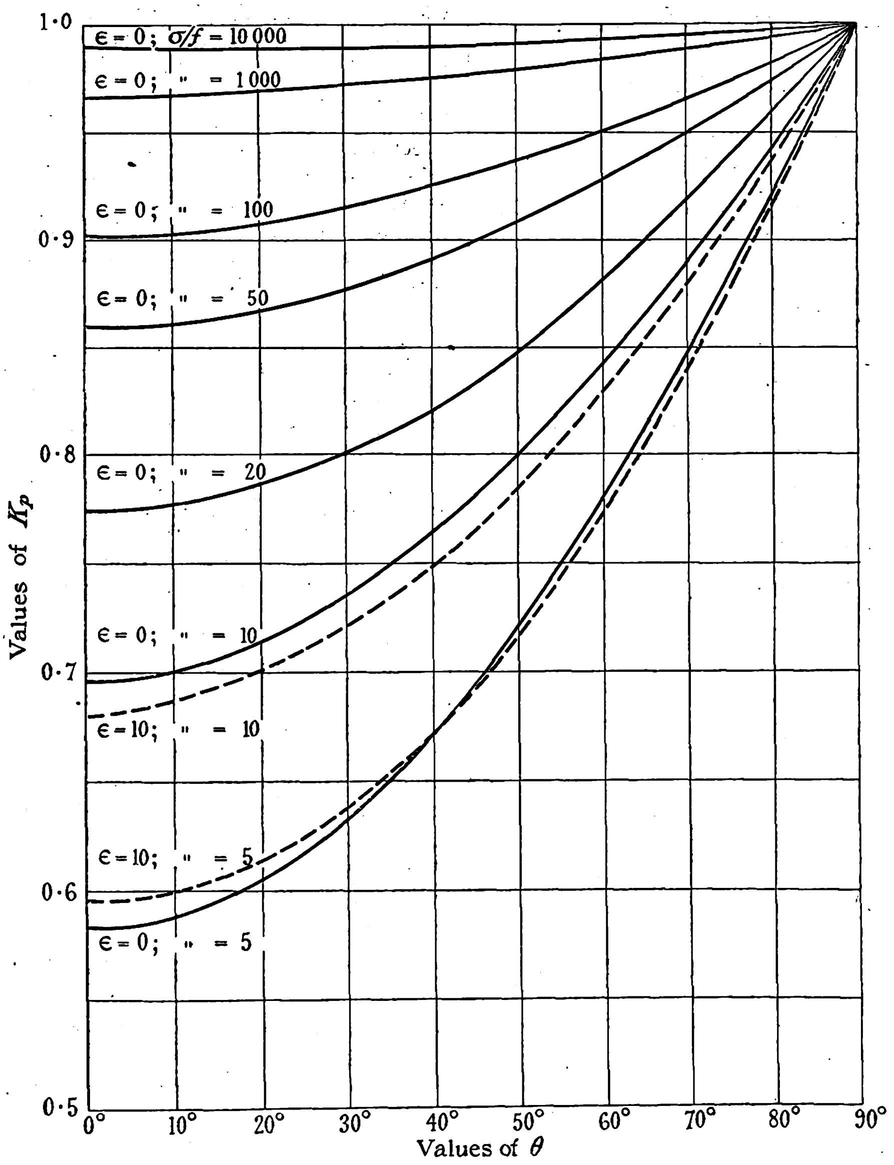

FIG. 7.

$$K_p = \frac{c^2 + d^2 - \cos^2\theta}{c^2 + d^2 + \cos^2\theta + 2c\cos\theta}$$

$$\text{where } c^2 = \tfrac{1}{2}\Big[(\varepsilon - \sin^2\theta) + \sqrt{\{(\varepsilon - \sin^2\theta^2) + 4\sigma^2/f^2\}}\Big]$$

$$d^2 = \tfrac{1}{2}\Big[-(\varepsilon - \sin^2\theta) + \sqrt{\{(\varepsilon - \sin^2\theta) + 4\sigma^2/f^2\}}\Big]$$

When $\varepsilon = 0$

$$K_p = \frac{2(\sigma/f) - \cos^2\theta}{2(\sigma/f) + \cos^2\theta + 2(\sigma/f)\cos\theta}$$

(*b*) *Case of n Branches meeting in a Point.*

Consider an antenna consisting of a single wire from the end of which n wires branch off. It does not matter what wires are connected to the end of these. Let the lengths of these branches be $l_1, l_2 \ldots$ and the equivalent lengths of the impedance at their ends be $b_1, b_2 \ldots$

Let the current and potential along the single wire, with the point O as origin, be respectively

$$I \sin \frac{2\pi}{\lambda}(x+b) \text{ and } jIa \cos \frac{2\pi}{\lambda}(x+b) \quad . \quad (17)$$

Then, if v_0 is the potential at the point O, we have

$$\begin{aligned} v_0 = jIa \cos\left(\frac{2\pi b}{\lambda}\right) &= jI_1a_1 \cos \frac{2\pi}{\lambda}(l_1+b_1) \\ &= jI_2a_2 \cos \frac{2\pi}{\lambda}(l_2+b_2) = \ldots \quad . \quad (18) \end{aligned}$$

and

$$\begin{aligned} I \sin\left(\frac{2\pi b}{\lambda}\right) &= I_1 \sin \frac{2\pi}{\lambda}(l_1+b_1) \\ &\quad + I_2 \sin \frac{2\pi}{\lambda}(l_2+b_2) + \ldots \quad . \quad (19) \end{aligned}$$

From equations (18) the ratios of the currents in the various branches can be calculated. Also, combining equations (17) and (18), we have

$$\begin{aligned} \frac{1}{a} \tan\left(\frac{2\pi b}{\lambda}\right) &= \frac{1}{a_1} \tan \frac{2\pi}{\lambda}(l_1+b_1) \\ &\quad + \frac{1}{a_2} \tan \frac{2\pi}{\lambda}(l_2+b_2) + \ldots \quad . \quad (20) \end{aligned}$$

from which b can be readily obtained, thus giving the current distribution from equations (17).

The branches are commonly the same in diameter and of equal lengths l, in which case equations (19) and (20) reduce to

$$\left.\begin{aligned} I &= I_1 n \sin\left(\frac{2\pi l}{\lambda}\right) \sin\left(\frac{2\pi b}{\lambda}\right) \\ \text{and} \quad \tan\left(\frac{2\pi b}{\lambda}\right) &= n \tan\left(\frac{2\pi l}{\lambda}\right) \end{aligned}\right\} \quad . \quad . \quad (21)$$

In the special case when $\tan(2\pi l/\lambda) = 0$, $I = I_1$.

Thus, at the point of discontinuity there is an effective loss of length equal to $(l - b)$ as far as the current distribution is concerned.

(c) Effect of a Lumped Inductance.

Suppose that at a distance l along the length of an antenna there is a self-inductance L_0 having negligible capacity. Let the current and potential above this inductance be given by

$$i = I \sin \frac{2\pi}{\lambda}(l+b) \quad \text{and} \quad v = jIa \cos \frac{2\pi}{\lambda}(l+b)$$

while that below the inductance is given by

$$i' = I' \sin \frac{2\pi}{\lambda}(l+b') \quad \text{and} \quad v' = jI'a' \cos \frac{2\pi}{\lambda}(l+b')$$

Since $i = i'$ and $v - v' = jL_0\omega i$, we have

$$\left.\begin{aligned} \cot \frac{2\pi}{\lambda}(l+b') &= \frac{L}{L'} \cot \frac{2\pi}{\lambda}(l+b) - \frac{2\pi}{\lambda} \cdot \frac{L_0}{L'} \\ &= \frac{C'}{C} \cot \frac{2\pi}{\lambda}(l+b) - \frac{2\pi}{\lambda} c^2 C' L_0 \end{aligned}\right\} \quad (22)$$

while

$$\frac{I'}{I} = \frac{\sin 2\pi(l+b')}{\sin 2\pi(l+b)} \quad . \quad . \quad . \quad . \quad (23)$$

where L, C and L', C' are the distributed constants of the wire above and below the self-inductance respectively. Thus the effect of the discontinuity is to change the ratio of the maximum currents in the ratio given by equation (23) and at the same time produce the effect as though a length of antenna wire equal to $(b' - b)$ were concentrated at the point of discontinuity as given by equations (22).

In most cases the wire will have the same diameter above and below the lumped inductance, in which case $L = L'$ and $C = C'$.

(d) Effect of a Change in the Distributed Constants.

If there be a sudden change in the diameter of the wire, the effect of the discontinuity can be obtained directly by putting $L_0 = 0$ in equations (22), whence we obtain

$$\cot \frac{2\pi}{\lambda}(l+b') = \frac{L}{L'} \cot \frac{2\pi}{\lambda}(l+b) = \frac{C'}{C} \cot \frac{2\pi}{\lambda}(l+b) \quad (24)$$

$$\text{and} \qquad \frac{I'}{I} = \frac{\sin 2\pi(l+b')}{\sin 2\pi(l+b)} \quad . \quad . \quad . \quad . \quad (25)$$

It is difficult to calculate accurately the value of C/C' or L/L', chiefly because the exact meaning of the distributed constants is somewhat vague and their use is essentially dependent on an approximation.* We may obtain a sufficiently good approximation by calculating the antenna capacity in two cases, assuming first that the distributed constants are L and C over the whole antenna and secondly that the distributed constants are L' and C'. It will generally be a sufficiently close approximation for this purpose to use the simple relation

$$\frac{L}{L'} = \frac{C'}{C} = \frac{\log(2l/d)}{\log(2l/d')} \quad . \quad . \quad . \quad . \quad (26)$$

where d and d' are the diameters of the wire and l the total length of the antenna. If the antenna is several wavelengths long, it will be close enough to assume $l = \frac{1}{4}\lambda$.

It will be seen that, if the diameter of the wire is greater *above* than it is *below* the point of discontinuity, there is an effective *loss* of length at that point, and vice versa.

(5) EFFECT OF IMAGE IN THE GROUND.

The full formulæ for calculating the effect of an imperfect earth have been given by the author.† Unfortunately, owing to an unnoticed ambiguity, errors were made in some of the signs. The corrected equations are given below. On this theory, which was first suggested by T. L. Eckersley ‡ and amplified by the author,§ an element of current $I\delta l$ has for image a similar element as shown (Fig. 3) but of strength $(K - jK')I\delta l$, where K and K' are real functions of the angle of transmission or reception to the vertical and also depend on whether the element of current lies in the plane or perpendicular to that in which propagation is considered, i.e. on the polarization of the ray.

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* See Bibliography, (14). † *Ibid.*, (15). ‡ *Ibid.*, (16). § *Ibid.*, (17).

In the special case that is approached at long waves and over water when the earth acts as a perfect conductor, $(K - jK') = 1$.

When the element of current lies in the plane of propagation under consideration K and K' are represented by K_i and K_i' and have values given by

$$K_i - jK_i' = \frac{(\epsilon^2 + 4\sigma^2/f^2)\cos^2\theta - (c^2 + d^2) - 2j\cos\theta\left\{2c(\sigma/f) - \epsilon d\right\}}{(\epsilon^2 + 4\sigma^2/f^2)\cos^2\theta + c^2 + d^2 + 2\cos\theta(\epsilon c + 2d\sigma/f)} \quad . \; . \; . \; . \; . \; . \quad (27)$$

where σ is the conductivity in electrostatic units, ϵ is the dielectric constant, f is the frequency, $j = \sqrt{-1}$, and c and d are given by $c^2 - d^2 = \epsilon - \sin^2\theta$ and $cd = \sigma/f$, c and d being both real and positive. These two equations are easily solved by using Pierce's tabulated f and g functions.*

When σ/f can be neglected in comparison with ϵ this expression reduces to

$$K_i - jK_i' = \frac{\epsilon\cos\theta - \sqrt{(\epsilon - \sin^2\theta)}}{\epsilon\cos\theta + \sqrt{(\epsilon - \sin^2\theta)}} \quad . \quad (28)$$

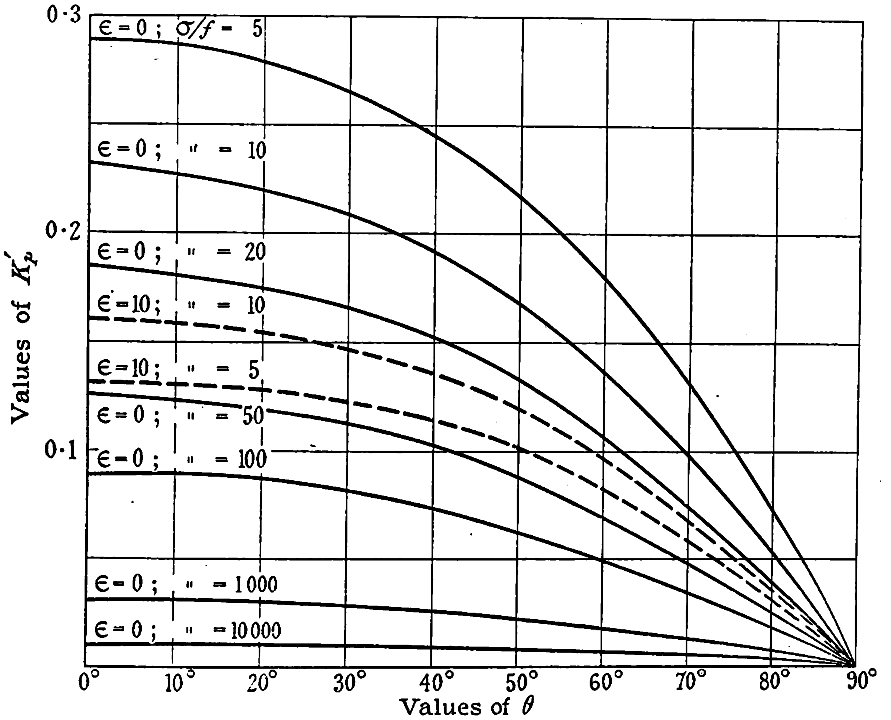

FIG. 8.

$$K_p' = \frac{2d\cos\theta}{c^2 + d^2 + \cos^2\theta + 2c\cos\theta}$$

where $c^2 = \frac{1}{2}\left[(\varepsilon - \sin^2\theta) + \sqrt{\{(\varepsilon - \sin^2\theta)^2 + 4\sigma^2/f^2\}}\right]$

$d^2 = \frac{1}{2}\left[-(\varepsilon - \sin^2\theta) + \sqrt{\{(\varepsilon - \sin^2\theta)^2 + 4\sigma/f^2\}}\right]$

When $\varepsilon = 0$

$$K_p' = \frac{2(\sigma/f)\cos\theta}{2(\sigma/f) + \cos^2\theta + 2(\sigma/f)\cos\theta}$$

When ϵ and $\sin^2\theta$ can be neglected in comparison with σ/f, the expression reduces to

$$K_i - jK_i' = \frac{(2\sigma/f)\cos^2\theta - 1 - 2j(\sigma/f)^{\frac{1}{2}}\cos\theta}{(2\sigma/f)\cos^2\theta + 1 + 2(\sigma/f)^{\frac{1}{2}}\cos\theta} \quad (29)$$

In the same way, when the plane of propagation under consideration is perpendicular to the current element, $K - jK'$ is written $K_p - jK_p'$ and is given by

$$K_p - jK_p' = \frac{c^2 + d^2 - \cos^2\theta - 2jd\cos\theta}{c^2 + d^2 + \cos^2\theta + 2c\cos\theta} \quad (30)$$

When σ/f can be neglected in comparison with ϵ this expression becomes

$$K_p - jK_p' = \frac{\sqrt{(\epsilon - \sin^2\theta)} - \cos\theta}{\sqrt{(\epsilon - \sin^2\theta)} + \cos\theta} \quad . \quad (31)$$

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* See Bibliography, (18).

When ϵ and $\sin^2\theta$ can be neglected in comparison with σ/f the expression reduces to

$$K_p - jK_p' = \frac{(2\sigma/f) - \cos^2\theta - 2j(\sigma/f))^{\frac{1}{2}}\cos\theta}{(2\sigma/f) + \cos^2\theta + 2(\sigma/f)^{\frac{1}{2}}\cos\theta} \quad (32)$$

These expressions are somewhat laborious to evaluate, and a number of curves have been calculated. These are shown in Figs. 4 to 9. It may be noted that the value of K_i is not very much affected by the dielectric constant of the ground unless this is larger than $2\sigma/f$, but this is not so for K_i'. This means that the amplitude of the reflected ray will not in general be very much affected by the dielectric constant but that the phase of this ray will be affected to a much greater extent. This leads incidentally to the deduction that, if a method of measuring the dielectric constant of the ground based on the electromagnetic wave propagation is developed, it is desirable that it should depend on a phase measurement rather than on amplitude, unless the measurement is made in the neighbourhood of Brewster's angle.

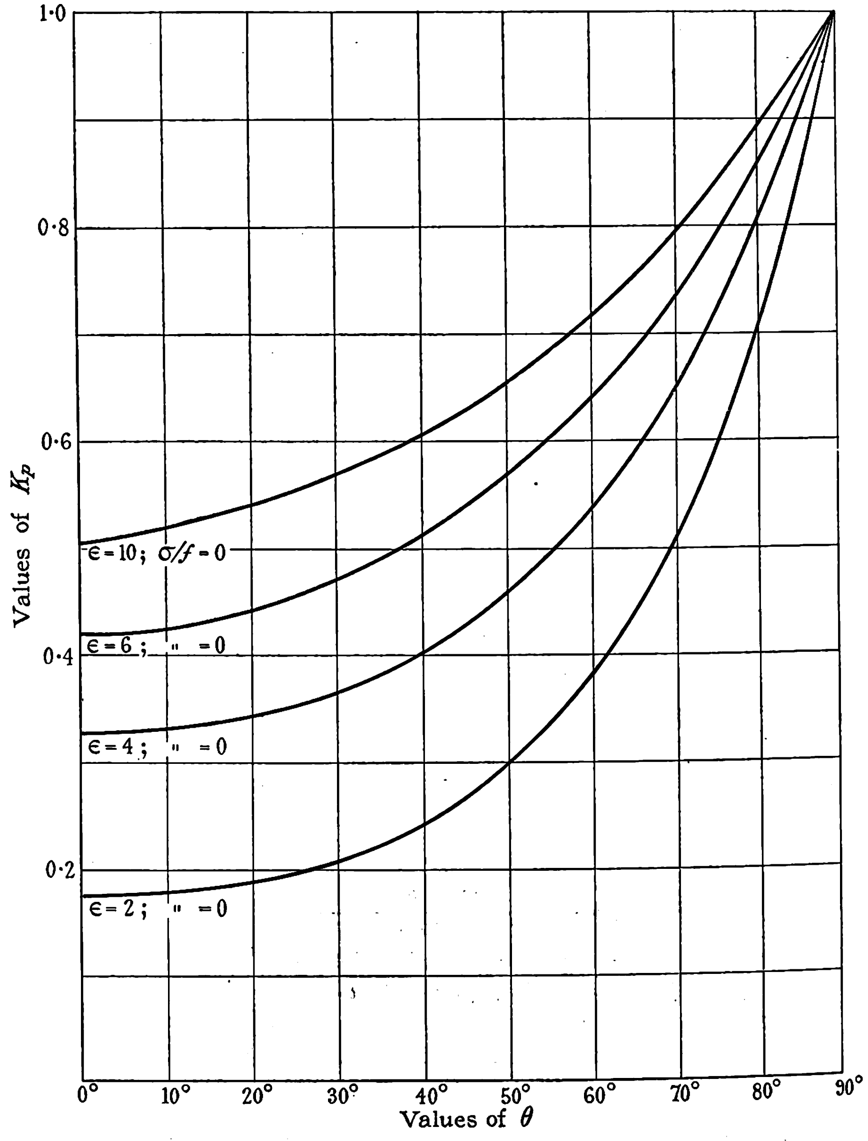

FIG. 9.

When $\sigma/f = 0$

$$K_p = \frac{\sqrt{(\varepsilon - \sin^2\theta)} - \cos\theta}{\sqrt{(\varepsilon - \sin^2\theta)} + \cos\theta}$$

$$K_p' = 0$$

From the curves given in Figs. 4 to 9 we can readily deduce the field from any element of current over an imperfect earth. Consider the field at a distant point P the radius vector of which makes an angle θ with the vertical. If h is the height of a vertical element above the ground we have, for the field E_v at P,

$$E_v = \frac{60\pi I\delta l \sin\theta}{\lambda r}$$
$$\left\{(1 + K - jK')\cos\gamma + j(1 - K + jK')\sin\gamma\right\} \quad (33)$$

where $\gamma = \dfrac{2\pi h \cos\theta}{\lambda}$

Therefore

$$|E_v| = \frac{60\pi I\delta l \sin\theta}{\lambda r}$$
$$\sqrt{[1 + K^2 + K'^2 + 2K\cos^2\gamma - 2K'\sin 2\gamma]} \quad . \quad (34)$$

In the case of a horizontal element lying in a plane perpendicular to the direction of transmission or reception it can be readily shown that the field E_h is given by

$$|E_h| = \frac{60\pi I\delta l \cos\theta}{\lambda r}$$
$$\sqrt{[1 + K^2 + K'^2 - 2K\cos 2\gamma + 2K'\sin 2\gamma]} \quad (35)$$

By differentiation it may be shown that E_v is a maximum and E_h is a minimum when

$$2\gamma = (2n - 1)\pi - \text{arc tan } (K'/K) \quad . \quad (36)$$

while E_v is a minimum and E_h a maximum when

$$2\gamma = 2n\pi - \text{arc tan } (K'/K) \quad . \quad . \quad (37)$$

where n is an integer. It should be noted that K may either be K_i or K_p, depending on the direction of the antenna element, and similarly for K'.

As K'/K is always positive except for angles with the vertical greater than Brewster's angle, we should expect all those maxima and minima of the radiation distribution, which are produced by the interference of the antenna with its image, to tend to shift towards the Brewster's angle as the conductivity of the ground decreases. In any given case the amount of this shift should be a measure of the ratio K'/K, from which the conductivity of the ground might be deduced.

(6) RADIATION DISTRIBUTION OF A STRAIGHT WIRE INCLINED AT ANY ANGLE.

(a) *General Case.*

For the computation of many of the formulæ the curves given in Figs. 12 and 13 will be found useful.

Consider the straight wire AB (Fig. 10) lying in the plane $\phi = \beta$. Let this antenna be of length l and let it make an angle α with the vertical, its lowest point A having co-ordinates $(r_0 \cos\beta,\ r_0 \sin\beta,\ z_0)$. That is, its lowest point is at a height z_0 and its projection on to the horizontal plane is at a distance r_0 from the origin. To make the problem as general as possible, we shall assume that the antenna is loaded at its end B with a load equivalent to a length l_1 of the antenna, so that the current, i, flowing in the direction AB, at any point Q on the antenna, distant z from A, is given by

$$i = I_0 \sin\frac{2\pi}{\lambda}(l + l_1 - z)\sin\omega t \quad . \quad . \quad (38)$$

The general formula, which will be given below, can be used for any individual straight portion of an antenna, and, by adding the field due to all these portions which form the whole antenna system, it is possible to obtain an expression for the radiation distribution of any antenna system. In complicated systems, however, the expressions are much too cumbersome and a combination of formulæ and graphical methods becomes more suitable.

Consider the distant point P having its horizontal projection at N. Let PO make an angle ψ with the antenna AB. If the distance of the point P is large compared with the length of the antenna, the value of ψ will not vary materially, whatever be the position of the point Q on AB, and we may assume that the angle ψ is constant, so that

$$\cos\psi = \sin\alpha\sin\theta\cos(\phi - \beta) + \cos\alpha\cos\theta \quad (39)$$

Now the field at P due to the element of wire of length δz at Q is inversely proportional to the distance PQ. As before, we may assume that the distance PQ is independent of the position of Q on AB and is equal to r. We must, however, take into account the phase at which the radiation from Q reaches P, for this is dependent on the position of Q, unless the length AB is small compared with the wavelength. A current at the origin in phase with that at Q would send a radiation which would arrive at P, τ seconds after that from Q, where

$$c\tau = \text{PO} - \text{PQ} = d + z\cos\psi \quad . \quad . \quad (40)$$

where d is the length of the projection of OA on OP and is given by

$$d = x_0 \sin\theta\cos(\phi - \beta) + z_0\cos\theta \quad . \quad . \quad (41)$$

From equations (3), (4) and (38) we obtain for the radiation distribution of the whole antenna AB that

$$f_\theta + jf'_\theta = \int_0^l \sin\frac{2\pi}{\lambda}(l + l_1 - z)\left\{\cos\alpha\sin\theta - \sin\alpha\cos\theta\cos(\phi - \beta)\right\}\left\{\cos\pi l\,(d + z\cos\psi) + j\sin\frac{2\pi}{\lambda}(d + z\cos\psi)\right\}dz$$

and

$$f_\phi + jf'_\phi = \int_0^l \sin\frac{2\pi}{\lambda}(l + l_1 - z)\sin\alpha\sin(\phi - \beta)\left\{\cos\frac{2\pi}{\lambda}(d + z\cos\psi) + j\sin\frac{2\pi}{\lambda}(d + z\cos\psi)\right\}dz$$

where the current is measured at the mathematical current maximum, even if such a maximum does not occur within the length AB.

If F is the resultant of $(f_\theta + jf'_\theta)$ and $(f_\phi + jf'_\phi)$, so that

$$F^2 = (f_\theta + jf'_\theta)^2 + (f_\phi + jf'_\phi)^2$$

then the above integrals reduce to

$$F = \frac{\lambda}{2\pi \sin\psi}\Big[\cos A \cos D - \cos B \cos C - \cos\psi\,(\sin A \sin D - \sin B \sin C) + j\big\{\cos A \sin D - \cos B \sin C + \cos\psi\,(\sin A \cos D - \sin B \cos C)\big\}\Big] \quad . \quad (42)$$

$$f_\theta + jf'_\theta = \frac{\{\cos\alpha \sin\theta - \sin\alpha \cos\theta \cos(\phi - \beta)\}}{\sin\psi}F \qquad (43)$$

and

$$f_\phi + jf'_\phi = -\frac{\sin\alpha \sin(\phi - \beta)}{\sin\psi}F \quad . \quad . \quad (44)$$

where $A = 2\pi l_1/\lambda$
$B = 2\pi(l + l_1)/\lambda$
$C = 2\pi d/\lambda$
$D = 2\pi(d + l\cos\psi)/\lambda$

The values of $\cos\psi$ and d are given by equations (39) and (41). The sign of $\cos\psi$ will come automatically from equation (39), while that of $\sin\psi$ is immaterial so long as it is taken consistently the same, for $\sin\psi$ only occurs in the final expression for the field strength as a square.

In order to find the effect of the image it is necessary to put $(\pi - \alpha)$ for α, $-z_0$ for z_0 in the above expressions, and multiply the result by the factor $-(K - jK')$ as explained in section (5) above and given in Figs. 4 to 9. The result should then be added to the radiation distribution for the antenna without its image in the ground.

These expressions as they stand are much too complex for practical use. They reduce considerably, however, in a large number of special cases, some of which will now be considered.

(b) *Vertical Antenna Loaded at the Top.*

In this case $\alpha = 0$ and $x_0 = 0$, so that $d = z_0 \cos\theta$ and $\cos\psi = \cos\theta$.

Hence

$$f_\theta + jf'_\theta = \frac{\lambda}{2\pi\sin\theta}\Bigg[\cos\frac{2\pi l_1}{\lambda}\Big\{\cos\frac{2\pi\cos\theta(l + z_0)}{\lambda} + j\sin\frac{2\pi\cos\theta(l + z_0)}{\lambda}\Big\} - \cos\frac{2\pi(l + l_1)}{\lambda}\Big\{\cos\frac{2\pi z_0\cos\theta}{\lambda} + j\sin\frac{2\pi z_0\cos\theta}{\lambda}\Big\} - \cos\theta\Big[\sin\frac{2\pi l_1}{\lambda}\Big\{\sin\frac{2\pi\cos\theta(l + z_0)}{\lambda} - j\cos\frac{2\pi\cos\theta(l + z_0)}{\lambda}\Big\} - \sin\frac{2\pi(l + l_1)}{\lambda}\Big\{\sin\frac{2\pi z_0\cos\theta}{\lambda} - j\cos\frac{2\pi z_0\cos\theta}{\lambda}\Big\}\Big]\Bigg]^{*} \quad . . . . \quad (45)$$

and $f_\phi + jf'_\phi = 0$.

The expression for the image, if we assume a perfect earth, is identical with expression (45), except that $(l + z_0)$ becomes $(l - z_0)$ and all the imaginary terms have their signs reversed, so that, if $z_0 = 0$, the total effect of the antenna and its image together is to double the real part of equation (45) and bring the imaginary part to zero.

If there is no load at the top and the antenna reaches to the ground (i.e. $l_1 = 0$ and $z_0 = 0$), expression (45) reduces (not taking the image into account) to

$$f_\theta + jf'_\theta = \frac{\lambda}{2\pi\sin\theta}\Big[\cos\frac{2\pi l\cos\theta}{\lambda} - \cos\frac{2\pi l}{\lambda} + j\Big\{\sin\frac{2\pi l\cos\theta}{\lambda} - \cos\theta\sin\frac{2\pi l}{\lambda}\Big\}\Big] \quad . \quad (46)$$

(c) *Horizontal Antenna not Loaded at the End.*

In this case $\alpha = \frac{1}{2}\pi$, $x_0 = 0$, $l_1 = 0$.

Hence
$$F = \frac{\lambda}{2\pi\sin\psi}\Big[\cos\frac{2\pi(z_0\cos\theta + l\cos\psi)}{\lambda} - \cos\frac{2\pi l}{\lambda}\cos\frac{2\pi z_0\cos\theta}{\lambda} + \cos\psi\sin\frac{2\pi l}{\lambda}\sin\frac{2\pi z_0\cos\theta}{\lambda} + j\Big\{\sin\frac{2\pi(z_0\cos\theta + l\cos\psi)}{\lambda} - \cos\frac{2\pi l}{\lambda}\sin\frac{2\pi z_0\cos\theta}{\lambda} - \cos\psi\sin\frac{2\pi l}{\lambda}\cos\frac{2\pi z_0\cos\theta}{\lambda}\Big\}\Big] \quad . . . . \quad (47)$$

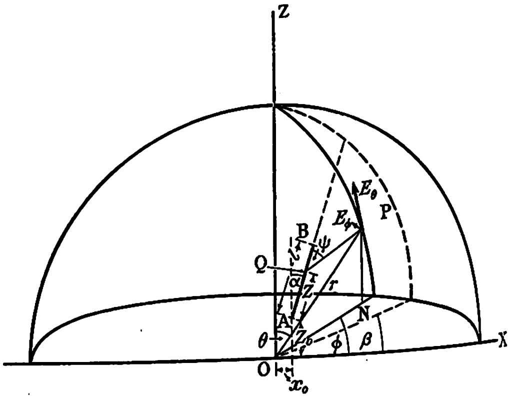

FIG. 10.

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* Curves of $\cos\{2\pi(l/\lambda)\cos\theta\}$, $\cos\{2\pi(l/\lambda)\sin\theta\}$, $\sin\{2\pi(l/\lambda)\sin\theta\}$ and $\sin\{2\pi(l/\lambda)\cos\theta\}$ for various values of l/λ are given in Figs. 12 and 13.

$$\left.\begin{aligned} f_\theta + jf'_\theta &= -\frac{\cos\theta\cos(\phi-\beta)}{\sin\psi}F \\ \text{and}\qquad f_\phi + jf'_\phi &= -\frac{\sin(\phi-\beta)}{\sin\psi}F \end{aligned}\right\} \quad . \quad . \quad (48)$$

where $\cos\psi = \sin\theta\cos(\phi-\beta)$.

The expression for the image, if we assume a perfect earth, is identical with expression (47), except that z_0 becomes $-z_0$ and F becomes $-F$. The expression for the total field due to the antenna and its image in the earth will be given by equations (48), where

$$F = \frac{\lambda}{\pi\sin\psi}\sin\frac{2\pi z_0\cos\theta}{\lambda}\left[\cos\psi\sin\frac{2\pi l}{\lambda} - \sin\frac{2\pi l\cos\psi}{\lambda} + j\left\{\cos\frac{2\pi l\cos\psi}{\lambda} - \cos\frac{2\pi l}{\lambda}\right\}\right] \quad (49)$$

By adding the expressions in this section to the suitable expressions from section (6) (*b*), the radiation distribution of any inverted "L" antenna can be obtained.

(*d*) *Two Equal Horizontal Antennæ in One Straight Line with Currents Flowing in Opposite Directions.*

If we put $(\pi+\beta)$ for β in equations (47), (48) and (49) we shall obtain the expression for an equal horizontal antenna with current flowing in the opposite direction to that in the first. The two expressions can be added together, giving the formula required.

For the antenna alone we have, together with equations (48),

$$F = \frac{\lambda}{\pi\sin\psi}\left\{\cos\psi\sin\frac{2\pi l}{\lambda} - \sin\frac{2\pi l\cos\psi}{\lambda}\right\}\left\{\sin\frac{2\pi z_0\cos\theta}{\lambda} - j\cos\frac{2\pi z_0\cos\theta}{\lambda}\right\} \quad . \quad (50)$$

The expression for the total antenna with its image in a perfect earth is given by equation (48), where

$$F = -\frac{2\lambda}{\pi\sin\psi}\sin\left(\frac{2\pi z_0\cos\theta}{\lambda}\right)\left\{\cos\psi\sin\left(\frac{2\pi l}{\lambda}\right) - \sin\left(\frac{2\pi l\cos\psi}{\lambda}\right)\right\} \quad . \quad (51)$$

It should be noted that the current measured is the mathematical maximum of either limb of the antenna. By combining the expressions in this section with the suitable expressions from section (6)(*b*), the radiation distribution of any "T" antenna can be obtained. In doing this the effect of discontinuity produced by the double branch at the top of the vertical portion must be taken into account. For this purpose equations (21) should be used.

(*e*) *Two Equal Horizontal Antennæ in One Straight Line with Current Flowing in the Same Direction.*

This is similar to the problem of the preceding paragraph. The required expression is obtained by putting $(\pi+\beta)$ for β in equations (47), (48) and (49) and subtracting the two expressions in each case.

For the antenna alone we have, in combination with equation (48),

$$F = \frac{\lambda}{\pi\sin\psi}\left\{\cos\frac{2\pi l\cos\psi}{\lambda} - \cos\frac{2\pi l}{\lambda}\right\}\left\{\cos\frac{2\pi z_0\cos\theta}{\lambda} + j\sin\frac{2\pi z_0\cos\theta}{\lambda}\right\} \quad . \quad (52)$$

The expression for the total antenna and its image in a perfect earth is given by equations (48), where

$$F = j\frac{2\lambda}{\pi\sin\psi}\sin\frac{2\pi z_0\cos\theta}{\lambda}\left\{\cos\frac{2\pi l\cos\psi}{\lambda} - \cos\frac{2\pi l}{\lambda}\right\} \quad . \quad (53)$$

These expressions represent the radiation distribution of a horizontal antenna excited at the centre.

(*f*) *General Case when Current is Uniform instead of Sinusoidal.*

It has been pointed out by the author[*] that an increase in directivity could be obtained by reducing the space taken by those portions of the antenna in which the current is small. This can be done in practice by means of the device employed by Franklin in which the antenna wire is bent on itself several times, so that large portions of the current distribution for a simple straight wire are concentrated into a relatively small space. Carrying this out to the extreme would result in a nearly uniform current distribution along the antenna instead of the usual sinusoidal distribution. It may be of interest for design purposes to find whether the attainment of a more uniform current distribution is of value. For this purpose it is necessary to know what is the limiting condition that can thus be obtained. Such a condition can, of course, never be actually reached, but in many cases it could be very nearly obtained. The following formulæ refer to such limiting cases, in which the current is assumed perfectly uniform over the whole antenna.

The general case gives the following:—

$$f_\theta + jf'_\theta = \frac{\cos\alpha\sin\theta - \sin\alpha\cos\theta\cos(\phi-\beta)}{\sin\psi}F \quad (54)$$

$$f_\phi + jf'_\phi = -\frac{\sin\alpha\sin(\phi-\beta)}{\sin\psi}F \quad . \quad . \quad (55)$$

where

$$F = \frac{\lambda}{2\pi}\tan\psi\left[\sin\frac{2\pi(d+l\cos\psi)}{\lambda} - \sin\frac{2\pi d}{\lambda} + j\left\{\cos\frac{2\pi d}{\lambda} - \cos\frac{2\pi(d+l\cos\psi)}{\lambda}\right\}\right] \quad . \quad (56)$$

$$\cos\psi = \sin\alpha\sin\theta\cos(\phi-\beta) + \cos\alpha\cos\theta$$

$$\text{and}\qquad d = x_0\sin\theta\cos(\phi-\beta) + z_0\cos\theta$$

As before, F is the resultant of $(f_\theta + jf'_\theta)$ and $(f_\phi + jf'_\phi)$.

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[*] See Bibliography, (19).

(7) A System of Similar Parallel Antennæ Spaced in any Given Manner.

(*a*) *General Case.*

It often occurs in a system of antennæ that there are a number of parallel portions of equal length and carrying similar distributions of current. Instead of adding the field due to each portion separately, we may proceed as follows.

Let there be n such portions and let $O_1, O_2, \ldots, O_n$ be points on the 1st, 2nd, . . ., nth portion respectively. These points are in the same relative position on each individual portion. Taking a single portion we can calculate its radiation distribution from the equations given in section (6). Let this be $(f + jf')$, this expression representing in fact two functions, one for each component in space of the field.

Supposing that the co-ordinates of $O_1, O_2, \ldots, O_n$ are $(x_1, y_1, z_1), (x_2, y_2, z_2), \ldots (x_n, y_n, z_n)$ respectively, and that the currents $I_1, I_2, \ldots I_n$ flowing at these points are in advance on some arbitrary phase by $\beta_1, \beta_2, \ldots, \beta_n$ respectively, we may write for the radiation distribution $(F + jF')$ of the whole system

$$F + jF' = (f + jf') \left[\frac{\sum\limits_{r=1}^{r=n} I_r \cos\left\{\beta_r + \frac{2\pi d_r}{\lambda}\right\} + j \sum\limits_{r=1}^{r=n} I_r \sin\left\{\beta_r + \frac{2\pi d_r}{\lambda}\right\}}{\sum\limits_{r=1}^{r=n} I_r} \right] \tag{57}$$

where $d_1, d_2, \ldots, d_n$ are the projections of $OO_1, OO_2, \ldots, OO_n$ on the direction considered, O being the origin. Thus, if the direction considered is (θ, ϕ),

$$d_r = (x_r \cos\phi + y_r \sin\phi) \sin\theta + z_r \cos\theta \quad . \tag{58}$$

If there are not several systems to add together, it is unnecessary to consider the phase of the radiation distribution. Hence, if f_0 is the resultant of $(f + jf')$ and F_0 that of $(F + jF')$, equation (57) reduces to

$$F_0^2 = f_0^2 \frac{\sum\limits_{r=1}^{r=n} \sum\limits_{s=r}^{s=n} \left[I_r I_s \cos\left\{\beta_r - \beta_s + \frac{2\pi}{\lambda}(d_r - d_s)\right\}\right]}{\left(\sum\limits_{r=1}^{r=n} I_r\right)^2} \tag{59}$$

It was mentioned in section (1) that the point of the antenna system at which the current is measured should be stated; in this particular case the current is not measured at a single point, but it is taken as the sum (irrespective of phase) of all the currents at the points $O_1, O_2, \ldots, O_n$.

(*b*) *Uniform Spacing, Uniform Variation of Phase and Equal Currents.*

This is a condition frequently met with in practice, and for this case equation (57) adopts a simpler form. If the portions of the antenna system are uniformly spaced, the projection of the lengths $OO_1, OO_2, \ldots, OO_n$ on to the direction required can be written in the form $d_1,\ d_1 + d, \ldots,\ d_1 + (n-1)d$ respectively, the values of d_1 and d being readily obtained from equation (58). If, in the same way, the phases are $\beta_1, \beta_1 + \beta, \ldots, \beta_1 + (n-1)\beta$ and the current is of the same amplitude in each portion of the antenna system, equation (57) becomes

$$F + jF' = \frac{(f + jf')}{n} \left[\frac{\cos\left\{\beta_1 + \frac{2\pi d_1}{\lambda} + (n-1)\left(\frac{\beta}{2} + \frac{\pi d}{\lambda}\right)\right\} \sin n\left(\frac{\beta}{2} + \frac{\pi d}{\lambda}\right)}{\sin\left(\frac{\beta}{2} + \frac{\pi d}{\lambda}\right)} + j \frac{\sin\left\{\beta_1 + \frac{2\pi d_1}{\lambda} + (n-1)\left(\frac{\beta}{2} + \frac{\pi d}{\lambda}\right)\right\} \sin n\left(\frac{\beta}{2} + \frac{\pi d}{\lambda}\right)}{\sin \frac{\beta}{2} + \frac{\pi d}{\lambda})} \right] \quad . \tag{60}$$

If there are not several systems to add together, it is unnecessary to consider the phase of the radiation distribution. In this case the resultant, F_0, is given by

$$F_0 = \frac{f_0}{n} \cdot \frac{\sin n\left(\frac{\beta}{2} + \frac{\pi d}{\lambda}\right)}{n \sin\left(\frac{\beta}{2} + \frac{\pi d}{\lambda}\right)} \quad . \; . \; . \tag{61}$$

In the limiting case, as $n \to \infty$ and the spread of the antenna system remains constant, i.e. $n\left(\frac{\beta}{2} + \frac{\pi d}{\lambda}\right) = \frac{\beta_0}{2} + \frac{\pi d_0}{\lambda}$, equation (61) becomes

$$F_0 = f_0 \frac{\sin\left(\frac{\beta_0}{2} + \frac{\pi d_0}{\lambda}\right)}{\left(\frac{\beta_0}{2} + \frac{\pi d_0}{\lambda}\right)} \quad . \; . \; . \tag{62}$$

As before, the current is the sum of the currents in all the portions of the antenna system irrespective of phase.

In the special case, when $n = 2$, we have

$$F_0 = f_0 \cos\left(\frac{\beta}{2} + \frac{\pi d}{\lambda}\right) \quad . \; . \; . \tag{63}$$

(8) Antennæ Having Symmetrical Radiation About a Vertical Axis.

(*a*) *General Case.*

If the vertical axis of symmetry pass through a point O, in order to keep rigorous symmetry the antenna system must be uniformly distributed around the circumference of one or more horizontal circles having O as centre. The individual antennæ on each circle must be identical and must carry the same amplitude of current. Symmetry can still be kept if the currents in the antennæ are not in the same phase, but in this case the phase must vary uniformly round the circumference of each circle, and the total phase difference in a complete revolution must be a multiple of 2π, otherwise a discontinuity would occur.

The above conditions are necessary for exact symmetry. It may be possible to devise systems which do not conform with the above conditions, and yet give fairly correct symmetry, but it will probably be found that they approximate in some way to these conditions.

Let us consider the general case of n identical antennæ, uniformly distributed along the circumference of a circle of radius R (Fig. 11). Since the radiation is symmetrical about the vertical axis through the centre O, it is only necessary to consider the radiation distribution in a single vertical plane. Let it be OX. We shall take as the basis of phase the current in the antenna M, so that the phase of the current in the antenna A is $(n\phi)$ in advance of that in the antenna M. In order to preserve symmetry, n must be an integer.

The phase of the radiation in the vertical plane through OX at an angle of θ with the vertical from the antenna A will be in advance of that from an imaginary antenna at O, excited in the same phase as the antenna M, by an angle $(n\phi + \delta \cos \phi)$

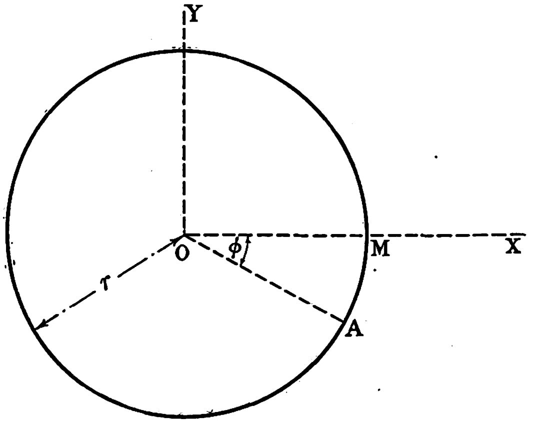

FIG. 11.

where

$$\delta = \frac{2\pi R}{\lambda} \sin \theta \quad . \quad . \quad . \quad . \quad (64)$$

If $(f + jf')$ is the radiation distribution of each individual antenna, the radiation distribution $(F + jF')$ for the whole circle will be given by

$$F + jF' = \int_0^{2\pi} \frac{1}{2\pi}(f + jf') \left\{ \cos (n\phi + \delta \cos \phi) + j \sin (n\phi + \delta \cos \phi) \right\} d\phi \quad . \quad (65)$$

As in section (7), the current is not measured at a single point but is taken to be the sum (irrespective of phase) of all the currents in the individual antennæ. The current in each of these is measured at the point which makes their radiation distribution $(f + jf')$.

The integral of equation (65) can be solved in certain special cases. In order to obtain as general a case as possible, let us assume that f and f' can each be expanded in Fourier series with the angle ϕ as variable.

$$f + jf' = \sum_m \left\{ (A_m + jA'_m) \sin (m\phi) + (B_m + jB'_m) \cos m\phi \right\} \quad . \quad (66)$$

where m is an integer and A_m, A'_m, B_m, B'_m are functions of θ.

Equation (65) can be shown to reduce, when $m > n$, to

$$F + jF' = \tfrac{1}{2}\sum_m (-1)^{\frac{1}{2}(m-n+1)} \Big[(A_m + jA'_m) \left\{ J_{m-n}(\delta) + (-1)^{n+1} J_{m+n}(\delta) \right\} + (B'_m - jB_m) \left\{ J_{m-n}(\delta) - (-1)^{n+1} J_{m+n}(\delta) \right\} \Big] \quad . \quad . \quad . \quad (67)$$

when $(m + n)$ is odd, and to

$$F + jF' = \tfrac{1}{2}\sum_m (-1)^{\frac{1}{2}(m-n)} \Big[(B_m + jB'_m) \left\{ J_{m-n}(\delta) + (-1)^{n} J_{m+n}(\delta) \right\} - (A'_m - jA_m) \left\{ J_{m-n}(\delta) - (-1)^{n} J_{m+n}(\delta) \right\} \Big] \quad . \quad . \quad . \quad (68)$$

when $(m - n)$ is even, where J_r is a Bessel function of the first kind, tables of which are readily available.

Equations (67) and (68) only hold if $m > n$. When $m < n$ it is necessary to put m for n and n for m in these equations without changing any of the signs.

These general formulæ simplify considerably in a large number of special cases, some of which will now be considered.

(b) *Circle of Vertical Antennæ all Excited in the Same Phase.*

In this case $m = n = 0$, and from equation (7) $f'_\theta = f_\phi = f'_\phi = 0$, so that the radiation distribution of each individual antenna is a single function of the angle θ (this function is not complex). Let it be f_θ. The radiation distribution of the whole circular system will then be given by

$$\left. \begin{aligned} F_\theta + jF'_\theta &= f_\theta J_0(\delta) \\ F_\phi + jF'_\phi &= 0 \end{aligned} \right\} \quad . \quad . \quad . \quad (69)$$

When the height of the individual antenna is small $f_\theta = \delta l \sin \theta$ [see equation (3)].

It may be noted that the number of antennæ in the circle does not enter into equation (69). That is so because, as in section (7), the total current is measured and not the current in an individual antenna. This convention will be adopted in all the following cases.

(c) *Circle of Small Vertical Radial Coils Excited in the Same Phase.*

If the vector representing the coil at M [see section 2 (b)] is along the Y axis (Fig. 11), then equation (11) gives

$$f_\theta = 0, \quad f_\phi = 0, \quad f'_\theta = -(2\pi/\lambda) \cos \phi \, \delta A$$

and

$$f'_\phi = -(2\pi/\lambda) \cos \theta \sin \phi \delta A$$

Hence, the radiation distribution of the whole circle is given by

$$\left.\begin{aligned} F_\theta + jF'_\theta &= j\frac{2\pi\delta A}{\lambda}J_1(\delta) \\ F_\phi + jF'_\phi &= 0 \end{aligned}\right\} \quad . \quad . \quad . \quad (70)$$

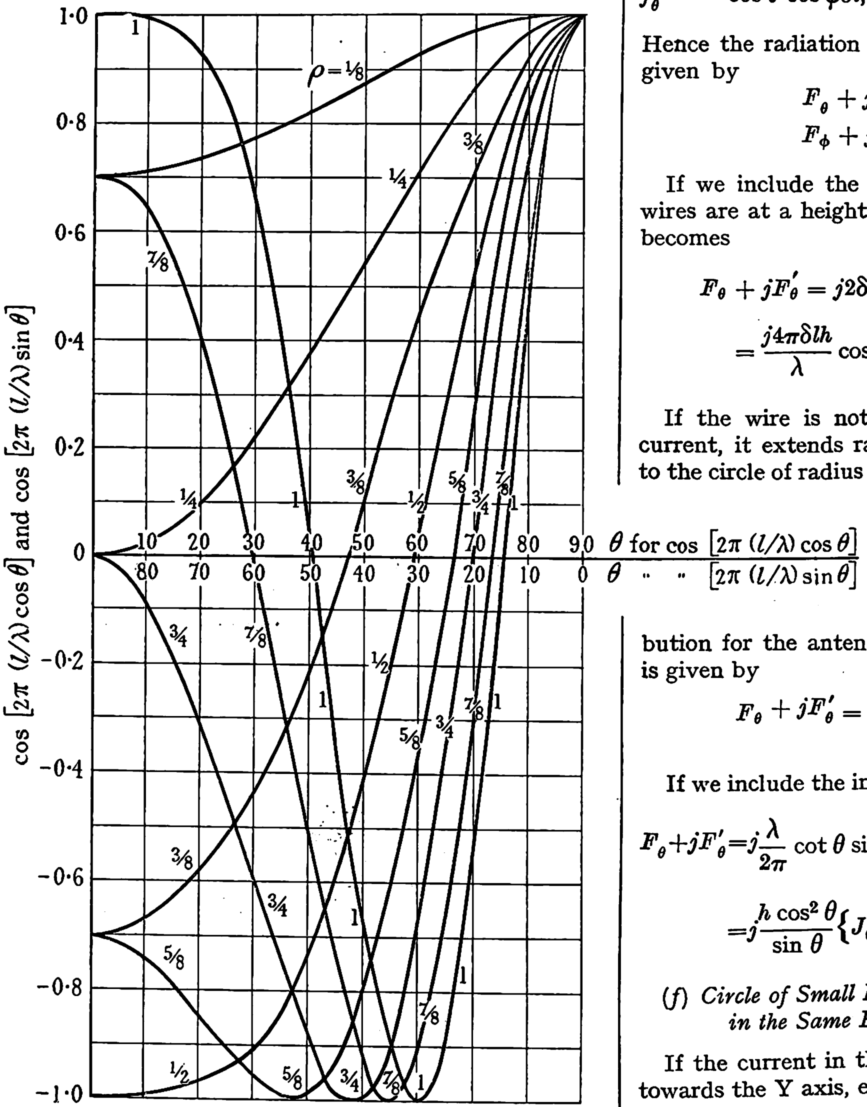

FIG. 12.—Curves of cos $\{2\pi(l/\lambda)\sin\theta\}$ and cos $\{2\pi(l/\lambda)\cos\theta\}$ for various values of l/λ.

(*d*) *Circle of Small Vertical Tangential Coils Excited in the Same Phase.*

If the vector representing the coil at M is radially outwards, then equation (10) gives

$$f_\theta = 0, \quad f_\phi = 0, \quad f'_\theta = (2\pi/\lambda)\sin\phi\delta A,$$
$$f'_\phi = -(2\pi/\lambda)\cos\theta\cos\phi\delta A$$

Hence the radiation distribution for the whole circle is given by

$$\left.\begin{aligned} F_\theta + jF'_\theta &= 0 \\ F_\phi + jF'_\phi &= j\frac{2\pi\cos\theta\delta A}{\lambda}J_1(\delta) \end{aligned}\right\} \quad . \quad . \quad (71)$$

(*e*) *Circle of Small Horizontal Radial Wires Excited in the Same Phase.*

If the current is flowing radially outwards, equation (8) gives

$$f_\theta = -\cos\theta\cos\phi\delta l, \quad f_\phi = -\sin\phi\delta l, \quad f'_\theta = 0, \quad f'_\phi = 0$$

Hence the radiation distribution for the whole circle is given by

$$\left.\begin{aligned} F_\theta + jF'_\theta &= \delta l\cos\theta J_1(\delta) \\ F_\phi + jF'_\phi &= 0 \end{aligned}\right\} \quad . \quad . \quad . \quad (72)$$

If we include the image in a perfect earth, and the wires are at a height h above the ground, equation (72) becomes

$$F_\theta + jF'_\theta = j2\delta l\cos\theta\sin\left(\frac{2\pi h\cos\theta}{\lambda}\right)J_1(\delta) \quad . \quad (73)$$

$$= \frac{j4\pi\delta lh}{\lambda}\cos^2\theta J_1(\delta) \text{ if } (h/\lambda) \text{ is small} \quad . \quad . \quad (74)$$

If the wire is not small, but still carrying uniform current, it extends radially from the circle of radius r_1 to the circle of radius $r_2 (r_2 > r_1)$, and the radiation distribution for the antenna system alone without its image is given by

$$F_\theta + jF'_\theta = \frac{\lambda}{2\pi}\cot\theta\left\{J_0(\delta_1) - J_0(\delta_2)\right\} \quad . \quad (75)$$

If we include the image in a perfect earth this becomes

$$F_\theta + jF'_\theta = j\frac{\lambda}{2\pi}\cot\theta\sin\left(\frac{2\pi h\cos\theta}{\lambda}\right)\left\{J_0(\delta_1) - J_0(\delta_2)\right\} \quad (76)$$

$$= j\frac{h\cos^2\theta}{\sin\theta}\left\{J_0(\delta_1) - J_0(\delta_2)\right\} \text{ if } (h/\lambda) \text{ is small} \quad (77)$$

(*f*) *Circle of Small Horizontal Tangential Wires Excited in the Same Phase.*

If the current in the vector at M (Fig. 11) is flowing towards the Y axis, equation (9) gives

$$f_\theta = -\cos\theta\sin\phi\delta l, \quad f_\phi = \cos\phi\delta l, \quad f'_\theta = 0, \quad f'_\phi = 0$$

Hence the radiation distribution due to the whole circle without its image is given by

$$\left.\begin{aligned} F_\theta + jF'_\theta &= 0 \\ F_\phi + jF'_\phi &= -\delta l J_1(\delta) \end{aligned}\right\} \quad . \quad . \quad . \quad (78)$$

If we include the image in a perfect earth, this becomes

$$F_\phi + jF'_\phi = -j2\delta l\sin\left(\frac{2\pi h\cos\theta}{\lambda}\right)J_1(\delta) \quad . \quad . \quad . \quad (79)$$

$$\doteq -j\frac{4\pi h\delta l}{\lambda}\cos\theta J_1(\delta) \quad \text{when } (h/\lambda) \text{ is small} \quad . \quad (80)$$

(8) Example.

A case which occurs in engineering practice is that of the beam antenna. As an example, suppose a beam system to consist of n equal vertical antennæ carrying equal currents and spaced a distance d apart. Let us further suppose that each antenna consists of m positive half-waves of current superposed one above the other, the negative half-waves being suppressed by the Franklin or other system.

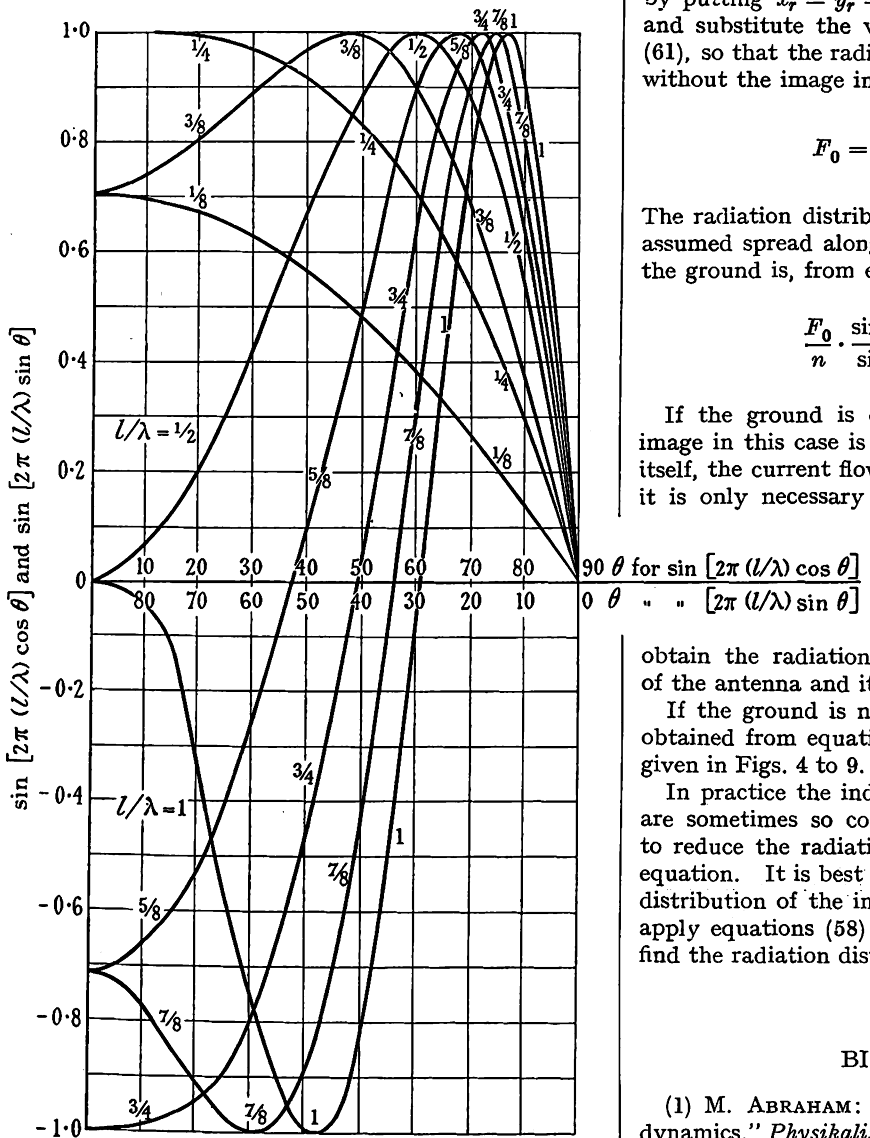

Fig. 13.—Curves of sin $\{2\pi(l/\lambda)\sin\theta\}$ and sin $\{2\pi(l/\lambda)\cos\theta\}$ for various value of l/λ.

From equation (46) a half-wave vertical antenna has a radiation distribution given by

$$f_0 + jf'_0 = \frac{\lambda}{2\pi\sin\theta}\left\{\cos(\pi\cos\theta) + 1 + j\sin(\pi\cos\theta)\right\} \quad . \quad (81)$$

The resultant of this is given by

$$f_0 = \frac{\lambda}{\pi\sin\theta}\sqrt{\left[\tfrac{1}{2}\{1 + \cos(\pi\cos\theta)\}\right]}. \quad . \quad (82)$$

By means of equations (58) and (61) we can superpose m of these half-wave elements on the top of one another by putting $x_r = y_r = 0$ and $z_r = \frac{1}{2}\lambda$ in equation (82), and substitute the value of d obtained from equation (61), so that the radiation distribution of each antenna without the image in the ground is given by

$$F_0 = \frac{f_0}{m}\cdot\frac{\sin(m\pi\cos\frac{1}{2}\theta)}{\sin(\pi\cos\frac{1}{2}\theta)} \quad . \quad . \quad . \quad (83)$$

The radiation distribution for the whole antenna array assumed spread along the X axis without the image in the ground is, from equations (58 and (61),

$$\frac{F_0}{n}\cdot\frac{\sin(n\pi d\cos\phi\sin\theta/\lambda)}{\sin(\pi d\cos\phi\sin\theta/\lambda)} \quad . \quad . \quad . \quad (84)$$

If the ground is of perfect conductivity, since the image in this case is identical with the antenna system itself, the current flowing in the same direction in both, it is only necessary to replace m by $2m$ in order to obtain the radiation distribution for the combination of the antenna and its image.

If the ground is not perfect, the total result can be obtained from equation (34), making use of the curves given in Figs. 4 to 9.

In practice the individual antennæ forming an array are sometimes so complicated that it is not practical to reduce the radiation distribution to the form of an equation. It is best in this case to obtain the radiation distribution of the individual antennæ graphically, and apply equations (58) and (61) to the result in order to find the radiation distribution for the whole array.

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THE RADIATION DISTRIBUTION OF ANTENNÆ IN VERTICAL PLANES.*

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(*Paper first received* 16*th November*, 1929, *and in final form* 22*nd February*, 1930.)

SUMMARY.

The radiation distribution of an antenna in a vertical plane was obtained by measuring in an aeroplane the strength of a received signal from an excited antenna on the ground. The position of the aeroplane relative to the antenna was obtained by means of a theodolite on the ground, the signal strength being recorded on a cinematograph film.

Although the ground site appeared very good, it was found that spurious radiations were obtained and these were probably the cause of the discrepancies found between the theoretical and the experimental results. The measurements were made on a horizontal antenna at several frequencies. The reason for this particular arrangement is that it should be possible to separate the effect of the reflection of the antenna in the earth from that of the antenna itself, and thereby obtain a double result from a single measurement.

The results showed very definite maxima and minima and the position of these could be ascertained accurately within a few degrees, but the difficulties of the experiment prevented an accurate value of the field strength being obtained. Substantial agreement was obtained between theory and experiment, the discrepancies increasing with the frequency.

The radiation distribution was also obtained for one of the beam stations erected by the Marconi Co. Owing to the sharpness of the beam, considerable experimental error was liable to occur. Nevertheless, substantial agreement between theory and experiment was also obtained in this case.

(1) INTRODUCTION.

A considerable amount of experimental data has been obtained on the radiation distribution from antennæ in a horizontal plane, and all the evidence strongly shows that the theoretical and the experimental results are in very close agreement, particularly for short-wave stations. On longer waves the mast system is usually a much more important part of the whole erection and it is probable that the discrepancies, which are often found where steel masts are used, are due to induced currents in the masts which are not allowed for in the calculations. There are very few cases, with the conspicuous exception of the Beverage antenna, in which the radiation distribution in a horizontal plane depends on the distribution of current along a horizontal wire, and it was with the double purpose of investigating whether such a radiation distribution could be calculated and of examining the effect of the reflection in the earth that the experiments described in this paper were undertaken.

The distribution of current along a transmitting antenna has been discussed theoretically by Macdonald * and Abraham † with substantial disagreement as to the size of the first loop near the end of the wire. Macdonald makes the distance to the first current node as low as $\lambda/5$ in some cases, while Abraham obtains $\lambda/4{\cdot}2$ for this distance. Abraham considered the case of a thin ellipsoid, and Lord Rayleigh ‡ has shown that, in spite of the tapering of the wire which this assumption involves, the result is applicable to a thin circular wire. The experimental evidence is to some extent conflicting, but most of the results date from the time when spark sets were the only available source of oscillations. Few experiments have been carried out on current distribution since the advent of the wireless valve. The author § recently published some results on an 11-metre vertical antenna over a range of wavelengths from 15 m to 800 m and found agreement with Abraham's theory to an order of accuracy of some 5 per cent. This means that the accuracy was not sufficient to discriminate between Abraham's theory ($\lambda/4{\cdot}2$) and the simple sinusoidal theory ($\lambda/4$). The current was measured by ammeters, the capacity and self-inductance effects of which were accurately considered. C. R. Englund || also obtained agreement with the simple theory, by finding the natural frequency of straight rods. It would therefore appear that, to a sufficient degree of accuracy, one can assume that the current distribution follows a simple sinusoidal law with small corrections for the end effects (see Appendix 1), the distance between nodes and antinodes being $\lambda/4$.

There is some further evidence from certain field-strength measurements that the simple sinusoidal law of current distribution holds and that, moreover, there is no appreciable change in phase along the antenna. One of these confirmatory results was recently given by P. P. Eckersley, T. L. Eckersley and H. L. Kirke,¶ who showed that the field strength on the ground from the half-wave vertical antenna was double that of a quarter-wave antenna to an accuracy of 5 per cent (well within the limits of experimental error), showing that both quarter wavelengths of the antenna were radiating equally and were in the same phase. Further evidence was obtained from investigations carried out by G. H. Munro in connection with attenuation experiments undertaken by R. H. Barfield.** In order to obtain the effective height of an antenna, Munro suggested using a "T" antenna and increasing the length of the horizontal portions until the signal received from a constant source remained substantially constant, when the effective height could be assumed to be equal to the actual height. The variation of effective height, calculated by the author from the simple sinusoidal current distribution theory,* is shown in Fig. 1. The crosses represent the experimental values obtained by Munro. It is interesting to note how closely the experimental and theoretical results agree.

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* See Reference (1).
† *Ibid.*, (2).
‡ *Ibid.*, (3).
§ *Ibid.*, (4).
|| *Ibid.*, (5).
¶ *Ibid.*, (6).
** See *Journal I.E.E.*, 1928, vol. 66, p. 215.

There is considerable evidence, therefore, in favour of the simple sinusoidal theory of current distribution, and this is the theory used in this paper in comparing the theoretical and experimental radiation distribution diagrams. A number of general formulæ for this have been obtained by the author.†

The other factor that enters into the theoretical consideration of this problem is the effect of the earth and its imperfect conductivity. A theory has been put forward by T. L. Eckersley‡ and amplified by the author § (Appendix 2), but there has not yet been any satisfactory experimental confirmation of this theory.

the instrument. The galvanometer was fitted with shunts of several values so that, by means of a switch, it could be made more or less sensitive, and it was the duty of the observer in the aeroplane to operate the switch in order to keep the galvanometer at some suitable deflection.

A better, method but one which would be slightly more cumbersome to apply satisfactorily, would have been to insert a potentiometer or attenuator device in the intermediate-frequency amplifier (as in the field-strength measuring set due to Friis and Bruce*) and thus control the galvanometer deflection, but it was not considered at first that the experimental accuracy, especially in locating the aeroplane over the whole flight, would warrant this extra encumbrance. The experience gained, however, showed that this was an error of judgment and that more reliable field-strength measurements would have been useful.

The receiving set was calibrated on the ground by means of a small local oscillator in which the antenna current could be varied and measured over a range of 100 to 1.

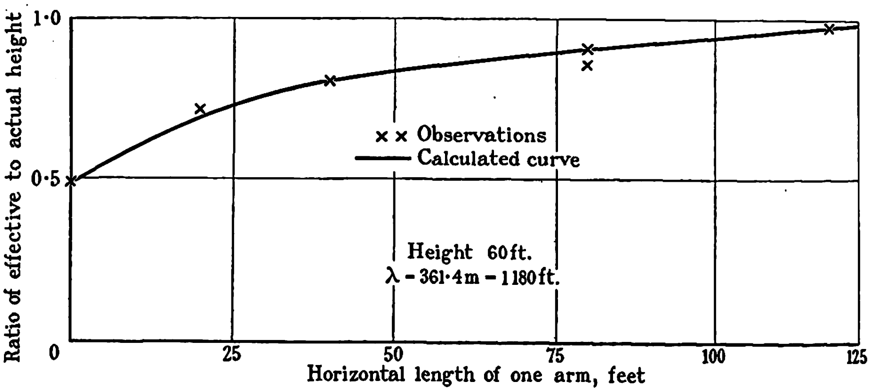

FIG. 1.—Effective height of " T " antenna.

(2) APPARATUS AND PROCEDURE.

For the purpose of these experiments the Air Ministry kindly placed an aeroplane at the disposal of the Radio Research Board. It was fitted with a " T " antenna having a horizontal portion 27 ft. long spread between two uprights 4 ft. high at each wing tip and supported at the centre. A supersonic heterodyne receiver was used. The intermediate- and low-frequency amplifiers were standard R.A.F. equipment. The low-frequency output was measured on a valve voltmeter using anode rectification. The detecting instrument consisted of a double-pivot microammeter from which the pointer had been removed, a small mirror being substituted. A small 2-volt lamp was focused on the mirror and reflected on to a cinematograph film kept moving by means of a gramophone motor at the rate of about 30 ft. per hour. The sensitivity for full-scale deflection was 50 μA. The whole was, of course, completely screened from external light. In order that the observer in the aeroplane might ensure that the spot of light remained on the film, the beam was intercepted by a semi-silvered mirror which reflected some of the light on to a red ground-glass screen on which the observer could see the deflection of

The transmitting antenna was spread between two wooden masts. The ground was flat and free from obstructions, and the site appeared to be very suitable and likely to approach fairly closely to the ideal case. There were a number of buried metal pipes and electric cables in the neighbourhood, as well as an earth which consisted of long aluminium strips embedded in the ground and spreading out radially from the centre of the antenna.

The aeroplane was piloted to glide from a height of 5 000 ft. down to 500 ft. from one side of the antenna to the other in such a direction that the two masts and the aeroplane remained in the same vertical plane. In this way it was possible to ascertain the position of the aeroplane from the horizontal and vertical angles obtained with a single theodolite. The theodolite was situated at a distance of some 3 miles from the station in a direction perpendicular to the direction of flight. At this distance three men were able after some practice to follow accurately the course of the flight and take readings on the theodolite every 10 seconds.

It is no easy matter for a pilot to keep his aeroplane flying accurately in one plane for, when a cross wind is blowing, as was almost invariably the case, the nose of the aeroplane may point 30° or more away from the true direction of flight. In order to give the pilot an indication by which to correct his direction of flight his telephones were connected in series with those of the observer in the aeroplane so that he could hear the modulated signal transmitted from the ground station. This signal was stopped for the space of a dot or a dash. A dot meant that he should turn one way and a dash the other way: if he were much out of his course a double signal would be sent. In this way the pilot could adjust his course correctly within a few degrees.

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* See Appendix 1 of Reference (4).

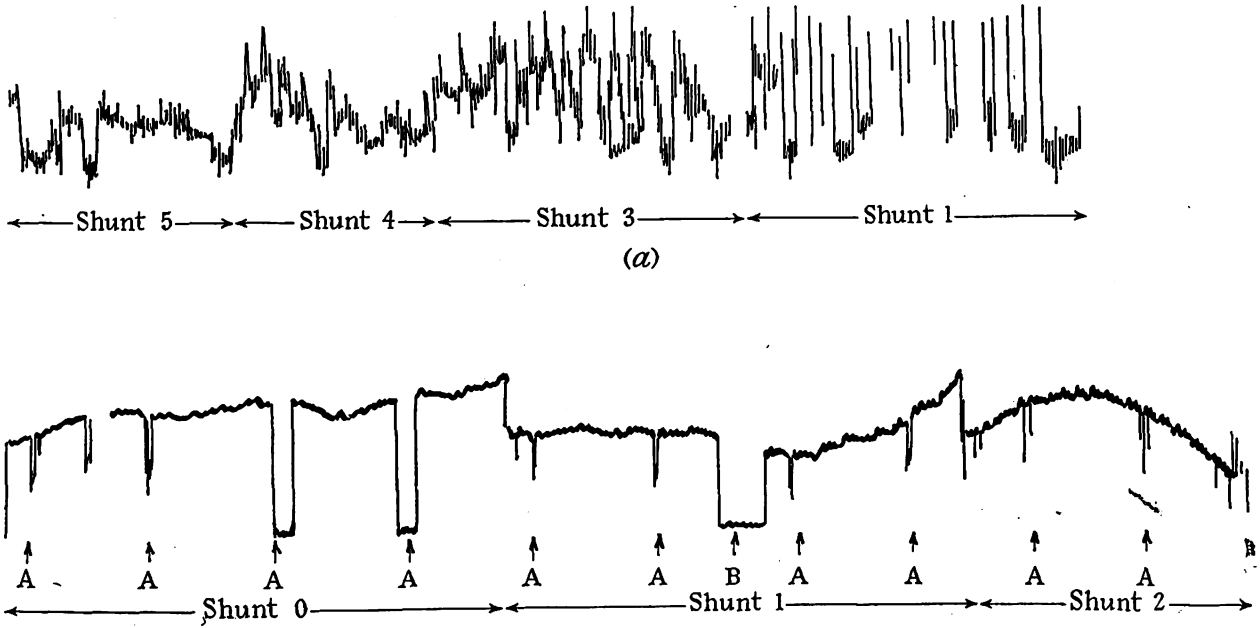
† See Reference (7)

‡ *Ibid.*, (8).

§ *Ibid.*, (9).

* See Reference (10).

The directional signals were sent every 10 seconds in synchronism with the readings taken on the theodolite, so that the cinematograph film on which the signal strength was recorded had a time scale automatically recorded on it [see Fig. 2 (*b*)]. Every minute a special signal was sent.



(*a*)

(*b*)

Fig. 2.

It may be realized that the experiments might have been inversed, i.e. a transmitter might have been installed in the aeroplane and the signal received on the ground. Such an arrangement would have permitted the use of a more elaborate signal-measuring set, but the directional indications to the pilot by means of the scheme described would not have been possible. Such indications would have necessitated communication on another frequency and probably the erection of a second antenna on the aeroplane. This was not considered advisable, for the radiation distribution of the aeroplane antenna is an unknown quantity and it seemed dangerous to distort it unnecessarily.

Baldus and Hase,[*] while investigating the radiation distribution of a trailing antenna in an aeroplane, employed transmissions from the aeroplane. They did not use any signal to direct the pilot, who found it almost impossible to fly correctly. The method employed in this case to locate the aeroplane was to take photographs of the ground and read the height. This method is liable to considerable error, first because the aeroplane may not be flying horizontally and a correction has to be applied from the readings of the levels, and secondly because the height is not easily measured. An accurate pressure altimeter was installed in the aeroplane used by the author. On one occasion when it was checked against the theodolite reading it showed very good agreement, but when the temperature correction was applied considerable divergence was found.

The preliminary experiments consisted mainly in adjusting the sensitivity of the receiver. The engine was found to be insufficiently screened. The comparison of the film readings shown in Fig. 2 are interesting. Fig. 2 (*a*) shows the type of field strength received when the aeroplane was first tried. After investigating the sources of radiation on the engine and screening a 2-in. length of exposed lead, the signal received was steadied to that shown in Fig. 2 (*b*). To compare Figs. 2 (*a*) and 2 (*b*), it is necessary to compare those parts for which the receiving set was of the same sensitivity. As explained above, variation of sensitivity was obtained by means of a series of shunts numbered from 0 to 6 (shunt 0 being the condition for which the set was most sensitive). Changes in shunt can be seen by the sudden changes in the signal strength, which are readily noticed in Fig. 2 (*b*). The sudden dips marked A in Fig. 2 (*b*) are the directional signals explained above, and the long dash seen at B is the distinguishing signal sent every minute. A more quantitative investigation of shielding in aeroplanes has been carried out recently by Drake.*

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[*] See Reference (11).

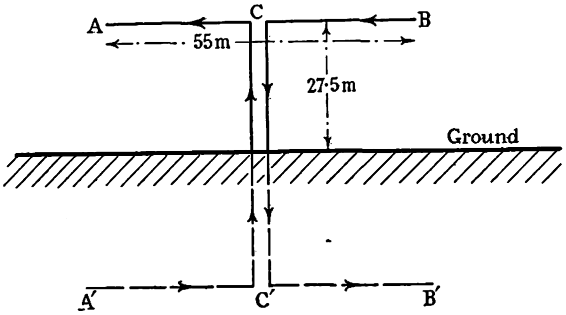

Fig. 3.

The antenna investigated was a horizontal one (Fig. 3) supported by wooden masts 150 m apart. It was excited by means of a push-pull oscillator, and the currents in the two leads were adjusted to equality at the foot of the antenna. The vertical leads were spaced 6 in. apart and the radiation from them was calculated to be quite negligible. This type of antenna is particularly interesting in this experiment because the whole of its radiating portion is at a constant height above the ground. Suppose an element P of the antenna together with its image has a radiation distribution of $I_p f_r$, where I_p is the current, then the function f_r will be the same for all the other elements of the antenna. If the whole antenna AB, considered in free space without its image, has a radiation distribution of f_a, then the total radiation distribution of the complete antenna with its image will be $f_a \times f_r$. By investigating such an antenna it should be possible to gain information regarding both f_a and f_r separately.

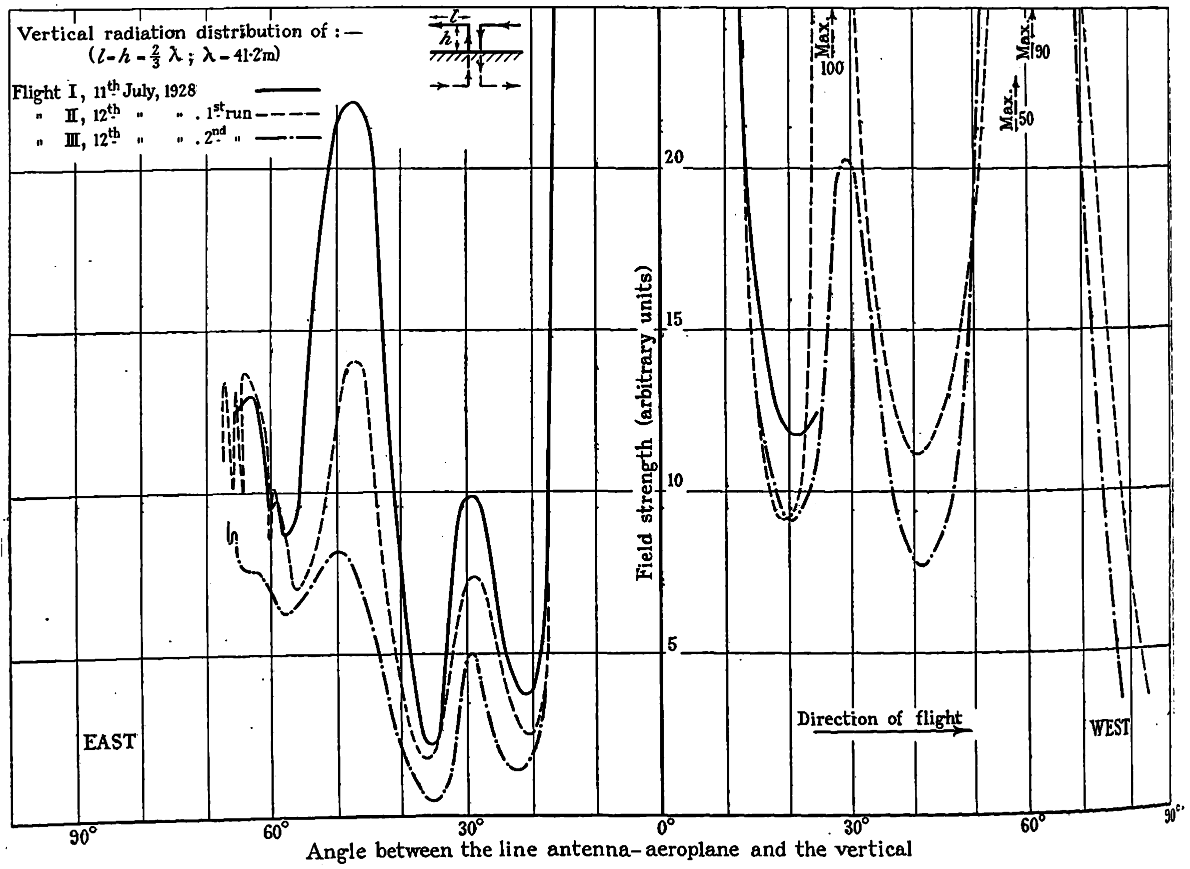

Fig. 4.

From the theory for the effect of the earth, mentioned above, it can be shown that, if $f_r = 0$ for a certain angle to the vertical in the case of a perfect earth, f_r will reach a minimum at a larger angle to the vertical when the earth is imperfect, and, moreover, f_r will never become zero in this case.

The variation of field strength recorded on the cinematograph film can only be construed into radiation distribution on two assumptions, viz.

(*a*) That the field strength varies inversely as the distance, and

(*b*) That the radiation distribution of the aeroplane antenna is sinusoidal.

The first assumption would appear to be incorrect for the ground ray, on account of attenuation, but along any other line there is no reason to suppose that this would be so. In fact, experimental evidence in support of the assumption is given below.

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* See Reference (12).

Some experiments described below were carried out in an endeavour to verify or alter the second assumption, but the results did not justify the use of any more definite law than the simple sinusoidal distribution, which is based on the fact that the aeroplane antenna was invariably small compared with the wavelength. It will be seen that this gives rise to considerable difficulty when the aeroplane is vertically above the transmitting antenna, for, in that case, if the signal strength in the aeroplane is not zero, the calculated strength of the radiation from the transmitter will be infinite. In fact, for all angles within some 7° of the vertical the radiation distribution will be very inaccurate indeed and will consequently be omitted in the radiation distribution diagrams found experimentally. These diagrams are not plotted in the usual polar co-ordinates but in cartesian co-ordinates, so as to make the discrepancies more clearly visible. The angles in degrees measured from the vertical are plotted along the abscissæ, while the field strengths are plotted along the ordinates. Since the absolute values of field strengths were not determined the units used are absolutely arbitrary.

(3) Experimental Results on Simple Antennæ.

The first tests were carried out at a wavelength of 41·1 m ($h = \frac{2}{3}\lambda$) on a horizontal antenna as shown in Fig. 3, and the results of three flights all in the same direction are shown in Fig. 4.

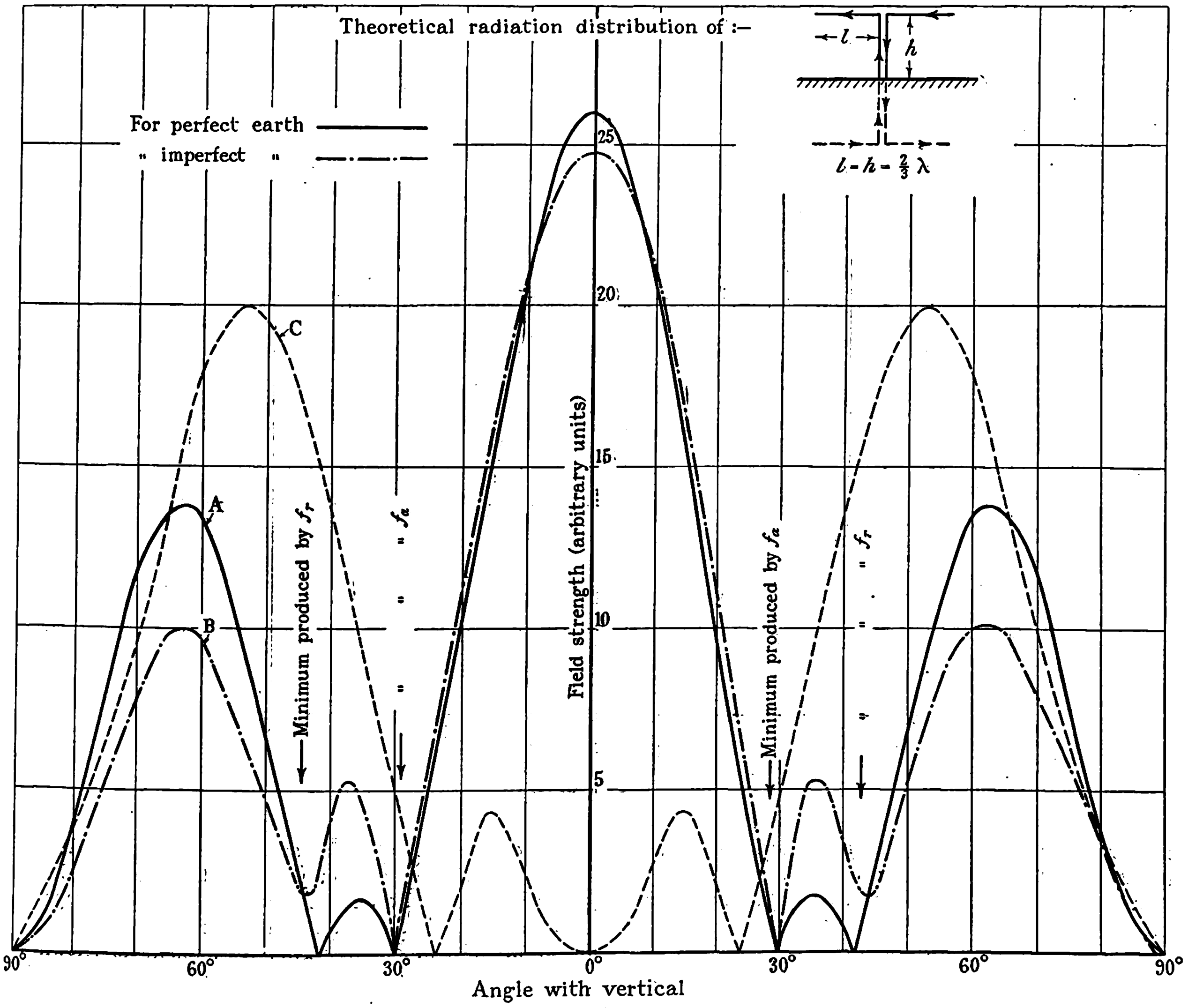

Fig. 5.

In analysing the experimental results it is essential to endeavour to discriminate between the radiation distribution due to the antenna alone (f_a) and that due to the effect of reflection in the earth (f_r). The radiation distribution in the case of a perfectly conducting earth is shown by the full line in Fig. 5, curve A. The minimum at 30° is due to f_a, while that at 41·5° is due to f_r. Mr. Barfield kindly measured the conductivity of the ground on the site of the transmitting antenna, by observing the tilt of the ground wave. He obtained values which varied between $0\cdot8 \times 10^8$ and 2×10^8 electrostatic units at various frequencies, the variation being caused, he thought, by buried conductors. Assuming that the conductivity is $1\cdot5 \times 10^8$ electrostatic units, the radiation can be calculated as explained in Appendix 2, and gives a distribution shown by the chain curve in Fig. 5 (curve B). It will be seen that the minimum due to f_a remains unaltered, while that due to f_r does not come to zero and is shifted to a slightly larger angle with the vertical. If the end-effect correction explained in Appendix 1 be applied, the curve will not be affected to a very great extent, but the minimum due to f_r will be shifted some 3° towards the vertical.

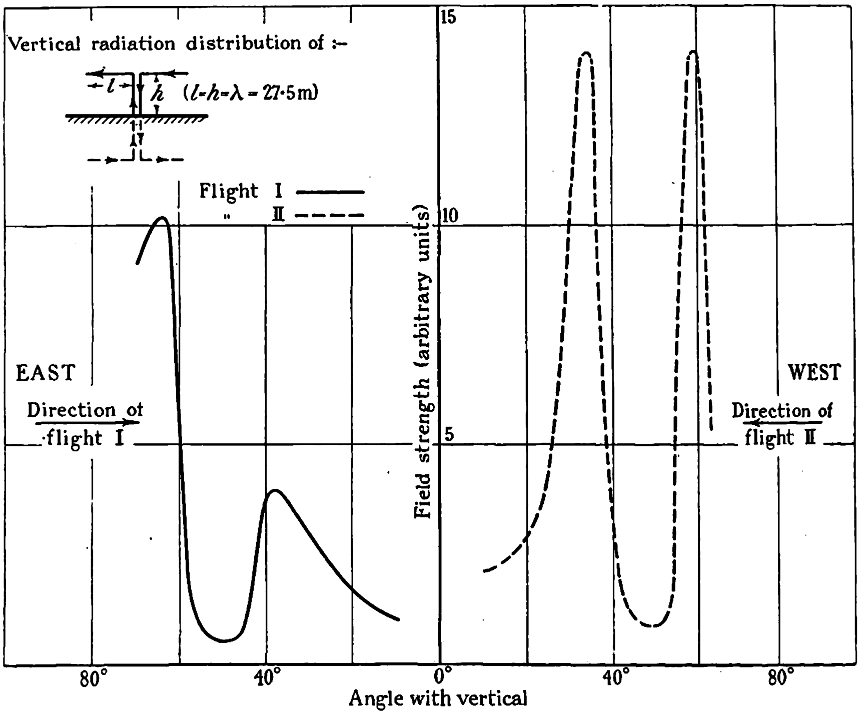

Fig. 6.

On examining Fig. 4 a number of points may be noted:

(*a*) The positions of the main maxima and minima repeat to an accuracy of less than 2°.

(*b*) The positions of the main maxima and minima are slightly different on the two sides of the transmitting antenna and occur at a greater angle to the vertical than the theory would lead one to expect.

(*c*) The signal strength on the east side is much weaker than that on the west.

The accuracy with which the results repeat leaves very little room to doubt that all the effects noted truly exist and are not merely due to experimental error. The asymmetry of the positions of the maxima and minima on either side of the antenna might be caused by some error due to synchronizing the watches. An error of 1 second might account for this, and, although the watches were thoroughly tested and were checked before and after the flights, such an error might be conceivable owing to changes of temperature in the course of the flights, which were some 2 hours in duration. It will be noted, however, that the error repeats accurately on two different days and it is difficult to imagine how such a consistent error could occur.

It was thought that some of the discrepancies between the theoretical and the experimental curves might be caused by slightly unequal excitation of the two halves of the antenna. Calculation showed, however, that this could not cause asymmetry and that its effect would only be of the second order, as it would produce a component of the radiation distribution in time quadrature with the main component. This component is shown by the broken line C in Fig. 5 and it does not appear that any satisfactory deduction can be made from it.

The minimum that should theoretically occur at 43° is the minimum produced by the interference of the antenna and its image. Experimentally it is found to occur at 36° on one side and 41° on the other, giving a mean of $38\frac{1}{2}$°. If the earth were a perfect conductor this minimum would occur at 41°. It would appear, therefore, that the minimum is shifted by the imperfection of the earth by the correct amount but in the wrong direction.

The position of the other minimum, which is produced by the antenna alone, shows a discrepancy of as much as 9° between the experimental and theoretical values.

If allowance is made for end effects, as explained in Appendix 1, this discrepancy can be reduced to 5°.

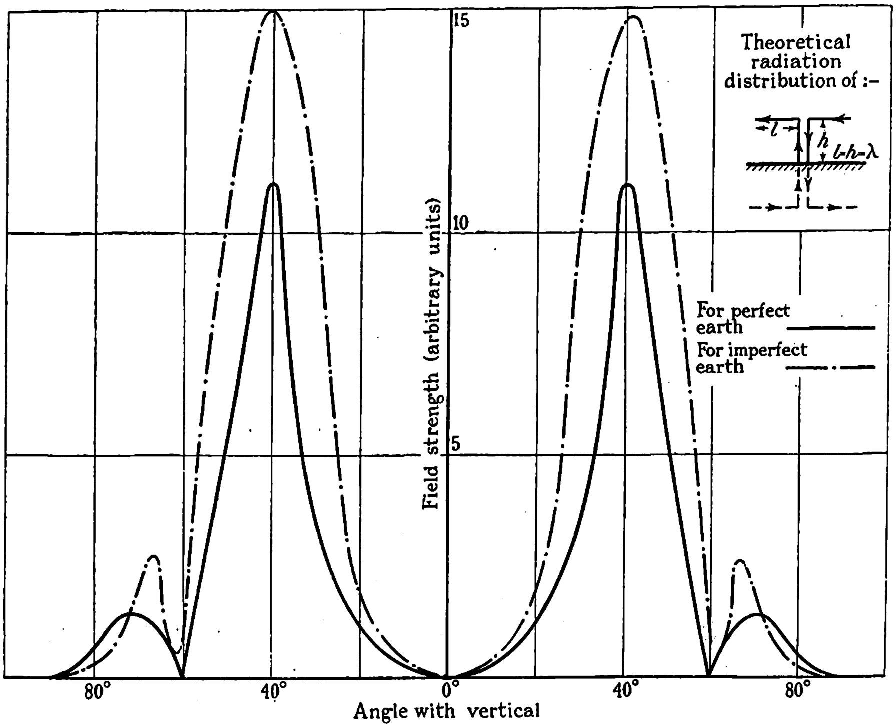

FIG. 7.

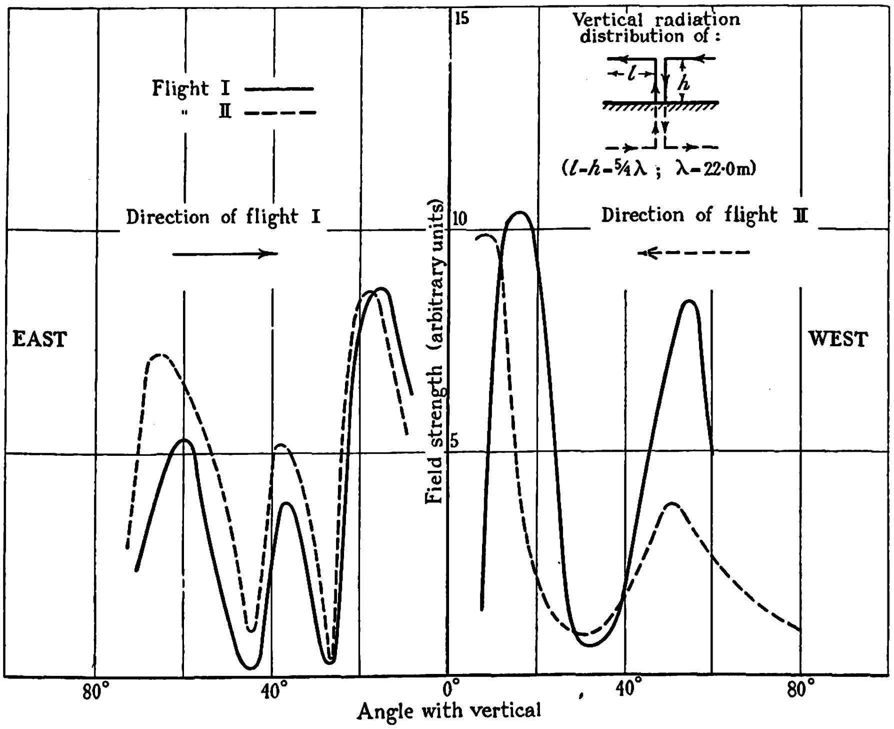

FIG. 8.

The author believes that the reason for these discrepancies may well be found in the site—buried conductors, etc.—and evidence for this will be given below.

The next experiments were carried out on the same antenna with a wavelength of 27·5 m ($h = \lambda$). The experimental results are shown in Fig. 6. In this case the flights were carried out over the antenna from both directions in the hope of eliminating the effect of the directive properties of the aeroplane itself. It will be seen later that this could not give the expected results.

The curves of Fig. 6 are to be compared with the theoretical curves of Fig. 7.

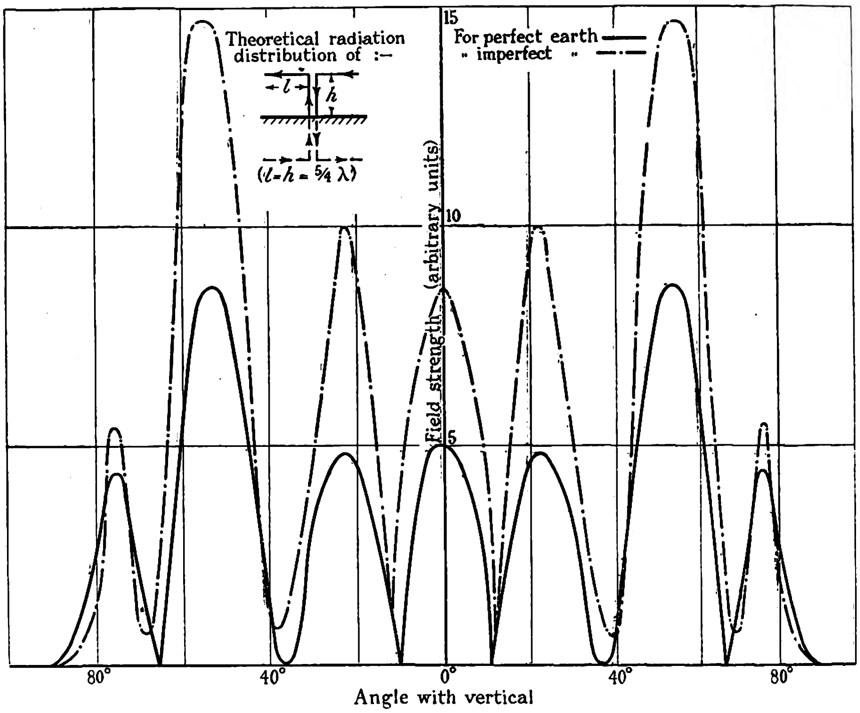

Fig. 9.

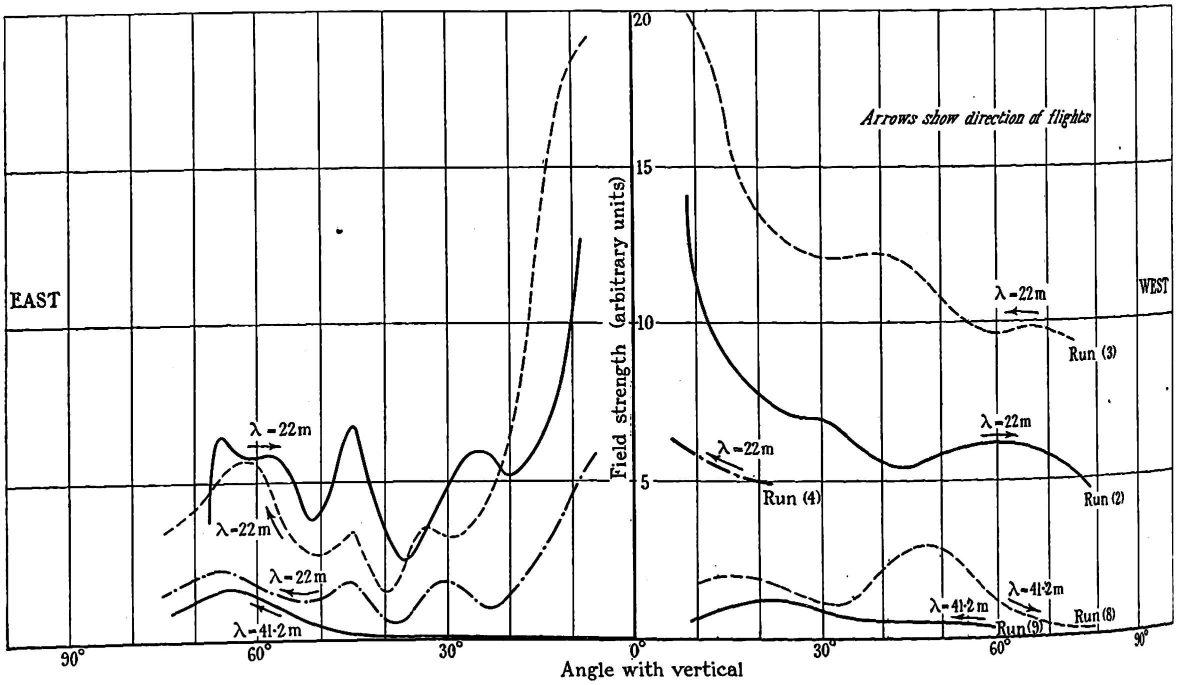

Fig. 10.—Radiation distribution with short vertical antenna.
Arrows show direction of flights.

Deductions similar to those in the previous case can be made, namely, asymmetry on the two sides of the antenna and a shifting of the minima and maxima towards the vertical as compared with the theoretical curves.

Similar tests were made with the antenna excited at a wavelength of 22 m ($h = \frac{3}{4}\lambda$). The experimental results are shown in Fig. 8, which should be compared with the theoretical curves of Fig. 9. Here, again, deductions similar to those in the two previous cases can be made.

In order to allow for the radiation distribution of the antenna on the aeroplane, the field strength received from a small vertical antenna was analysed with the aeroplane in the same way as in the case of the horizontal antenna. By a small antenna is meant an antenna not greater than $\frac{1}{8}$th wavelength in height. In order to increase the effective height of this antenna, a horizontal portion was added in the plane perpendicular to the plane of flight of the aeroplane, so that radiation from this horizontal portion might affect the result to a negligible extent. In these conditions it was thought reasonable to assume that the radiation distribution of the transmitter would be sinusoidal. That is, if the signal strength (corrected for distance) were divided by sin θ (where θ is the angle with the vertical) the result should give the radiation distribution of the aeroplane antenna. In this, however, the experiments led to disappointment. The results obtained are shown in Fig. 10.

Two wavelengths were studied (41·2 m and 22 m). The aeroplane was flown both from east to west and from west to east, so that in some cases the engine would lie between the receiving and the radiating antenna and in the other cases it would lie on the other side of the receiving antenna, and the screening effect might be expected to be different in the two cases. On examining Fig. 10, however, it will be found that the radiation distribution diagram is substantially independent of the direction of flight of the aeroplane. Yet the curves obtained are far from uniform and the signal strength on the east side of the transmitting antenna is always much stronger than that on the west. Looking back at Figs. 4, 6 and 8 we see that this result was obtained in every case. We are finally led to the

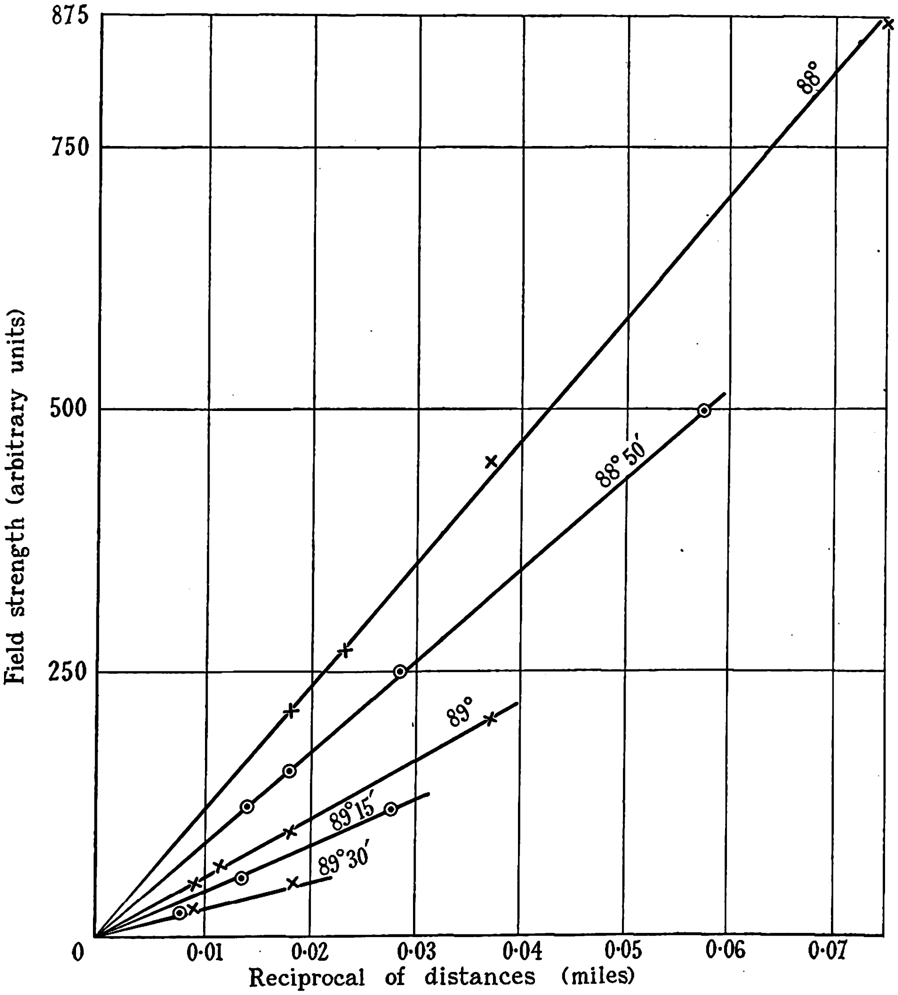

FIG. 11.—Signal strength plotted against reciprocal of distance for various inclinations to vertical. $\lambda = 185$ m.

conclusion that the radiation distribution of the aeroplane antenna may be sinusoidal and that the irregularities noted are due to the nature of the neighbouring objects around the transmitter. This result was unexpected as the site was considered to be clear of interfering obstructions. The building in which the oscillator was housed at the foot of the antenna was made of concrete without any metal, but the back of it contained electrical power generators some 60 ft. from the foot of the antenna. There were also some conductors buried in the ground. The masts were made of wood and held up by steel-rope stays, but the masts were 500 ft. apart and the antenna, held in the centre, was only 170 ft. long. There were, moreover, no trees for some considerable distance from the site. However unexpected the result may be, there does not appear to be any way of evading the conclusion that the variations shown in Fig. 10 were due to the ground or objects in the neighbourhood of the transmitting antenna. A further confirmation of this was obtained by finding the radiation distribution of the aeroplane antenna on the ground by rotating the aeroplane about a vertical axis. The signal strength during any one rotation was found not to vary by more than 5 per cent even at a wavelength as low as 15 m.

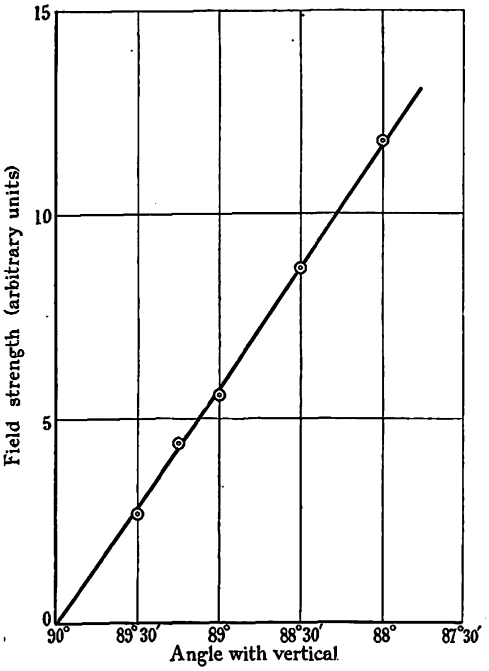

FIG. 12.—Variation of signal strength with angle to vertical. $\lambda = 185$ m.

In the calculation of the foregoing experimental curves it has been tacitly assumed that the signal strength varies inversely with the distance. While this is known to be true for comparatively short distances on long wavelengths, it is known to be false for short waves on the ground, the law in this case being very nearly inversely as the square of the distance. The author believed that this was due to the attenuation produced by the ground, but that the inverse-distance law would hold along any radius even at very small angles of elevation from the ground. Some rough experiments carried out by the author confirmed this, but far more elaborate experiments have been carried out by D. K. Martin * of the Bell Telephone Laboratories. In these experiments the signal strength was measured at various heights above the ground, travelling horizontally for a distance as great as 120 miles from the transmitter. From these results Fig. 11 has been calculated. This shows the variation of signal strength with the reciprocal of the distance along radii making various angles with the vertical. It will be noted that all the points lie on a series of straight lines to a very high degree of accuracy, thus effectively proving the inverse-distance law up to angles of 89½° with the vertical.

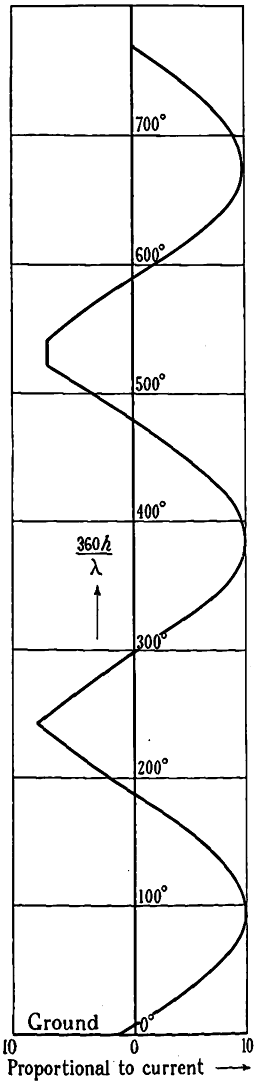

FIG. 13.—Current distribution in Australian beam antenna at Grimsby. $\lambda = 25 \cdot 9$ m.

This series of curves is very interesting in another

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* See Reference (13).

respect. If we write $(\frac{1}{2}\pi - \delta)$ for θ in equation (3) of Appendix 2, and make δ very small (δ being the angle of elevation with the ground) we have

$$K_i - jK_i' = -\left\{1 - 2\delta\sqrt{(\sigma/f)} + 2j\sqrt{(\sigma/f)}\delta\right\}$$

The signal strength for small values of δ is, therefore, proportional to

$$2\delta\sqrt{(2\sigma/f)}$$

The gradient of the straight lines in Fig. 11 will be a measure of the field strength for various values of δ and, according to the above, this should be a linear relation. That this is so is well shown in Fig. 12. The gradient of this line depends on the conductivity of the ground and on the effective height and the current in the transmitting antenna. Knowing the latter, the conductivity of the ground could be deduced.

The linear relation of Fig. 12 is a very striking, though far from complete, confirmation of the equations (8) and (9) explained in Appendix 2. It is very interesting, however, in tending to show that only the constants of the ground in the immediate neighbourhood of the ground station affect the signal strength of the direct ray in aeroplane-to-ground communication.

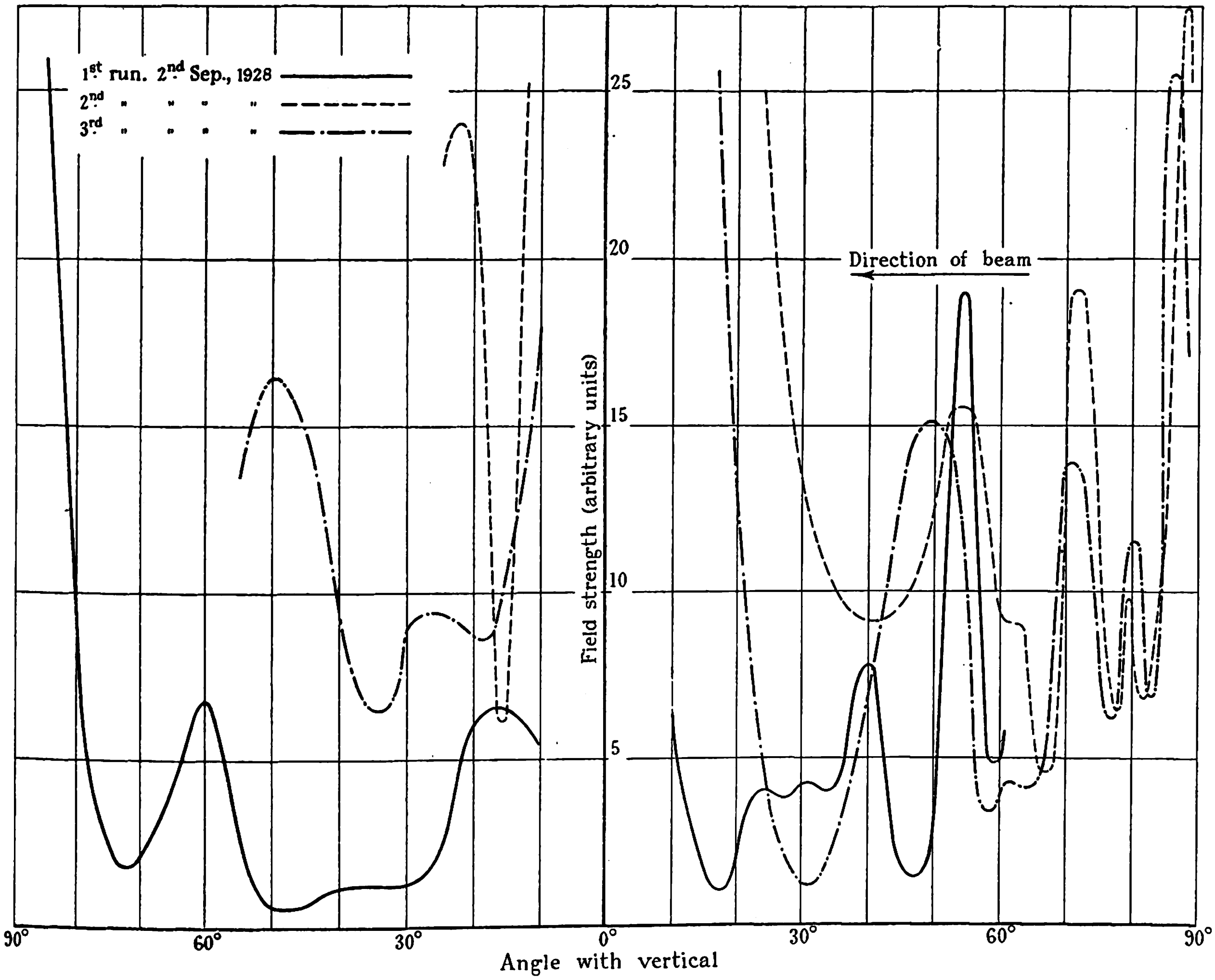

FIG. 14.—Vertical radiation distribution of Australian beam aerial at Grimsby. $\lambda = 25 \cdot 9$ m.

(4) EXPERIMENTAL RESULTS ON A BEAM ANTENNA.

With the co-operation of the Post Office, a number of flights were made over the beam antenna erected near Grimsby by the Marconi Co. for transmissions to Australia. The beam array consists of a large number of vertical wires spread over a span of 1 300 ft. Each wire is built on the Franklin system, with portions of current loops eliminated. The current distribution, on the simple sinusoidal theory, is shown in Fig. 13. The ordinates are measured in degrees instead of metres (a distance h corresponds to $360\ h/\lambda$ degrees), to simplify the calculations. In order to obtain a theoretical radiation distribution curve the current areas are divided up into a large number of small areas having a height of not more than 45°, and the distances of their centres of gravity from the ground are read off in degrees. If A is an area and h_1 the height of its centre of gravity from the ground, the field strength in a direction making an angle θ with the vertical in the case of a perfect earth will be proportional to

$$A \cos (h_1 \cos \theta)$$

The total field strength due to the whole antenna is obtained by adding all such terms. In the case of an imperfect earth the field strength has to be calculated as explained in Appendix 2.

It should be pointed out that the radiation distribution should be identical in form but not in strength in all vertical planes passing through the centre of the antenna array, if the reflector is neglected. The reflector consists of simple straight wires 960° high situated $\frac{1}{4}$ wavelength behind the transmitting array itself. This beam is so arranged as to permit of transmission either way round the earth. It was a simple matter, therefore, to find the ratio of front-to-back radiation, by simply reversing the direction of the beam, leaving the measuring receiver in the same place. The ratio on the ground of the field strength in front and behind was found to be of the order of 2 : 1, which value roughly checked with calculations based on the current measurements made on the reflectors and the transmitters, together with a rough estimate of the phase relation between them (see Appendix 2). This showed that the reflector would not affect the radiation distribution in a vertical plane to a very large extent, and, considering the errors liable to be found, it was not considered necessary to allow for it. The experimental results are given in Fig. 14 and the theoretical curve calculated for a perfect earth is shown in Fig. 15.

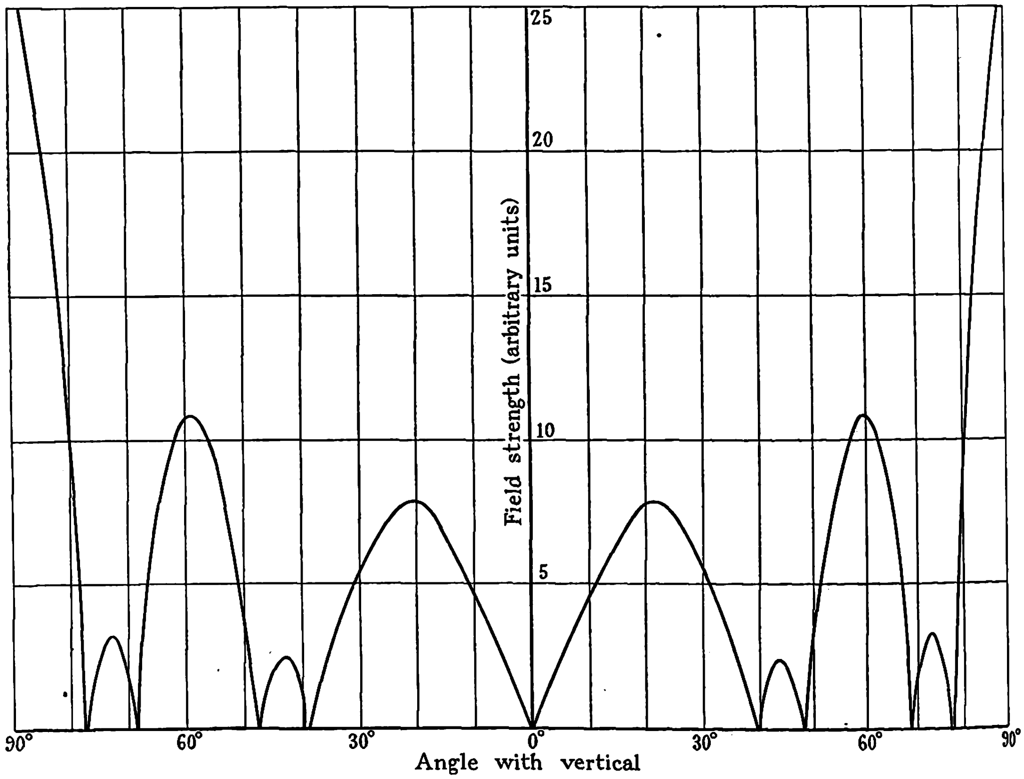

FIG. 15.—Theoretical radiation distribution from Australian beam over a perfect earth. $\lambda = 25{\cdot}9$ m.

The difficulty of investigating experimentally the radiation distribution of a beam compared with that of the simple antenna, lies in the very high directive properties of the former. Should the aeroplane fly in a plane slightly displaced from the true plane, the result would be very considerably distorted. Actually it was noted from the ground that the aeroplane flew in a plane parallel to, but slightly displaced from, the true plane. The true flight of the aeroplane was in a plane containing the main beam (i.e. perpendicular to the antenna array), and a displacement horizontally of as small an angle as 5° would reduce the signal from a strong maximum to a minimum. The size of the antenna system produced a further error, as it was not possible to reach such a height that the distance of the aeroplane from the antenna was large compared with the size of the antenna system itself. This error, however, when flying in the plane of the beam, is only of a second order. The aeroplane flight was practically a perfect straight line in space, starting at an altitude of 8 000 ft. at a horizontal distance of about 4 000 ft. behind the antenna, and ending at an altitude of some 500 ft. at a horizontal distance of about 25 000 ft. in front of the antenna. In flight 1 the signal strength was noted to be comparatively weak. This was no doubt due to the aeroplane flying appreciably out of the true plane, and it explains why the radiation distribution on this flight differs so considerably from that of the other two flights. The agreement between the other two flights is considered very satisfactory, in view of the experimental difficulties, and the results of flight 1 may, on this evidence, be discarded as untrustworthy.

The comparison of the experimental results and theoretical curves, as shown in Figs. 14 and 15, is very interesting. The large value of field strength obtained experimentally at 0° is probably due to a small asymmetry in the excitation of the beam system, and also to the fact that the aeroplane was not flying absolutely in the true plane. The first minimum between 30° and 65° is not so good. The third at 75° no doubt corresponds to the theoretical minimum at 69°, while the fourth at 82° corresponds to that at 77°. Then follows a very interesting result. Instead of increasing to reach a maximum of field strength on the ground, the field strength reaches a maximum at 86° and falls rapidly. Such an effect would be expected if the ground were not a perfect conductor. The angular position of the maximum can be used in obtaining an estimate of the conductivity of the ground. This would appear to be of the order of 4×10^8 electrostatic units. If this figure were used for correcting the theoretical radiation distribution curve given in Fig. 15, very little difference would be found except for angles greater than 82°.

(5) Conclusion.

From these results we may conclude that the experimental values are reliable but that very accurate analysis of the differences between the experimental and theoretical results is rendered impossible by the nature of the transmitting site.

There is considerable evidence that the minor irregularities seen in Figs. 4, 6 and 8 are due to ground effects and are not to be found in the transmission from the special antenna construction used. On the other hand, it seems difficult to attribute the discrepancies between the experimental and theoretical results to the same cause, although, judging from the size of the variations noted in Fig. 10, they may well be sufficient to explain all the discrepancies. In all the cases investigated with the simple horizontal antenna, the maxima and minima were all shifted towards the vertical, and this shift increased with decrease of wavelength. This occurred irrespectively of the nature of such maxima and minima, i.e. whether they were due to the antenna alone or to the interference between the antenna and its image (as explained above).

Evidence has been given that the inverse-distance law of field strength holds for angles of elevation at least as small as ½°.

The results on the beam antenna show comparatively good agreement with theory, considering the very much greater experimental difficulties of this case. It is interesting to note that the shift of the maxima and minima in this case is away from the vertical, which is the reverse of the results obtained on the simple antenna.

The final conclusion to be drawn from this is that the theory of radiation distribution is substantially correct, but, in order to examine its accuracy in great detail, it would be necessary to carry out experiments over some irreproachable site, and this might be more difficult to find than would at first appear. The necessity for this would in any case be somewhat academic, for in practice it might be difficult to find such a site for the erection of a transmitting station, and if this were not obtained the ordinary calculations would never give a very high order of accuracy. It would have been desirable to carry out a few more tests in order to confirm the deductions reached, but the author was unable to continue the experiments.

In conclusion the author wishes to thank the many workers who have helped him in carrying out this investigation. In particular, his thanks are due to the Air Ministry, who generously supplied the aeroplane for carrying out the tests; also to Squadron-Leader A. L. Gregory, Messrs. F. S. Barton, N. F. S. Hecht, T. H. Gill and members of their staff at the Royal Aircraft Establishment, who gave him all the facilities and advice that could be desired during the progress of the work.

The author has also to thank the General Post Office and in particular Colonels A. G. Lee and A. S. Angwin, and Mr. De Wardt, for permitting and giving every assistance in carrying out the measurement on the beam antenna.

Finally, and principally, he wishes to thank Flight-Lieut. Ragg, R.A.F., whose skill and patience in piloting the aeroplane were largely responsible for the unexpected accuracy of the measurements, and also Messrs. J. S. McPetrie, B.Sc., and B. J. Byrne, of the National Physical Laboratory, without whose efficiency and patience the work would not have reached its comparatively satisfactory conclusion.

This work was carried out as part of the programme of the Radio Research Board and is published by permission of the Department of Scientific and Industrial Research.

APPENDIX 1.

Correction for End Effects.

The author has shown experimentally* that in a straight vertical antenna the first half-loop of current was some 8 per cent greater in area than the half-loop of a sine wave. At the foot of the antenna the effect may be expected to depend on the length and the proximity to the ground. If the length is l and the wavelength λ, the charge per unit length near the top when the current at the centre of a loop is I will be proportional to I, while that at the foot will be proportional to $I \cos (2\pi l/\lambda)$.

The end effect is produced by a sudden discontinuity in the charge. At the top, from a value proportional to I it suddenly changes to zero, while at the foot it changes from $I \cos (2\pi l/\lambda)$ to $-I \cos (2\pi l/\lambda)$. When the foot of the antenna is in close proximity to the ground it is to be expected, therefore, that the end effect at the foot will be $2 \cos (2\pi l/\lambda)$ as large as that at the top. To simplify calculations we may, with sufficient accuracy, represent the end effects by an area 8 per cent as great as a half-loop of current concentrated at the top end, together with one $16 \cos (2\pi l/\lambda)$ per cent concentrated at the foot. The radiation distribution from such concentrated areas may be very readily calculated, and superposed on the radiation distribution calculated from a simple sinusoidal distribution.

The case of a horizontal antenna as shown in Fig. 3 is similar to that of a vertical antenna turned through 90°.

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* See Reference (4).

The centre point C now corresponds to the foot of the antenna. It must be remembered, however, that these end effects have their images at A′, B′ and C′ in the ground.

APPENDIX 2.

MEASUREMENT OF THE PHASE RELATIONS IN ANTENNA ARRAYS.

For the purpose of measuring the phase difference between two antennæ a low-voltage cathode-ray oscillograph was used. E.M.F.'s from the two antennæ A and B (Fig. 16) whose phase difference is to be measured are induced in two coils C and D connected to the opposite plates of the oscillograph. An ellipse is obtained the size and ellipticity of which varies with the e.m.f.'s induced in C and D. These are adjusted until the axes of the ellipse bisect the line joining the plates, as shown. It can readily be shown then that, if γ is the phase angle and a and b are the axes of the ellipse,

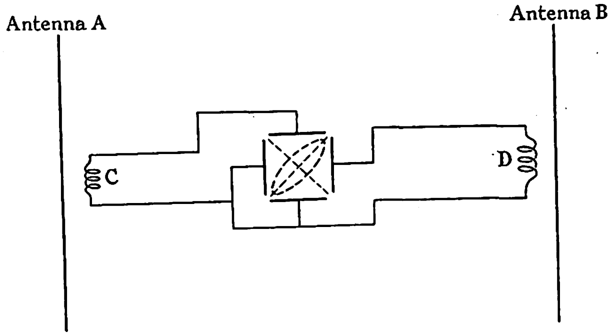

FIG. 16.

$$\tan \gamma = a/b.$$

It will be noted that an ambiguity exists, for

$$\gamma = \text{arc tan } (a/b) \quad \text{or} \quad \pi + \text{arc tan } (a/b).$$

An error may occur at very high frequencies, owing to the fact that the deflecting plates of the oscillograph are not at the same distance from the cathode. This error may be readily eliminated by interchanging the connections of the coils C and D to the oscillograph plates and taking a mean of the results.

The instrument used was placed in a metal box in which a small hole was cut for the purpose of observation. In front of the tube a number of wires were stretched at 45° to the deflecting plates. The distance between the wires was such as to show deflections in the ratio of 1: 2: 3: 4, etc., of the spot on the screen. The wires were faintly lighted by a means of a neon lamp working from the high-tension supply of the oscillograph. In this way the axes of the ellipse could be readily adjusted to the correct direction and their lengths read off. The leads and coils connected to the instrument were made as identical as possible.

Good consistency was obtained at 26 m, but considerable irregularities were found at 15 m. Such an instrument should be very valuable during the erection of a complicated beam system, but the author feels that the measurements made with it should be subjected to more thorough investigation. The phase relation between a pair of isolated, spaced antennæ can be obtained by taking measurements of the radiation distribution along the ground, and this method might be used as a check in measurements made with the cathode ray.

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C. R. ENGLUND and H. T. FRIIS: "Methods for the Measurement of Radio Field Strengths," *Transactions of the American I.E.E.*, 1927, vol. 46, p. 492.

(11) R. BALDUS and R. HASE: "Measurement of Energy Radiated by an Aeroplane Antenna," *Jahrbuch der drahtlosen Telegraphie und Telephonie*, 1920, vol. 15, p. 354.

(12) F. H. DRAKE: "An Aircraft Radio Receiver for Use with Rigid Antenna," *Proceedings of the Institute of Radio Engineers*, 1929, vol. 17, p. 306.

(13) D. K. MARTIN: "Laying a Foundation for Aircraft Communication," *Bell Laboratories Record*, 1929, vol. 7, p. 315.

THE PULLING INTO STEP OF A SYNCHRONOUS INDUCTION MOTOR.*

(AN APPLICATION OF THE M.I.T.† INTEGRAPH.)

By HAROLD E. EDGERTON and FREDERICK J. ZAK.

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SUMMARY.

The problem of the pulling into step of a synchronous motor has proved very difficult to solve, since it centres about a non-linear differential equation. One solution of the equation is not enough. All possible solutions with all combinations of the coefficients need to be made and classified into two groups, those that synchronize and those that do not. Until recently this has been practically impossible because of the amount of time required to make the solutions by graphical or point-by-point methods.

The development of the integraph by Dr. Bush and his associates at the Massachusetts Institute of Technology has made it possible to solve this problem by machine integration. This integraph, which performs two successive integrations simultaneously, is particularly adapted to the solution of first- and second-order total differential equations. The solutions described in this paper were obtained by using the integraph in this way.

This paper presents the complete solution of the problem for the case of a non-salient-pole synchronous motor. The results are put in a simple form convenient for practical use. By means of these results all of the necessary relationships between field current, induction-motor torque and slip, which determine whether or not a given load of a definite flywheel effect can be brought into synchronism, are determined. An example of a practical application is given.

LIST OF SYMBOLS USED IN THE PAPER.

P_j = synchronous torque in kW per electrical degree of acceleration per second per second (at synchronous speed).
P_d = synchronous torque in kW per electrical degree of slip per second.
P_m = maximum synchronous torque from synchronous motor characteristics, kW.
P_l = synchronous load torque, kW.
$\mathbf{1}$ = Heaviside's unit function.
θ = angle between terminal voltage and the e.m.f. generated in the armature by the action of the direct field current.
k = relative damping coefficient = $P_d/\sqrt{(P_m P_j)}$.
Wr^2 = total moment of inertia of motor and load, lb.-ft.^{2}.
I = Wr^2/g in lb.-ft.-sec. units.
f = frequency, cycles per sec.
p = number of poles.
s = slip as a fraction of unity.
V = terminal voltage per phase.
E = induced voltage per phase.
X = synchronous reactance, ohms per phase.
n = synchronous speed, r.p.m.

INTRODUCTION.

A synchronous induction motor is brought up to speed as a wound-rotor induction motor. External resistance in the rotor circuit gives large starting torque with moderate line currents. As the motor comes up to normal speed the rotor resistance is gradually reduced. At the end of the starting period the rotor is short-circuited and the motor runs steadily at a small slip, the load torque being balanced by the induction-motor torque.

Now, in order to synchronize, the rotor circuit is opened and immediately connected to an exciter. This switching takes place so quickly that the motor does not slow down appreciably. Of the several methods available for connecting the exciter in the rotor circuit, the best method short-circuits all the rotor phases, the exciter armature serving to short-circuit the alternating currents in the exciter phase or phases. Such a connection gives the maximum induction-motor torque characteristics. For this reason the motor tends to supply the load at the same slip.

There is now, however, a direct current superimposed on the low-frequency rotor current. The d.c. component in the rotor circuit rises to its final value practically instantaneously when compared with the slow mechanical oscillations. Synchronous-machine characteristics are produced by this direct current in the rotor circuit. The synchronous torque thus developed tends to pull the motor into synchronism.

It is now a matter of adjustment between the various components of torque. The motor may pull into synchronism and run as a synchronous motor. It may continue to supply the load as an induction motor but with speed and current pulsations. It may revolve several times and then pull into synchronism. The desired condition is to have the motor synchronize on the first swing through the steady-state operating angle.

The inertias of the motor and of the connected load are very important in this problem of pulling into step. Energy must be supplied to the rotating parts to get them from a speed lower than synchronism up to synchronous speed. The torque available to speed up the rotor depends upon the field current and upon the angular displacement between the terminal voltage and the e.m.f. generated in the armature by the action of the direct field current. The angular displacement varies with time in a manner determined by the differential equation.

The initial angle (determined by the point at which the exciter is connected) also influences the pulling into step. If the exciter is connected at an angle which initially causes generator action, the speed of the rotor decreases. This is because the energy of the rotating parts is initially the only available source of energy. As the rotor then swings into the region of motor characteristics the motor torque must supply more energy. This is due to the fact that the rotor must be speeded up from a greater slip than if the exciter were switched at a more favourable angle.

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The amount of field current in the rotor is the remaining important factor that influences the pulling into step. The larger the field current in practical machines the more favourable are the chances of synchronization, since more synchronizing torque is available. The synchronizing torque does not increase directly with field current, because of energy losses in the armature resistances. The practical limitation of the field current is determined by the allowable heating of the rotor.

There are two convenient ways of connecting the exciter to a 3-phase rotor. One is to connect each exciter terminal to a slip-ring and leave the other slip-ring open. The other is to connect two slip-rings to one terminal and the other ring to the other terminal of the exciter. The first method is not as satisfactory as the second from the standpoint of pulling into step, because the induction-motor characteristics are greatly influenced. Leaving one of the slip-rings open-circuited makes the rotor single-phase. Such a rotor gives a torque that is a sine-squared function of angular displacement as well as a linear function of slip. This would cause pulsations in the line currents, torque and speed. A motor with a single phase or an unbalanced rotor requires a larger slip to supply the same load. Pulling into synchronism is more difficult when one slip-ring is open-circuited. This problem is not considered in this paper.

All of the factors mentioned in the preceding paragraphs contribute to the problem of the pulling of a synchronous motor into step. Their effects have been difficult to find since the mathematical equations of the motor are not soluble by ordinary methods of analysis. Carr, Cotton, Dreyfus, Fraenckel, Böhm, Lindstrom and others have given approximate and step-by-step solutions which have been of great practical importance.[*]

The integraph, which was available to the authors, enabled them to make many transient solutions of the fundamental differential equation in a reasonable length of time. The integraph solutions, although subject to many small errors, are within engineering accuracy for this problem, i.e. within a few per cent.

STATEMENT OF THE PROBLEM.

The differential equation that characterizes the angular variations of a cylindrical-rotor synchronous machine, when in the transient conditions following the sudden introduction of a direct voltage into the rotor circuit, is generally accepted[*] to be of the following form:—

$$P_j\frac{d^2\theta}{dt^2} + P_d\frac{d\theta}{dt} + (P_m \sin\theta)\mathbf{1} = P_l \quad . \quad . \quad (1)$$

In deriving this equation it is assumed that the currents and potentials are sinusoidal, that the applied potential is constant and that the stator resistance and rotor leakage inductance are negligibly small. The first term represents the torque due to the acceleration of the moving parts of the rotor and connected apparatus. The second term represents the torque that results from the induction-motor effect. This term is used only for the portion of the slip-torque characteristic near synchronous speed. The third term represents the torque due to the synchronizing action of the motor after the field has been excited. Heaviside's unit function,[†] $\mathbf{1}$, which is zero before and unity after time equals zero, gives the boundary condition to the synchronizing term. The synchronizing torque is zero before and a sine function of angle after the exciter is connected.

Initially, before the field is applied, the load is supplied by the induction-motor torque. This gives the initial boundary conditions of the equation. The torque due to the slip, $d\theta/dt$, is just sufficient to supply the load torque. The acceleration, $d^2\theta/dt^2$, is equal to zero.

The coefficients and factors which influence the solution of the equation are listed and discussed below. The coefficients have been expressed in terms of power or synchronous torque.

P_j = coefficient which, when multiplied by the acceleration, gives the component of power due to inertia (at synchronous speed).

P_d = coefficient which, when multiplied by the slip, gives the component of power due to the induction-motor effect.

P_m = maximum power due to synchronizing action of the field current.

P_l = amount of shaft load (considered constant in the solutions).

θ_0 = initial angle between the applied stator potential and the e.m.f. generated in the stator by the action of the direct field current that exists when the exciter is connected.

The first three, which depend upon the motor that is under consideration, together with the inertia of its connected load, may be combined into one factor which has been termed the "relative damping coefficient" and has been given the symbol k. Also the load, P_l, is more conveniently expressed as a fraction of the maximum power, P_m, that is available. Both of these changes are accomplished by changing the variable, t, of equation (1) by the following relationship.

Let $$t = t'\sqrt{\frac{P_j}{P_m}}$$

where t' is a new dimensionless variable.

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[*] L. H. A. CARR: *Journal I.E.E.*, 1922, vol. 60, p. 165.
—— *Ibid.*, 1923, vol. 61, p. 692.
H. COTTON: *Ibid.*, 1925, vol. 63, p. 211.
—— *World Power*, 1924, vol. 1, p. 329.
—— *Ibid.*, 1924, vol. 2, p. 45.
L. DREYFUS: *Elektrotechnik Maschinenbau*, 1922, vol. 40, p. 457.
O. BÖHM: *Elektrotechnische Zeitschrift*, 1922, vol. 43, p. 426.
A. FRAENCKEL: *Elektrotechnik Maschinenbau*, 1923, vol. 41, pp. 377 and 393.
—— *Brown-Boveri Review*, 1922, vol. 9, p. 243.
A. LINDSTROM: *Electrician*, 1923, vol. 91, pp. 4 and 54.

[*] Various authors give modifications of this equation, which take into account the effect of salient poles, unsymmetrical rotor circuits, etc. (see, for instance, Dreyfus or Cotton, *loc. cit.*). These more involved expressions can be solved on the integraph, but the number of factors is increased so that a simple, general relationship, such as has been obtained in this paper, is improbable.

[†] O. HEAVISIDE: "Electromagnetic Theory," vol. 2, p. 36 (*The Electrician* Printing and Publishing Co., Ltd., London).
V. BUSH: "Operational Circuit Analysis," p. 41 (John Wiley and Sons, Inc., New York, 1929).

Introducing this into equation (1) gives, after dividing both sides by P_m,

$$\frac{d^2\theta}{(dt')^2} + k\frac{d\theta}{dt'} + (\sin\theta)1 = \frac{P_l}{P_m} \quad . \quad . \quad (2)$$

where

$$k = \frac{P_d}{\sqrt{(P_j P_m)}} \quad . \quad . \quad . \quad . \quad . \quad (2a)$$

The relative damping coefficient, k, is a numeric, but its numerical value depends upon the unit used for measuring angles. In the solutions that follow, electrical degrees are used as the units in which angles are measured. With electrical radians the value of k would differ by the square root of $(180/\pi)$.

The factors influencing the performance of the machine are now reduced to three:—

(1) k = relative damping coefficient.

(2) P_l/P_m = ratio of the shaft load to the maximum for slowly applied load.

(3) θ_0 = angle when the exciter is connected.

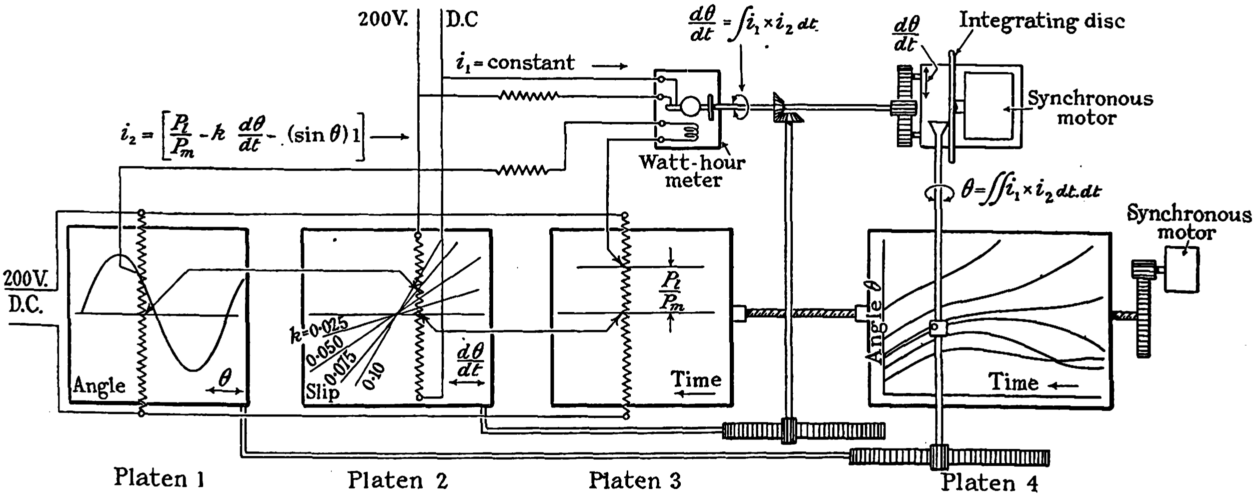

FIG. 1.—Schematic diagram of the M.I.T. integraph illustrating methods employed in solving the non-linear differential equation.

A solution of equation (2) for the angle against the dimensionless variable, t', shows how the rotor swings against time when the field is suddenly connected. The angle will either oscillate about its final steady-state value or it will continue to increase. The first type of solution indicates that the motor will synchronize, while the second shows that it will fail to pull into step.

As shown by the authors of the references that have been given, a mathematical solution of equation (2) by ordinary means is nearly an impossible task. For practical purposes many solutions are needed with different relative damping coefficients, switching angles and load ratios. Classification of these solutions would make it possible to predetermine the "pulling into step" characteristics of synchronous motors. Reduction of the solutions to the form of curves or simple equations would enable any problem connected with the pulling into step of a synchronous motor to be readily solved. For example, the minimum field current necessary to ensure that a motor with a large inertia and a certain load will always pull into step could be found.

The method of obtaining the solutions, and their practical application, are described in the succeeding sections of this paper.

INTEGRAPH SOLUTIONS.

The integraph,* produced after several years of research by Dr. Bush and others at the Massachusetts Institute of Technology, has given a method of solving the differential equation that is the basis of the pulling-into-step problem. A graphical solution of the equation is obtained as a plot of angular variation against time. From 3 to 5 minutes are required to make one solution. About 1 minute is needed between curves to "crank in the boundary conditions" and get the integraph ready for the next solution.

A diagram of the integraph is shown in Fig. 1. It consists of several platens that are free to slide. Across these are stationary potentiometers with sliding contacts that may be varied by a hand dial. Pointers indicating the positions of the contacts rest on the platens. The voltages from the potentiometers are connected together and, by the proper combination of the movements, are made to represent the values of the terms of the differential equation. A complete description of the construction and operation of the apparatus is given in the references.

Equation (2),† for solution on the integraph, is put into the integral form by transposing and integrating twice, giving

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* V. BUSH, F. D. GAGE and H. R. STEWART: "A Continuous Integraph," *Journal of the Franklin Institute*, 1927, vol. 203, p. 63.

V. BUSH and H. L. HAZEN: "Integraph Solution of Differential Equations," *Journal of the Franklin Institute*, 1927, vol, 204, p. 575.

Prof. JAMES THOMSON and Lord KELVIN (then Prof. Sir William Thomson) in the *Proceedings of the Royal Society*, A (1876, vol. 24, p. 262) describe an integrating machine. On page 269 Lord Kelvin proposed "Mechanical Integration of Linear Differential Equations of the Second Order with Variable Coefficients." Present-day electrical and mechanical devices, which were not at Lord Kelvin's disposal, have made possible the construction of a practical integraph.

† L. TEPLOW solved an equation of this form on the integraph for the case of a periodically impressed torque (see *General Electric Review*, 1928, vol. 31, p. 356). Also see W. V. LYON and H. E. EDGERTON: "Transient Torque-Angle Characteristics of Synchronous Machines," *Transactions of the American I.E.E.*, 1930, vol. 49, p. 686. The latter paper dealt with the sudden-load case.

$$\theta = \int_0^{t'}\int_0^{t'}\left[\frac{P_l}{P_m} - k\frac{d\theta}{dt'} - (\sin\theta)1\right]dt'\,dt' \quad . \quad (3)$$

The integraph performs the operations indicated by the expression on the right, plotting the angular displacement as a function of t'.

The way in which this is done by the integraph is indicated diagrammatically in Fig. 1. The potentiometers over platens 1, 2 and 3 are connected in series. The voltage from the potentiometer above platen 1 is proportional to sin θ at all times because the platen moves in the same manner as the pencil recording the angular displacement on the resultant platen 4, due to the back-coupling. The person operating the integraph follows the sine curve with the pointer on the potentiometer slider. Platen 2 moves backwards and forwards under the potentiometer, its displacement being proportional to the slip, $d\theta/dt$. The value of k determines the slope of the line which the potentiometer pointer is made to follow. The voltage from this potentiometer is then proportional to the term ($k\,.\,d\theta/dt$) in the equation. The voltage from the potentiometer over platen 3 is held at a constant value proportional to the load ratio.

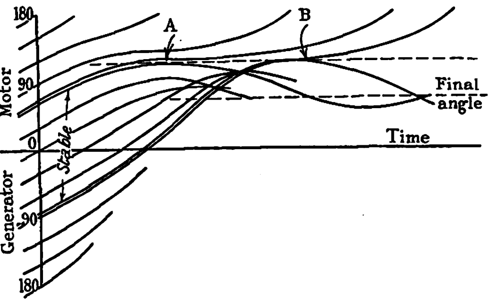

FIG. 2.—Transient angle/time curves following the connection of an exciter to a synchronous induction motor.

One of the initial conditions is that the load ratio term is equal to the slip term. The input shaft of the second integrating stage, the displacement of which is proportional to $d\theta/dt$, is initially set so that $k\,.\,d\theta/dt$ just equals the load ratio P_l/P_m, thus satisfying this initial condition. Platen 1 is set so that the potentiometer is on the initial switching angle. The pencil on platen 4 is set at θ_0 also.

When the integraph is started the pencil on platen 4 draws a line that has an initial slope which, multiplied by the relative damping coefficient, k, gives the load ratio, P_l/P_m. As the solution proceeds the influence of the sine term begins to be noticed. Its effect is to make the slope either smaller or greater as the initial angle is in the motor or generator region. The " back-coupling " moves the platens so that the angle and the change of angle with respect to time and slip are the same as those on platen 4 at all times during the solution.

The procedure used in making the solutions was to hold the relative damping coefficient, k, and the load ratio, P_l/P_m, constant, and then investigate the effects of different switching angles. The resultant solutions were of the general form, as shown by Fig. 2. For each angle at which the exciter may be connected, they show the way in which the angle subsequently varies. The initial slopes of all the curves are the same. As increasingly greater switching angles in the motor region are used, the following maximum angles reached approach a critical value, as shown in Fig. 2 at A. If, in any solution, the angle at any time reaches this critical value, it will continue to increase. Physically this means that the motor fails to synchronize during the first swing forward instead of returning to oscillate about the final steady-state angle. The critical angle, shown at A, is that which gives an unstable steady-state solution to the equation. As increasingly greater switching angles in the generator region are used an identical condition exists. The angle continues to increase instead of swinging back to the operating angle for steady-state conditions. The critical angle is the same.

From all the curves of the type shown in Fig. 2 another plot is constructed as shown in Fig. 3. The solid points are those that indicate, for the respective switching angles, that the rotor did not continue to swing forward, but that it swung back as shown by the curves (in Fig. 2) that are below the singular angle indicated by A and B. The open points are those which show that the rotor continued to swing forward. Other families of solutions similar to Fig. 2, except for different ratios of P_l/P_m, give other open and solid points in Fig. 3. The lines that are drawn are the approximate boundary of the different areas containing the points. The unstable range of angle becomes smaller as the load ratio is reduced, and finally becomes a point where the motor pulls into step for all switching angles. The angle at the point on Fig. 3 marked C is the most unfavourable angle of switching, and this point is the one of interest in this problem.

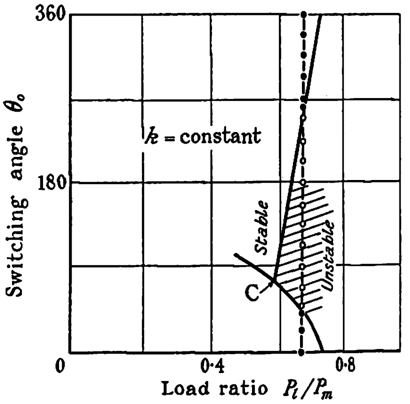

FIG. 3.—Chart for classifying switching angles and corresponding load ratios into stable and unstable regions.

The point C on Fig. 3 is now entered on the final chart, Fig. 4, together with corresponding points from other plots similar to Fig. 3, but with other relative damping coefficients. Fig. 4 is a plot of these critical load ratios against their corresponding relative damping coefficients. The determination of a single point on Fig. 4 requires many families of solutions such as Fig. 2 and then the results from these must be compiled in a curve such as Fig. 3, in order to find the point C where the load is small enough always to synchronize. Actually, however, the procedure is not as lengthy as this. After a little experience with the integraph it is quite easy to determine the important regions, A and B in Fig. 2, rather quickly, possibly from 6 to 10 solutions being sufficient to locate the boundary angle between the stable and unstable synchronizing characteristics. Four or five different values of load ratio are sufficient to determine the critical load at the point C in Fig. 3.

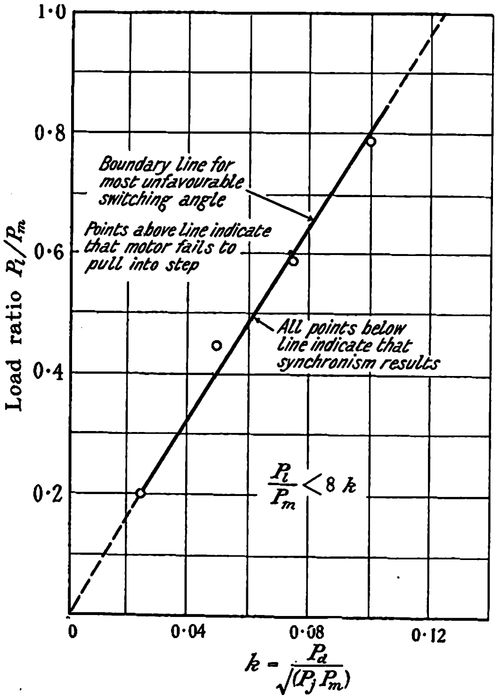

FIG. 4.—Chart for plotting the load ratio and corresponding relative damping factor for worst switching angle.

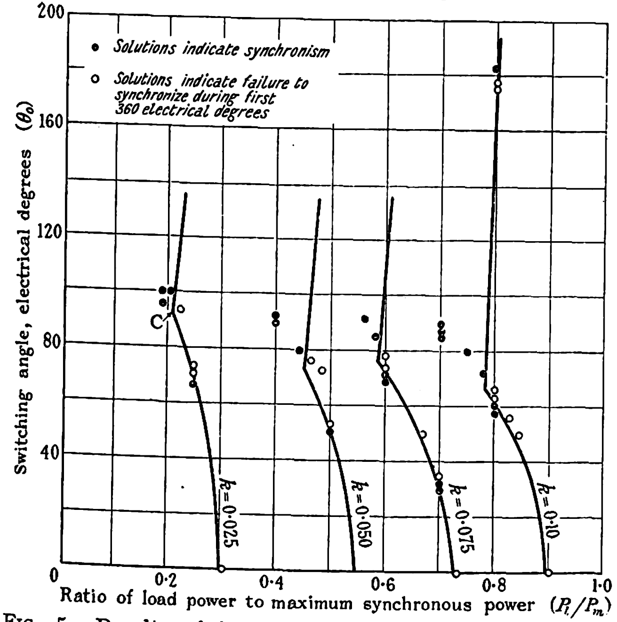

FIG. 5.—Results of integraph solutions for four relative damping coefficients.

The four points in Fig. 4 are those that were obtained by the method outlined. Fig. 5 shows the plot similar to Fig. 3, which contains the data from the integraph solutions. Only sufficient of the solutions are plotted to show how the curves bound the stable and unstable regions. If the lower part of the curve be extended upward beyond point C, it forms the boundary between two sorts of stable solutions. The region below this extension represents solutions in which synchronism is reached on the first swing, while those above correspond to synchronization after a swing of approximately 360 electrical degrees. The points in the region of switching angles from zero to 90° were the easiest to solve on the integraph. Within the limits of error of the integraph the points in Fig. 4 indicate that a straight-line relationship exists between the relative damping coefficient and the load ratio.

The following relationship then represents the " pulling into step " characteristics of synchronous motors:—

$$\frac{P_l}{P_m} < \frac{8P_d}{\sqrt{(P_m P_j)}} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The above expression, if written with an equality sign, is the equation of the straight line of Fig. 4. In words, the inequality states that the load ratio must be less than 8·0 times the indicated function of the three coefficients in order that a motor shall pull into step on the first swing. *Thus the original differential equation* (1) *represents a motor which will synchronize for all switching angles if its coefficients satisfy the condition above, i.e. expression* (4).

A more convenient form of (4) is secured by substituting in it the factors that determine the coefficients. In terms of synchronous kilowatts, electrical degrees and seconds the coefficients are:—

$$P_j = 18 \cdot 6\frac{(Wr^2)f}{p^2}10^{-6} \text{ kW/elec. deg./sec.}^2 \quad . \quad (5)$$

where Wr^2 = inertia, in lb.-ft.^{2},
f = frequency, in cycles per sec., and
p = number of poles.

$$P_d = \frac{P_l}{360\,fs} \text{ kW/elec. deg./sec.} \quad . \quad . \quad . \quad (6)$$

where P_l and s are taken from the slip-torque curve,
P_l = load, in synchronous kilowatts,
s = corresponding slip as a fraction of unity, and
f = frequency.

$$P_m = \frac{3VE}{1\,000X} \text{ kW}$$

where V = applied stator potential per phase,
E = induced stator e.m.f. per phase due to field current, and
X = synchronous reactance per phase (for a 3-phase motor).

Using the values for P_j and P_d and solving (4) for P_m gives the minimum synchronizing power that will just pull a motor into step when switching conditions are the worst.

$$P_m > 0 \cdot 0374\frac{s^2 f^3 (Wr^2)}{p^2}$$

or, since $\frac{f}{p} = \frac{n}{120}$ (n = speed in r.p.m.),

$$P_m > 2 \cdot 6\, s^2 f n^2 (Wr^2) \times 10^{-6} \text{ kW} \quad . \quad . \quad (7)$$

Knowing the characteristics of a synchronous motor, the field current that is necessary to enable the motor always to pull into synchronism may be determined.

Solving for the slip also gives a convenient form of the expression

$$s < \frac{620}{n} \sqrt{\left[\frac{P_m}{f(Wr^2)}\right]} \quad . \quad . \quad . \quad . \quad (8)$$

This gives the maximum value of slip at which the motor will always pull into step. If the induction-motor torque is not sufficient to bring the motor to the speed corresponding to this slip, the motor will fail to synchronize when the field is applied.

The previous expressions giving the conditions necessary for a synchronous motor always to pull into step are pessimistic, because they are taken for the most unfavourable switching conditions. The curves of Fig. 5 show that approximately 25 per cent more favourable synchronizing conditions result if the switching angles chance to be in the region of small angular displacement.

It must be remembered that the above solution is made on the assumption that a linear speed-torque relationship holds for the induction-motor action. This is not justified if the slip exceeds 2 or 3 per cent in most motors. The transient slip variation after the exciter is connected may easily be double the initial slip. Therefore the limiting slip equation (8) should not be taken as exact for values of slip exceeding 1·5 per cent. A margin should be allowed for cases where the initial slip is larger than about 1·5 per cent, to compensate for the change of slope of the induction-motor speed-torque curve.

NUMERICAL EXAMPLE.

This example uses the same data as those given by Carr.* These data were used also by Cotton † for two step-by-step solutions. The following calculation agrees with the two solutions given by Cotton, and shows the utility of equations (4), (7) and (8).

$\mathbf{T}_m = 2\,000$ lb.-ft.
$\mathbf{T}_l/\mathbf{T}_m = 0 \cdot 5$
$\mathbf{I} = 200$ lb.-ft.-sec. units
$(Wr^2) = \mathbf{I} \times 32 \cdot 2$ lb.-ft.^{2}
$p = 10$ poles
$s = 0 \cdot 025$ for 1 000 lb.-ft. (Cotton)
$f = 50$ cycles per sec.
$n = 600$ r.p.m.

More than sufficient data are given above. In case it is desired to find the maximum synchronizing torque in order to ensure synchronism for all conditions of switching, equation (7) gives

$$P_m > 2 \cdot 6\, s^2 f n^2 (Wr^2) \times 10^{-6} \quad . \quad . \quad . \quad (7)$$
$$> 2 \cdot 6\, (0 \cdot 025)^2\, 50\, (600)^2\, (200 \times 32 \cdot 2) \times 10^{-6}$$
$$> 188 \text{ kW}$$

so $$\mathbf{T}_m > \frac{188}{0 \cdot 746} \cdot \frac{33\,000}{2\pi \times 600} = 2\,210 \text{ lb.-ft.}$$

Thus if the field current is increased so that the maximum synchronizing torque is 2 210 lb.-ft. the motor will always synchronize. Cotton, in two step-by-step solutions, shows that with a maximum synchronizing torque of 2 000 lb.-ft. the motor will and will not synchronize if the switching angle is respectively 0 and 180 degrees. The relative damping coefficient and the load ratio can be calculated for the case used by Cotton.

$$k = \frac{P_d}{\sqrt{(P_m P_j)}} = \frac{0 \cdot 189}{\sqrt{(170 \times 0 \cdot 0598)}} = 0 \cdot 0592$$

[from equation (2a)]

since $$P_m = \frac{\mathbf{T}_m 2\pi n \times 0 \cdot 746}{33\,000} = 170 \text{ kW}$$

$$P_d = \frac{P_m(\mathbf{T}_l/\mathbf{T}_m)}{360\, fs} = \frac{170 \times 0 \cdot 5}{360 \times 50 \times 0 \cdot 025}$$
$$= 0 \cdot 189 \text{ kW/deg./sec.}$$ [from equation (6)]

$$P_j = 18 \cdot 6 \frac{(Wr^2) f}{p^2} \times 10^{-6} = \frac{18 \cdot 6 (200 \times 32 \cdot 2) 50}{10^2} \times 10^{-6}$$
$$= 0 \cdot 0598 \text{ kW/deg./sec.}^2$$ [from equation (5)]

With this relative damping coefficient of 0·0592 and the load ratio $P_l/P_m = 0 \cdot 5$, Fig. 5 may be used to show that the two points calculated by Cotton are approximately in the stable and unstable regions respectively, within the limits of interpolation and the errors of the integraph and the step-by-step calculation. This point, located on Fig. 4, is just above the boundary line in the unstable region.

In case the heating of the field definitely limits $\mathbf{T}_m$ to 2 000 lb.-ft. and the motor must always synchronize, then the load ($\mathbf{T}_l$) must be reduced until the initial slip satisfies expression (8).

$$s < \frac{620}{n} \sqrt{\left[\frac{P_m}{f(Wr^2)}\right]} = \frac{620}{600} \sqrt{\left[\frac{170}{50\,(200 \times 32 \cdot 2)}\right]}$$
$$= 0 \cdot 0238 \text{ or } 2 \cdot 38 \text{ per cent}$$

The corresponding load for this slip is 1 000 (2·38/2·50) = 950 lb.-ft. The motor will always synchronize if the load on the shaft is less than 950 lb.-ft. The two step-by-step solutions given by Cotton show that, with a load of 1 000 lb.-ft., synchronization will not result when the exciter is switched at 180 degrees.

ACKNOWLEDGMENT.

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* *Journal I.E.E.*, 1923, vol. 61, p. 693.

† *World Power*, 1924, vol. 2, p. 45.

THE RADIANT EFFICIENCY AND HEAT DISTRIBUTION OF ELECTRIC FIRES.*

By Professor S. PARKER SMITH, D.Sc., Member.

(*Paper first received 25th October, 1929, and in final form 19th February, 1930.*)

SUMMARY.

The paper details an attempt to measure the amount and distribution of the heat radiated from electric fires, employing the "Leeds" method already largely used for gas fires. A number of types of fire were tested, the radiant efficiency as measured lying generally within the limits of 55–70 per cent, with an average of about 60 per cent. The results are fairly reliable for comparative purposes, and the error in the radiant efficiency determination is probably well within 5 per cent.

INTRODUCTION.

As a converter of electric energy into heat, the electric fire may be said to have an efficiency of 100 per cent, but for many purposes it is desirable to know what part of this heat appears as radiant heat and in what manner it is distributed. This information is particularly desirable in view of the great variety of fires now on the market and the new designs developed year by year. Although it would be impracticable to test all available fires it was found that by selecting a suitable number of types a fair idea of the radiation from any given fire could be obtained. For the purposes of the test, fires were selected mainly from two large British manufacturers.

In the following tests, measurements of the radiant efficiency were taken by a modification of the "Leeds" method, which has been extensively used for measuring the radiant efficiency of gas and coal fires.

Owing to the approximate nature of some of the assumptions on which the method is based, a high degree of accuracy is not possible, but the results obtained are a sufficient guide for practical purposes.

METHOD OF MEASURING RADIATION.

The "Leeds" method for determining radiant efficiency was evolved in 1907 by a joint committee appointed by the University of Leeds and the Institution of Gas Engineers for the testing of gas fires. It has the advantage of giving both the radiant efficiency and the heat distribution. The two main assumptions on which the method rests are that all the radiant heat from the fire passes through a hemisphere, Fig. 1, which has its centre at the fire centre, and that the fire may be considered as a point source. Though neither of these assumptions is strictly correct, the errors introduced are not serious for commercial purposes. An idea of the amount of heat radiated from the back of the fire, i.e. away from the hemisphere, was obtained from measurements. These, together with other confirmatory tests, justify the neglect of this source of loss.

The underlying idea of the "Leeds" method is to determine the relation between the amount of radiation R passing through the whole area of the hemisphere and the amount r passing through the central equatorial area. This relation is called the distribution factor D, where $D = R/r$. By measuring the radiant heat h passing through the central equatorial area, the total radiant heat thrown off from the fire is then $H = h \times D$. The percentage of the energy input to the fire which this represents gives the radiant efficiency of the fire.

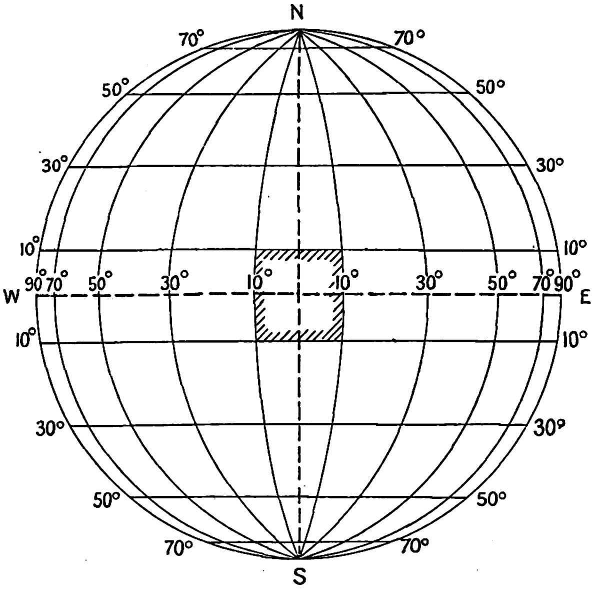

FIG. 1.—Division of hemisphere into 81 areas.

MEASUREMENT OF HEAT DISTRIBUTION.

In order to obtain the heat distribution, an imaginary hemisphere was chosen such that, when divided up by lines of latitude and longitude 20° apart, the centre equatorial area was 1 sq. ft. For this, the semi-circumference was 108 in., giving a radius of 34·4 in. The 9 lines of latitude and of longitude 20° apart divide the hemisphere into 81 areas. A thermopile in conjunction with a millivoltmeter was used to measure the heat radiated in each area. It was generally assumed that the thermopile readings taken at the centre of each area represented the mean radiant energy over that area. Particular care, however, was taken to ensure that a good approximation to the mean was obtained for the central equatorial area, a number of additional readings being taken where necessary. Since the 81 thermopile positions do not refer to the same surface area, the readings were weighted according to the area concerned, the correction factor being the cosine of the angle to the horizontal subtended by the thermopile.

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The use of a thermopile may introduce certain sources of error. Provided that the test conditions are such that the errors affect all readings alike, the results will not be vitiated, since the thermopile readings are used solely for comparison in determining the distribution factor, etc. The chief errors may be due to:—

(*a*) *Selective Absorption of Glass Screen.*—The waveband of radiation received by the thermopile is filtered by the glass screen used for protection against air currents, so that the scale of wavelengths received by the hot junctions will differ in quality from that impinging on the screen. The effect of this would, for comparative purposes, be of no account if the radiating bodies were of the same temperature. In general, the range of temperatures of the fires tested lay within 750–900° C., as measured by an optical pyrometer. An investigation carried out on a single fire over this range showed that the distribution factor was within 2½ per cent of a constant mean value throughout. Hence the variation of distribution factor due to selective absorption is not likely to be greater than that due to other factors.

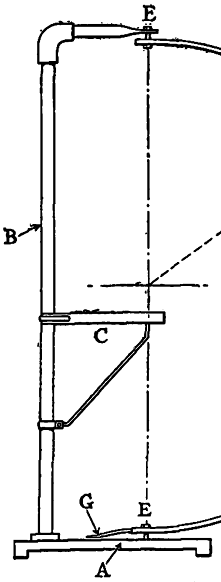

FIG. 2.—Apparatus used for taking thermopile readings.

(*b*) *Assumption of Proportionality between Radiated Energy and Thermopile Readings.*—Tests showed that over the experimental range the cold junctions maintained an even temperature; and it can be considered that practically all the radiation passing through the screen was absorbed by the black junctions for the small temperature range in question. It can therefore be assumed that the thermopile reading is proportional to the radiated energy.

After the cosine correction for variation of area with latitude had been applied, the sum of the 81 readings gave a figure H proportional to R, the total radiation passing through the hemisphere. In the same way the central reading h was proportional to r, so that the distribution factor D was found by dividing the corrected sum by the central reading. A radiometer of the Richmond type described below was used to determine the absolute value of the central thermopile reading, and this, multiplied by the distribution factor and expressed as a percentage of the energy input to the fire, gave the radiant efficiency.

DESCRIPTION OF TEST APPARATUS.

A sketch of the apparatus used for obtaining the thermopile readings is shown in Fig. 2. It consisted of a heavy cast-iron base A carrying a vertical post B to which was fitted an adjustable table C. A semicircular mild-steel hoop D was pivoted at EE so that it could move about a vertical axis. This hoop was marked off at 20° intervals. A sliding carrier F into which the thermopile fitted was attached to the hoop, the radius of the hoop being such that the elements of the thermopile were at a distance of 34·4 in. from the centre. The pointer G moved over a brass plate fixed to the base, the plate being marked off by radial lines 20° apart. Longitudinal positions of the hoop and the 9 lateral positions of the thermopile made it possible for the 81 required readings to be taken.

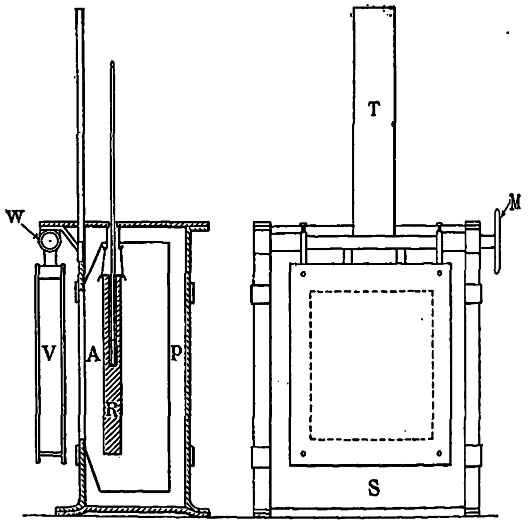

FIG. 3.—Radiometer.

The thermopile used was of the large-surface type constructed on a system devised by Dr. Moll. It consisted of 80 elements arranged in three rows in a circle of 2 in. diameter. The thermopile was mounted in a heavy brass cylinder closed on one side by an ebonite plate to which the two terminals were attached, and on the other side by a heavy brass lid into which a glass plate was fixed and which also carried a conical reflector. A polished brass disc, insulated from the body of the thermopile, was mounted at the back of the conical reflector to prevent the body of the thermopile from absorbing radiant heat. High sensitivity and rapidity of action were the features of the thermopile.

The millivoltmeter used in conjunction with the above instrument had an evenly graduated scale of 0–120 millivolts. Its resistance was 500 ohms.

A sketch of the Richmond radiometer used is given in Fig. 3. It consisted of a rectangular block of brass R, 6¾ in. × 6¾ in. × ¾ in., highly polished and having one side painted with a dull black paint. This absorbing block was suspended in an enclosure formed by a double metal case P. The air in the enclosure was maintained at a constant temperature by the circulation of a steady stream of water through the case. A polished sheet of brass S, having an opening A, 6 in. × 6 in., cut in it, was clamped to the front of the case. This opening was protected by a screen V formed by two sheets of polished brass spaced 1 in. apart, and pivoted at W so that by turning the handwheel M the screen could be removed and the blackened face of the block exposed to the source of radiation. A small hole drilled in the centre of the block along a vertical axis contained the thermometer bulb. The hole was filled with mercury to ensure good heat contact. The projecting stem of the thermometer was shielded by the vertical strip of polished brass T. The back and sides of the case were enamelled white. The thermometer was graduated in tenths of degrees C. from 10° C. to 20° C., and readings were taken by aid of a telescope.

Some difficulty was experienced in obtaining a suitable paint for the radiometer block, i.e. one which would give a dead black surface with no reflection. The paint finally employed was made from finely powdered drop-black bound with gold size. This was reduced to a thin paste by means of amyl acetate and applied to the brass block with a brush. After consulting various authorities and taking into account various sources of error, it was decided to assume an emissivity factor of unity for the blackened surface.

To avoid fluctuations of the voltage, the supply to the fires was taken from a small direct-current motor-generator set, a field rheostat being used to maintain the voltage at the required value. The input to the fire was measured on a combination voltmeter and ammeter set having substandard accuracy.

A draught-proof cubicle, approximately 9 ft. × 9 ft. in plan, was erected and all tests were carried out within this cubicle.

MODE OF CONDUCTING TESTS.

The tests were carried out in the following manner:—

The fire under test was placed on the platform, which was adjusted until the centre of the fire coincided with that of the hoop. The radiometer, with the water circulating through it, was placed in position in front of the fire, the screen being down. The distance of the radiometer from the fire was such that the centre of the brass block was 34·4 in. from the centre front of the fire. The supply was switched on and a period of time varying from ¾ hour to 1¼ hours, according to the type of fire, was allowed to elapse to ensure that conditions were steady before the readings were started.

Half-minute readings of the radiometer thermometer were then observed over a period of 6 minutes, the screen still being down. The screen was then lifted and the half-minute readings were continued for another 6 minutes. The screen was again lowered and the readings continued for a further 6 minutes.

The radiometer was then removed and the 81 thermopile readings were taken, care being taken that the thermopile was not kept too long in the regions of high intensity. At the end of the test the radiometer readings were repeated to confirm constancy of conditions.

TEMPERATURE-RISE OF RADIOMETER BLOCK.

The calculations are as follows:—

The radiometer thermometer readings are plotted to a base of time, Fig. 4. The gradient of the part AB gives the temperature-change θ_1 in deg. C. per minute before the screen is raised, while the gradient of the part DE gives the temperature-change θ_2 in deg. C. per minute after the screen is lowered. At the instant T_1 the screen is raised. The mean apparent temperature of the block at the instant T_2 when the screen is lowered is obtained by producing ED to cut in C the ordinate of time at T_2, thus giving the temperature t_2. If the temperature of the block when the screen is raised be t_1, then the apparent temperature-rise is $(t_2 - t_1)$ deg. C. In connection with this, two corrections must be considered, viz. the stem correction and the cooling correction.

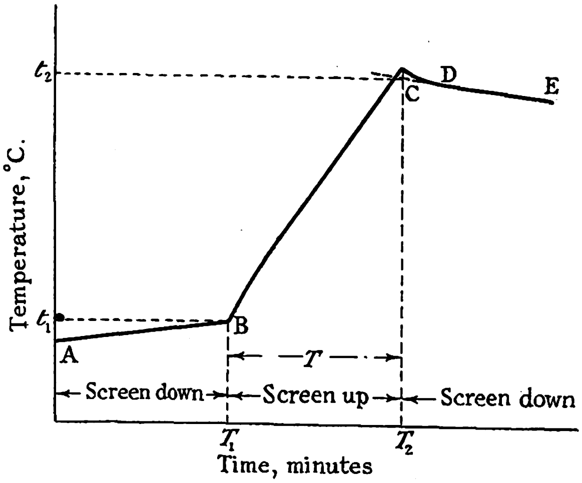

FIG. 4.—Typical temperature/time curve of radiometer block.

The *stem* correction was found in all cases to be negligible.

The *cooling* correction is applied to the apparent temperature-rise to take into account the temperature-rise of the block due to sources other than absorption by the blackened surface. If θ_1 is the temperature-rise in deg. C. per min. due to outside sources before the screen is raised, and θ_2 is the temperature-rise in deg. C. per min. after the screen is lowered, then the average temperature-rise due to such sources during the time the screen is opened is $-\frac{1}{2}(\theta_1 + \theta_2)$ deg. C. per min. The cooling correction is therefore $-\frac{1}{2}(\theta_1 + \theta_2)T$ deg. C., where $T = (T_2 - T_1)$ is the number of minutes the block is exposed.

Thus the final *corrected* temperature-rise θ_c is given by

$$\theta_c = (t_2 - t_1) - \tfrac{1}{2}(\theta_1 + \theta_2)T \text{ deg. C.}$$

HEAT ABSORBED BY THE BLOCK.

The heat passing into the block is given by $h = Ms\theta_c$ calories, where M = mass of block in grammes, including the mercury and the glass of the thermometer reduced to equivalent weight of brass, and s = specific heat of brass. The composition of the brass being known, its specific heat was found by interpolation of the values given by Griffiths and Griffiths in the "Dictionary of Applied Physics," vol. 1, p. 37. From these it was found that, between 10° C. and 20° C., $s = 0{\cdot}0918$.

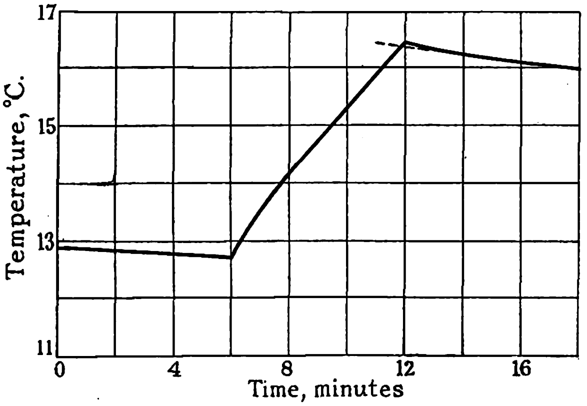

FIG. 5.—Temperature/time curve for example in Table 1.

The mass of the block was found to be 4 549·6 grammes. The equivalent weight of mercury and of glass was taken as 0·46, and the volume of mercury to fill the hole was 3·59 cm^3. Hence, equivalent weight of glass and mercury = $3{\cdot}59 \times 0{\cdot}46/0{\cdot}0918 = 18{\cdot}0$ grammes (of brass).

Thus $M = 4\,549{\cdot}6 + 18{\cdot}0 = 4567{\cdot}6$ grammes.

Since the exposed area of the radiometer block was $\frac{1}{4}$ sq. ft., the heat per square foot passing through the centre area is obtained by multiplying the heat absorbed by the block by 4. The absorption factor for the black paint used was taken as unity, as previously explained.

Thus
$$h = 4\,Ms\theta_c \text{ calories per sq. ft.}$$
$$= 16{\cdot}8\,Ms\theta_c \text{ joules per sq. ft.}$$

CALCULATION OF RADIANT EFFICIENCY.

The total radiant heat passing through the hemisphere in time $T = (T_2 - T_1)$ during which the block is exposed is

$$H = hD = 16{\cdot}8\,Ms\theta_c D \text{ joules,}$$

and the input during this period = $IVT \times 60$ joules, where I is the current and V the voltage.

Hence

$$\text{Radiant efficiency} = \frac{16{\cdot}8\,Ms\theta_c D}{60\,IVT} \times 100 \text{ per cent}$$
$$= K\frac{\theta_c D}{IVT} \times 100 \text{ per cent}$$

where K is a constant for the radiometer and is

$$K = \frac{16{\cdot}8\,Ms}{60} = \frac{16{\cdot}8 \times 4\,567{\cdot}6 \times 0{\cdot}0918}{60} = 117{\cdot}3$$

Thus

$$\text{Radiant efficiency} = 117{\cdot}3\,\frac{\theta_c D}{IVT} \times 100 \text{ per cent.}$$

ILLUSTRATIVE EXAMPLE.

To illustrate the application of the method, the results of the 3-unit fire "B" are worked out in Table 1.

Input:—Voltage = 250 volts, current = 12·0 amperes.

TABLE 1. *Illustrative Example.*

	Thermopile readings									Total	Cosine correction for variation of area	Corrected total
	To "West"					To "East"						
	80°	60°	40°	20°	0°	20°	40°	60°	80°			
80° North	5·0	7·0	8·6	10·6	11·9	11·5	10·0	8·0	6·0	78·6	0·174	13·7
60° North	9·8	22·0	36·3	44·0	47·1	45·0	38·5	25·6	12·5	280·8	0·500	140·4
40° North	15·3	40·4	61·0	74·5	79·9	77·0	64·5	44·0	18·5	475·1	0·766	365·8
20° North	14·0	50·8	73·0	84·0	88·0	85·1	75·0	54·0	17·5	541·4	0·940	508·9
0°	8·0	45·1	69·9	82·0	**86·1**	82·4	71·1	47·0	11·9	503·5	1·000	503·5
20° South	2·0	23·5	47·3	60·2	64·5	61·0	48·5	26·0	2·1	335·1	0·940	315·0
40° South	1·0	4·0	16·5	29·8	33·5	30·0	18·1	4·0	0·9	137·8	0·766	106·1
60° South	0	0	0·8	1·2	2·8	1·2	0·8	0	0	6·8	0·500	3·4
80° South	0	0	0	0	0	0	0	0	0	0	0·174	0
										TOTAL	.. ..	1 956·8

From the above we have:—

$$\text{Distribution factor} = \frac{1\,957}{86{\cdot}1} = 22{\cdot}7$$

and

$$\text{Radiant efficiency} = 117{\cdot}3 \times \frac{3{\cdot}93 \times 22{\cdot}7}{12 \times 250 \times 6} \times 100 \text{ per cent} = 58{\cdot}3 \text{ per cent.}$$

TABLE 2.

Radiant Efficiency of Electric Fires.

Test number	Fire*	Condition	Number of elements on	Current I	θ_c	D	Radiant efficiency	Distribution shown in fig.
				amps.	deg. C.		per cent	
1	A	Mounted vertically	1	4·00	1·27	24·4	55·8	—
2	B	Complete	3	12·00	3·93	22·7	58·3	6 (*a*)
3		Minus hob and back reflector ..	3	12·00	3·77	23·6	58·0	—
4		Minus hob	3	12·00	3·92	23·4	59·9	—
5		Minus back reflector	3	12·00	3·76	23·1	56·6	—
6		Minus hob: centre firebar off ..	2	8·00	2·47	23·2	56·0	—
7		Minus hob: top and centre firebars off	1	4·00	1·49	20·5	59·4	—
8		Minus hob: top firebar off	2	7·93	2·71	22·3	59·5	—
9	C	Complete	3	11·60	2·13	40·2	57·7	6 (*b*)
10		Top firebar off	2	8·00	1·88	32·0	58·8	—
11	D	Complete	3	11·80	3·04	29·2	58·7	6 (*c*)
12		Minus back reflector	3	11·80	2·98	29·5	58·3	—
13		Minus front guard-bars	3	11·80	3·26	28·4	61·4	6 (*d*)
14		Centre firebar off	2	7·90	2·06	28·5	58·2	—
15		Top firebar off	2	7·90	2·29	27·9	63·2	—
16		Top and centre firebars off	1	4·00	1·22	26·7	63·7	—
17	E	Complete	3	12·00	3·34	19·0	39·8	6 (*f*)
18		Minus front guard	3	12·00	4·22	20·5	56·5	6 (*e*)
19		Top firebar off	2	8·20	2·11	18·9	38·0	—
20		Bottom and centre firebars off ..	1	4·20	1·11	19·4	40·1	—
21	F	1 000-watt element	1	4·00	3·23	10·5	68·1	6 (*g*)
22		Minus guard: 1 000-watt element ..	1	4·00	3·50	10·2	70·0	—
23		750-watt element	1	3·00	2·80	9·4	68·3	—
24		600-watt element	1	2·27	1·94	10·2	68·3	—
25	G	1 000-watt element	1	4·00	4·95	7·1	68·6	6 (*h*)
26		Minus guard: 1 000-watt element ..	1	4·00	5·30	6·9	71·7	—
27		750-watt element	1	3·00	4·64	5·5	67·0	—
28		600-watt element	1	2·27	3·52	5·1	61·6	—
29	H	Complete	2	7·89	2·21	27·9	60·4	7 (*a*)
30		Top firebar off	1	3·92	1·25	24·9	62·0	—
31	J	Complete	2	9·0	2·50	26·4	57·3	7 (*b*)
32		Minus lamp	2	7·98	2·49	25·7	62·7	—
33		Bottom firebar off	1	5·00	1·39	29·0	63·0	—
34		Top firebar off	1	4·98	1·49	24·8	58·0	—
35	K	High heat	2	12·00	3·85	8·6	64·4	8 (*a*)
36		Medium heat	1	6·95	4·94	6·4	70·2	8 (*c*)

* *Types of fire:* A = Firebar; B, C, D and H = Ordinary glow; E = Imitation coal; F and G = Bowl; J = Glow, with convector lamp; K = Glow-bar.

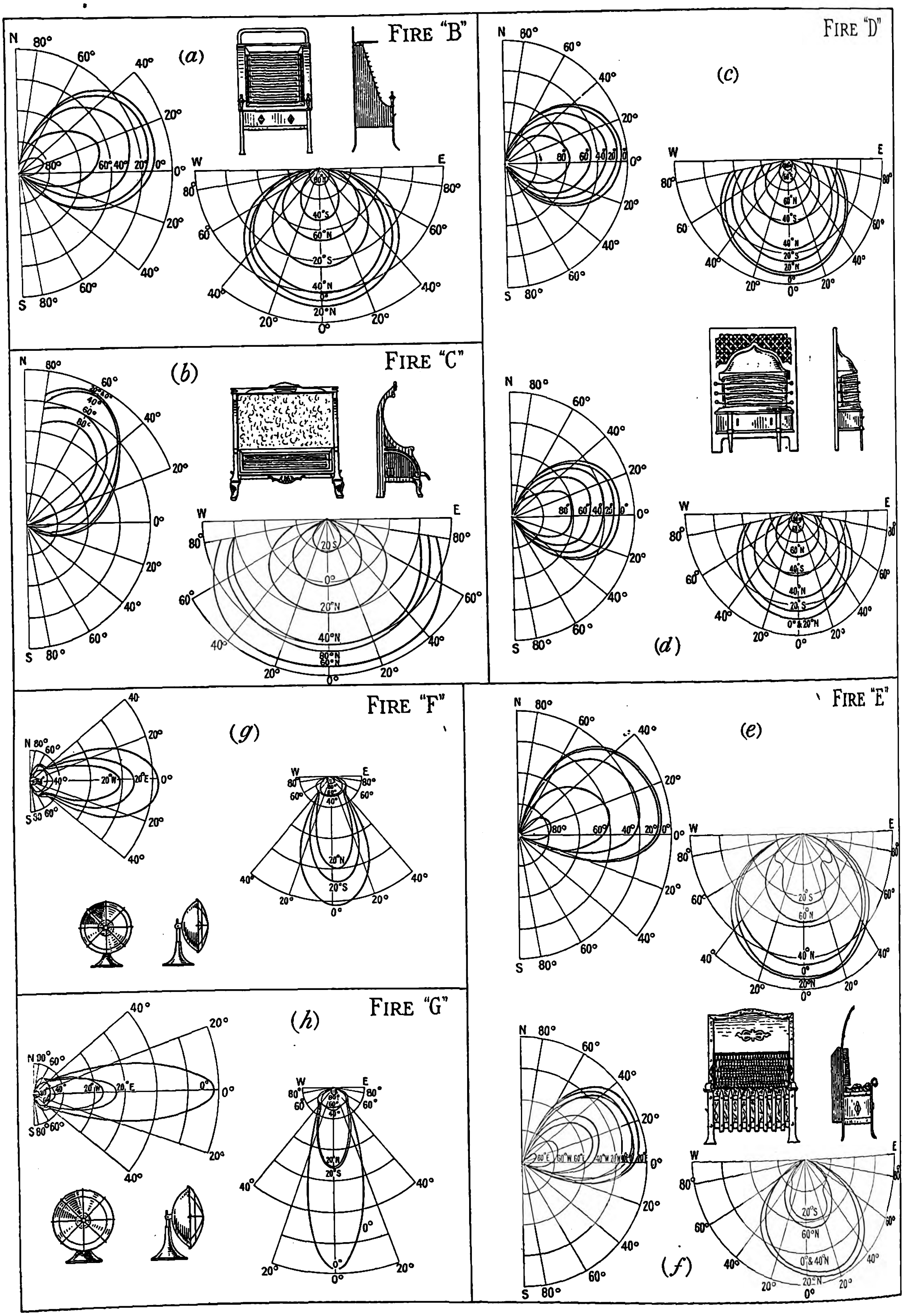

Fig. 6.—Radiant-heat distribution charts.
N–S = vertical distribution; W–E = horizontal distribution.

Cooling Correction.—The thermometer readings are plotted to a base of time in Fig. 5.

From this graph the following are obtained:—

$$\theta_1 = -0\cdot030 \text{ deg. C. per min.}; \ \theta_2 = -0\cdot062 \text{ deg. C. per min.}; \text{ time of exposure } T = 6 \text{ minutes.}$$

$$\begin{aligned}\theta_c &= (t_2 - t_1) - \tfrac{1}{2}(\theta_1 + \theta_2)T \\ &= (16\cdot37 - 12\cdot72) - \tfrac{1}{2}(-0\cdot030 - 0\cdot062)6 \\ &= 3\cdot65 + (0\cdot046 \times 6) = 3\cdot93 \text{ deg. C.}\end{aligned}$$

HEAT-DISTRIBUTION CHARTS.

Two charts were drawn for each fire—a horizontal distribution and a vertical distribution. The tabulated thermopile readings were used, curves being drawn through points in corresponding latitudes for the horizontal distribution and through points in corresponding longitudes for the vertical distribution.

SUMMARY OF RESULTS.

The results of 36 tests taken on electric fires are summarized in Table 2. All fires were tested at 250 volts. Typical examples of radiant-heat distribution have been selected for reproduction. These are shown in Figs. 6, 7 and 8. All radiometer exposures T were 6 minutes, except in tests 35 and 36, where T was 2 and 3 minutes respectively.

DISCUSSION OF RESULTS.

The results show that the radiant efficiency of various electric fires tested varies from 55 to 70 per cent, the comparatively low efficiency of 40 per cent in fire "E" being due to the presence of a particularly massive guard. When this guard is removed the radiant efficiency rises to 56 per cent. Ordinary electric fires are seen to have a radiant efficiency of about 60 per cent, while bowl types reach about 70 per cent. It is also seen that the switching off of one or more elements had not much influence on the radiant efficiency—in some cases the radiant efficiency was slightly greater, in others slightly less, than with the complete fire switched on.

It is interesting to note that the firebar element "A" —test 1—has a slightly lower radiant efficiency when mounted free than when built into fire "B" (test 2, etc.). This is no doubt due to convection, owing to the air current being less restricted.

Effect of Back Reflector Plate.—Fires "B" and "D" were fitted with back reflectors in the form of a sheet of highly polished metal fixed to the back plate of the fire and exposed to the backs of the elements. The effect on the radiant efficiency of removing this reflector is seen by comparing tests 2 and 5 and tests 11 and 12. In the first fire the radiant efficiency was reduced by 1·7 per cent and in the second by 0·4 per cent. The reflector on the first fire was fairly close up against the elements while, owing to the shape of the second fire, its reflector was a considerable distance away from the elements. This, no doubt, accounts for the difference in the effect of the reflectors. Though the reflector plate has not much effect on the radiant efficiency, the back of the fire is appreciably cooler when the plate is fitted.

Effect of Guards.—The effect of guards in front of the elements is more marked. The case has already been mentioned where the removal of a guard makes an increase of over 16 per cent in the radiant efficiency (see tests 17 and 18). This is an exceptional case; the guard consisted of an expanded-metal trellis mounted in a rectangular cast-iron frame, the trellis obscuring a considerable area of the elements. The trellis also had the effect of making the distribution unsymmetrical, since from a viewpoint about 40° E. the thickness of the metal only was visible, but from a point about 40° W. the breadth—equal to twice the thickness—was visible. Thus an object placed west of the fire only received about two-thirds of the radiation received by an object placed at a similar angle east of the fire. The heat distribution chart for this fire shows this graphically [see Figs. 6 (*f*) and 6 (*e*)]. In the other fires tested (see tests 11, 13; 21, 22; and 25, 26) the effect of the lighter guards was not so great, the increase in radiant efficiency due to the removal of the guard being of the order of 2 to 3 per cent. Any advantage gained by the addition of a back reflector is more than offset by the addition of a front guard. The design, and more especially the placing, of guard bars in front of a fire is therefore seen to be of sufficient importance to merit attention. The use of a hob is seen to reduce the radiant efficiency by about 1·6 per cent (compare tests 2 and 4).

Convection Currents.—In fire "J" (see tests 31 and 32) a lamp was placed at the head of an air passage which passed behind the elements. This was a 250-watt orange-sprayed lamp, and served to give appearance to the fire and also to induce a convection current. The backs of the elements were shielded from this current by a metal shield which was also designed to prevent any current due to the elements themselves being formed at the back. This shield was not polished. A comparison between tests 31 and 32 shows that convection due to the lamp apparently reduced the radiant efficiency by about 5 per cent, but in the complete fire it must be remembered that the lamp input has to be taken into account and its effect is considerable.

In general, it would seem that attempts at producing convection by directly increasing the amount of warmed air are not very successful, to judge from the fairly constant value of the radiant efficiency.

Bowl Fires.—Apart from the higher radiant efficiency of bowl fires, it would seem that at the normal working temperatures the radiant efficiency is not much influenced by the design. The effect of the design of the fire is seen in the radiant distribution [Figs. 6 (*g*) and (*h*)]. Since the total thermal efficiency of an electric fire as a heater is 100 per cent, and in most designs very little heat is emitted by conduction, it follows that practically all energy that is not radiated appears as convected heat.

Reflector Fires.—In the case of the two reflector fires "L" and "M" (tests 37 to 40, Table 3) it was found that a modification of the method was necessary because the intensity of radiation along the equator was so low that the resultant temperature-rise of the radiometer block was too small to be measured with any degree of accuracy. In order to estimate the efficiency of these fires the following procedure was adopted.

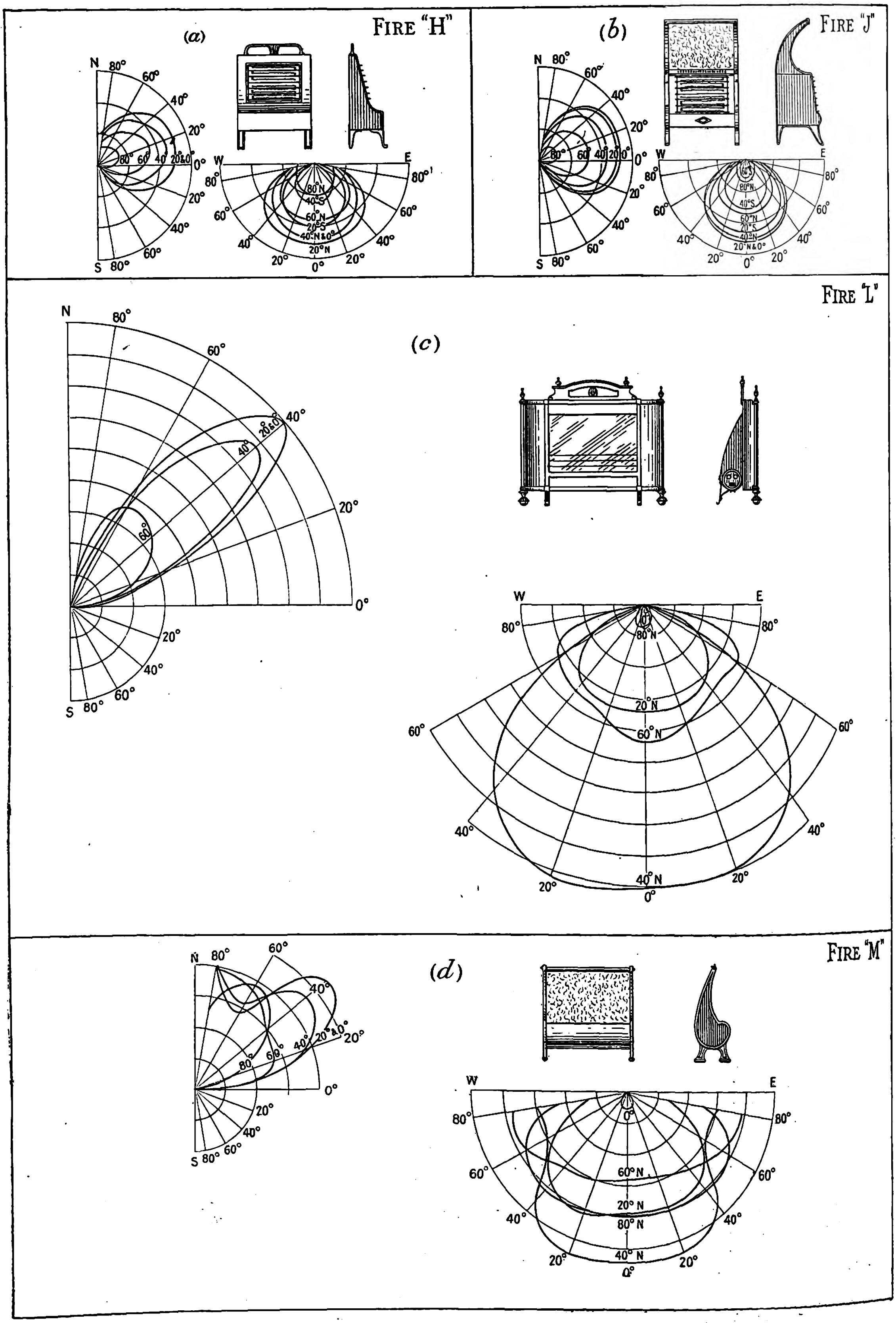

FIG. 7.—Radiant-heat distribution charts.
N–S = vertical distribution; W–E = horizontal distribution.

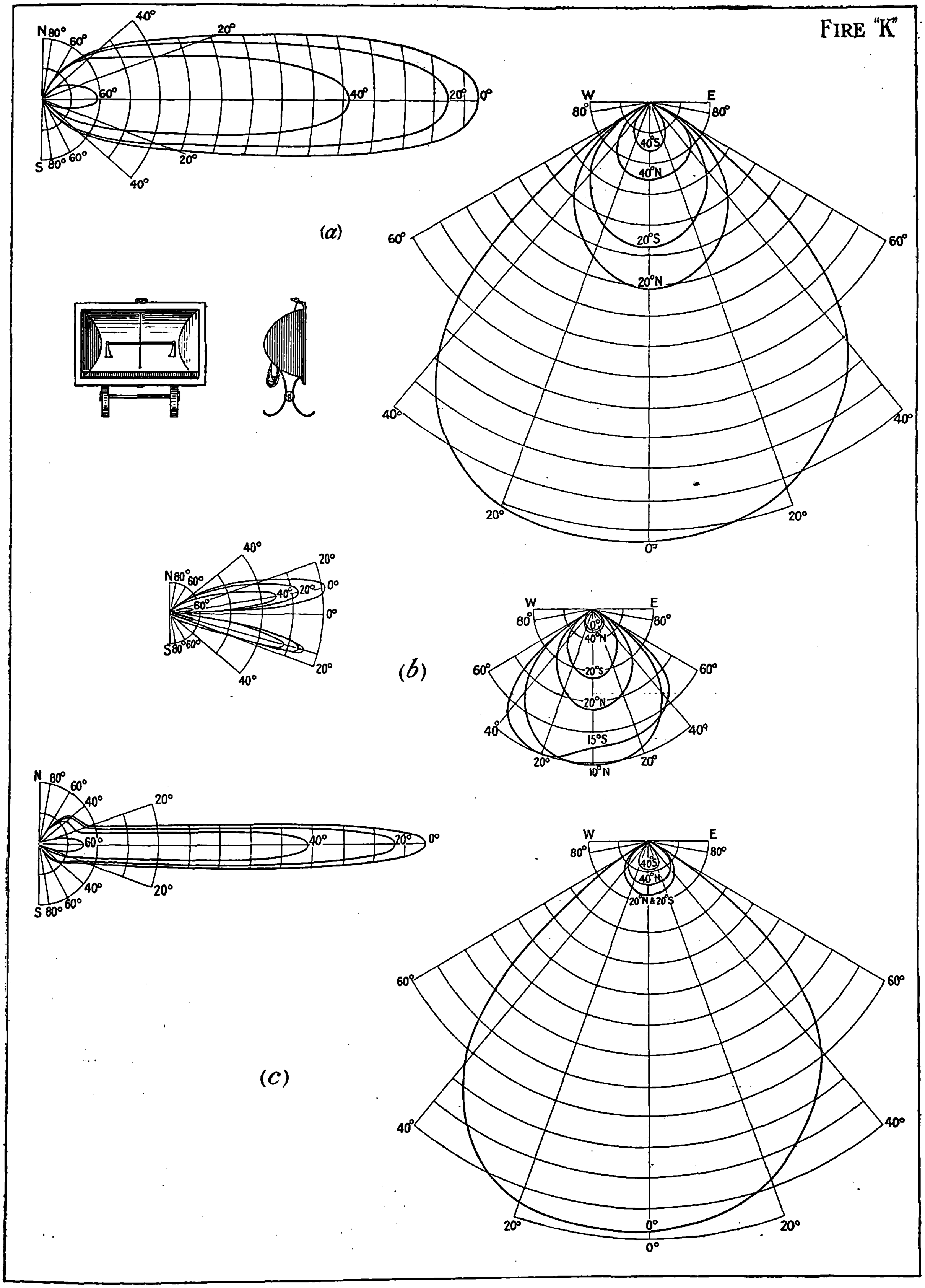

FIG. 8.—Radiant-heat distribution charts.

N-S = vertical distribution; W-E = horizontal distribution.

From the results of tested fires with fairly flat distribution curves about the "equator," an auxiliary curve was drawn of corrected temperature-rise θ_c of the radiometer block for 6 minutes to a base of central thermopile reading. This proved to be a straight line. On the distribution chart of the reflector fire an area was then taken such that the shape of the distribution curve at that area was similar to the shape of the distribution curves at the areas where the readings were taken from which the auxiliary curve was drawn. The thermopile reading h' at the centre of such an area was noted, and from the curve was obtained the corrected temperature-rise θ'_c which would have occurred in the radiometer block after 6 minutes had it been placed at that area.

The distribution factor with respect to this area is then $D' = H/(h' \times c)$, where H = total weighted sum of 81 readings and c is the cosine correction for the latitude in which the chosen area lies. The corresponding temperature-rise at the chosen area will be $c\theta'_c$ deg. C., and

$$\text{Radiant efficiency} = 117\cdot3 \times \frac{c\theta'_c \times H/h'c}{IVT}$$

$$= 117\cdot3 \times \frac{\theta'_c \times H/h'}{IVT}$$

Thus the cosine correction for latitude disappears from the final expression.

Example.—Reflector fire "M."

$$\text{Voltage} = 250\ \text{V, current} = 11\cdot5\ \text{A.}$$
$$H = 1\ 555\cdot8.$$

Taking the area at 40° N., 60° E.: $h' = 59\cdot0$.

From the auxiliary curve $\theta'_c = 2\cdot75$ deg. C.

$$\therefore\quad H/h' = 1\ 555\cdot8/59\cdot0 = 26\cdot4$$

Radiant efficiency

$$= 117\cdot3 \times \frac{2\cdot75 \times 26\cdot4}{250 \times 11\cdot5 \times 6} \times 100 \text{ per cent}$$
$$= 49\cdot5 \text{ per cent.}$$

TABLE 3.

Radiant Efficiency of Electric Fires.

Test number	Fire *	Conditions	Current I	H	Radiant efficiency	Distribution shown in Fig.
			amps.		per cent	
37	L	High heat	11·9	1 482·0	45	7 (*c*)
38		Low heat	5·89	774·8	51	—
39	M	High heat	11·5	1 555·8	49	7 (*d*)
40		Low heat	5·63	740·0	52	—
41	C	Top and bottom firebars off	4·0	589·0	58	—
42		Bottom firebar off	8·0	1 070·9	53	—

* *Types of fire:* L and M = Reflector; C = Ordinary glow.

The radiant efficiency was calculated in this way for as many areas as suited the conditions, and a mean was taken.

The above method was also used to obtain the efficiencies for the two lower heats of fire "C," and the accuracy attained can be judged by comparing the efficiencies thus found (tests 41 and 42, Table 3) with that obtained by the direct method (test 9, Table 2).

In the case of the low heat of the glow-bar fire "K," Fig. 8 (*b*), it was found to be impracticable to apply this modification since no part of an available distribution chart could be found suitable for comparison with the actual distribution chart.

It would seem that reflector fires such as the first two in Table 3 convect relatively more heat than the other types of fires, and are therefore better suited where a warm current of air is needed.

RADIATION, CONVECTION AND VENTILATION.

When judging the merits of an electric fire, the radiant efficiency must not be the sole consideration. While it is true that, with ample radiant heat, a room may be comfortable with an air temperature some 10 deg. F. lower than with convected heat only, yet extremes must be avoided. On a calm, cold day with strong sunshine, it may be agreeable to sit out-of-doors, but corresponding conditions do not exist indoors—a fire does not irradiate the body like the sun. For comfort in a room heated by an electric fire, the air temperature should not fall below, say, 50 to 55° F. The fire itself should therefore provide convection air-currents in addition to those produced by objects in the room receiving direct radiant heat.

Closely connected with convection is the question of ventilation. As a general rule, the creation of a draught up a flue by placing an electric fire in an ordinary fireplace is neither satisfactory nor economical. Where possible, means should be provided for admitting cool, fresh air, while the warmed air should escape near the ceiling; but even where no special ventilating arrangements have been made it is often not difficult to obtain satisfactory results. Advantage can be taken of the fact that with electric fires draughts through windows and under doors are not so strong as with coal fires, sufficient air movement and ventilation being obtained without discomfort or stuffiness.

It is not easy to make a close comparison between electric and gas fires. The latter must be fixed below a flue, and the flue heat can be made to produce ventilation. Portability is an asset of which the electric fire has a virtual monopoly. It has been seen that the radiant efficiency of electric fires varies from 55 to 70 per cent. The deficit from 100 per cent can be considered to be due to the heat emitted by convection, and, provided a suitable scheme of ventilation be arranged, practically the whole heat of the fire can be utilized. Tests carried out by the author on 5 modern types of gas fire showed that the radiant efficiency varied from 40 to 50 per cent. Of the remaining heat a large part escapes as flue heat, the balance being convection.

More knowledge is required concerning the factors which influence radiation. The hotter the elements the greater will be the amount of heat radiated, but the precise relation between power input and radiation must be separately determined for each type of fire. For example, suppose an " element " or firebar be supported in free air and supplied with a definite power, then, according to the inclination of the face of the element, so the relative proportions of convected and radiated heat will vary. If both conduction and convection are largely prevented, as in certain cases of ceiling-panel heating, the heat must escape chiefly by radiation and the temperature must rise; whereas floor and wall panels both assist convection. Experiment has shown that raising the temperature of the elements of a fire by over-running may not increase the amount of radiation in proportion to the increased rating, on account of a more rapid increase in convection, while from the physiological point of view a very brightly glowing body is harmful to the eyes.

Experience would seem to indicate that, in the electric fires now available, practical requirements regarding both radiation and efficiency are fairly well met.

ACKNOWLEDGMENTS.

This investigation was begun 4 to 5 years ago and much preliminary work had to be done before the research proper could be commenced. The majority of the apparatus was made in the Electrical Engineering Department of the Royal Technical College, Glasgow. Valuable aid in the early measurements was given by Mr. G. Shearer, B.Sc., Mr. N. M. MacElwee, B.Sc., and Mr. J. A. Cowan. The measurements in the paper were taken by Mr. J. Sorbie, B.Sc., and it is desired to acknowledge a grant by the Institution from the War Thanksgiving and Research Fund. Much valuable criticism was obtained from members of the staff of the Research Laboratories of the General Electric Co., Wembley.

THE MEASUREMENT OF HIGH VOLTAGES, WITH SPECIAL REFERENCE TO THE MEASUREMENT OF PEAK VOLTAGES.*

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[From the National Physical Laboratory.]

(*Paper received* 13*th March*, 1930.)

Summary.

Two methods of measuring peak voltage have been investigated. In the one method a condenser divider is used, and the voltage on the low-voltage arm of the divider is rectified. In the other the current through a condenser connected across the voltage to be measured is rectified, and the mean current so obtained is a measure of the peak voltage across the condenser. The accuracy of the methods is considered theoretically for different wave-forms, results arrived at by the two methods are compared, and agreement to about 2 parts in 1 000 is obtained.

Introduction.

For the measurement of high voltage, i.e. voltages between 10^5 and 10^6, the sphere gap has been largely used. The flash-over value of the gap has generally been determined either experimentally by means of a third winding on a suitably designed supply transformer, or by calculation. The accuracy claimed, however, is only of the order of 1 or 2 per cent.

The design of suitable instruments for the direct measurement of high voltages provides a difficult problem. This is being studied by the Bureau of Standards, which is developing the absolute electrometer for the purpose.

Measurements would be greatly simplified by the provision of some accurate form of potential divider. For use at high voltages the usual resistance form involves great difficulty, owing to capacity troubles and the large amount of power wasted, and for very high voltages is impracticable. A capacity divider offers much less difficulty, and it is possible to design a high-voltage condenser the capacity of which can be known or measured with reasonable accuracy. In this paper the authors consider the use of a condenser divider for the measurement of effective and peak voltages.

The knowledge of the peak value of the applied voltage is of importance in insulation testing, as it is this, rather than the applied R.M.S. voltage, which determines breakdown or flash-over. This paper is consequently largely devoted to the study of two methods of measuring peak voltage. In the first method considered a fraction of the applied voltage, as obtained from a condenser divider, is rectified, thus giving a measure of the peak, and in the second the current through a condenser connected across the supply voltage is rectified and measured on a direct-current ammeter, this current giving a measure of the peak voltage on the condenser.

The Condenser Potential-Divider.

Some preliminary experiments were made to investigate the use of the condenser divider as a potential divider, using the circuit illustrated in Fig. 1. By means of the switch S the supply voltage, about 200 volts (R.M.S.), could be applied either to the resistance or the condenser divider. It was found that the electrostatic voltmeter did not always read the appropriate R.M.S. voltage $C_1V/(C_1 + C_2)$. The explanation was found to be that when the supply to the condenser divider was removed, condensers C_1 and C_2 each received a charge depending on the point in the voltage wave at which the supply was interrupted. Then if one of the condensers was discharged, or if its charge leaked away at a quicker rate than the charge on the other, the voltmeter V_2 indicated, on the re-application of the voltage to the condenser divider, the alternating voltage $C_1V/(C_1 + C_2)$ plus a steady voltage which was proportional to the difference of the charges on C_1 and C_2, at the instant of the application of V, divided by $(C_1 + C_2)$.

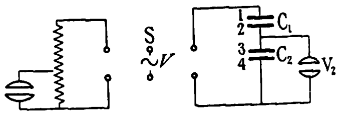

Fig. 1.

Thus, if Q be the quantity of electricity bound on C_1 and on C_2 when the supply is removed, and V_1 and V_2 be the potentials to which the condensers are raised by these charges, then $Q = C_1V_1 = C_2V_2$.

If condenser C_2 be discharged and the voltage V applied to the divider, the voltmeter connected across C_2 indicates the R.M.S. value $C_1V/(C_1 + C_2)$ plus the direct voltage $C_1V_1/(C_1 + C_2)$, since the condensers are now connected in parallel with respect to the quantity of electricity C_1V_1. This was confirmed experimentally.

The conclusion to be drawn is that the measuring arm of the condenser divider will indicate correctly the R.M.S. voltage applied to it, provided that neither condenser has an initial charge. In practice a transformer winding will be connected permanently across the divider, so that equal and opposite charges will not be bound on plates 1 and 4 of the divider system. A suitable leak connected across one arm will dissipate any charge on plates 2 and 3 and make the divider read correctly.

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APPLICATION OF THE CONDENSER DIVIDER TO THE MEASUREMENT OF PEAK VOLTAGE.

The use of a thermionic valve in conjunction with an electrostatic voltmeter for the measurement of peak voltage is well known and was described * by Sharpe and Doyle in 1916. The circuit is illustrated in Fig. 2, where D represents the thermionic valve rectifier and V the electrostatic voltmeter. A condenser connected in parallel with the voltmeter acts as a reservoir for the charge passed by the rectifier, and is an essential addition to the circuit. The general principles of the method are too well known to warrant any further description here.

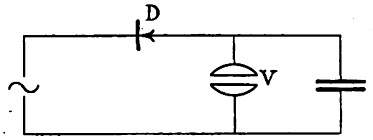

FIG. 2.

For the measurement of very high peak-voltages by this method a valve capable of withstanding twice the peak value must be used, a requirement clearly prohibitive, so that some potential-dividing device must be adopted. Fig. 3 (*a*) illustrates a circuit which might be used, in which this method of measuring peak voltage is used in conjunction with a potential divider. This circuit was investigated experimentally, and it was found that, if C_3 acquired a charge, the plates 2 and 3 of the condenser divider acquired an equal and opposite charge. This was demonstrated by removing the supply from the condenser divider, connecting electrodes 1 and 4 together to neutralize the equal and opposite charges acquired by these electrodes at the moment of switching off, and short-circuiting the rectifier D, whereupon voltmeter V_3 (and voltmeter V_2) indicated zero.

Let V_3 be the voltage acquired by condenser C_3. Then the charge on C_2 equals $-V_3C_3$ and the direct voltage acquired by C_2 equals $-V_3C_3/(C_1+C_2)$. The voltage V_3 will increase until it is equal to

$$\frac{k\,.\,VC_1}{C_1+C_2}-\frac{V_3C_3}{C_1+C_2}$$

where kV is the peak value of the applied R.M.S. voltage V. The voltmeter V_2 connected across C_2 should read, therefore, the voltage

$$\left[\left(\frac{VC_1}{C_1+C_2}\right)^2+\left(\frac{V_3C_3}{C_1+C_2}\right)^2\right]^{\frac{1}{2}}$$

and the voltmeter V_3 connected across C_3 should read

$$V_3=\frac{kVC_1}{C_1+C_2}-\frac{V_3C_3}{C_1+C_2}$$

i.e.

$$V_3\left(1+\frac{C_3}{C_1+C_2}\right)=\frac{kVC_1}{C_1+C_2}$$

i.e.

$$V_3=\frac{kVC_1}{C_1+C_2+C_3}$$

These conclusions were tested experimentally, using a voltage supply having a wave-form approximating to a sine curve in which k was assumed to be 1·41. Table 1 gives a typical result.

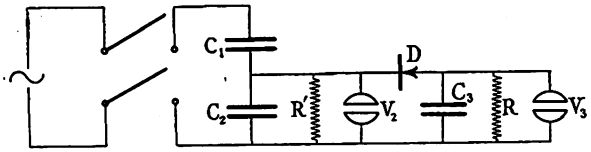

FIG. 3 (*a*)

The disagreement between the theoretical and observed values of V_3 (54·7 and 54·1) is presumed to be due to error in assuming a value for k of 1·41.

TABLE 1.

C_1	C_2	C_3	V	V_2	V_3	$\frac{1{\cdot}41\,VC_1}{C_1+C_2+C_3}$	$\left[\left(\frac{VC_1}{C_1+C_2}\right)^2+\left(\frac{V_3C_3}{C_1+C_2}\right)^2\right]^{\frac{1}{2}}$
μF 1	μF 1	μF 2	153·0	94·2	54·7	54·1	94·1

This preliminary investigation indicated the necessity for a modification of the circuit, to enable the charge built up on C_2 to be dissipated before the voltmeter V_3 could build up to the peak value. This can be done by shunting the condenser C_2 by a resistance, R′. The effect of this resistance on the divider ratio is determined from the following expression, in which V is the total voltage applied to the divider, V_2 the voltage on the measuring arm, C_1 and C_2 the high- and low-voltage arms of the divider respectively, R' the resistance across C_2, and $\omega = 2\pi \times$ frequency.

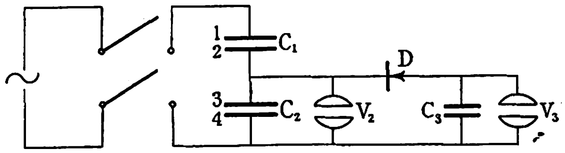

FIG. 3 (*b*).

$$\frac{V}{V_2}=\frac{C_1+C_2}{C_1}\left[1-\frac{1}{2\{\omega R'(C_1+C_2)\}^2}\right]$$

For a condenser divider for 10^6 volts, C_1 might be 10 μμF and C_2 10^5 μμF. The error introduced by a resistance of 1 megohm at a frequency of 50 cycles per sec. would be less than 3 in 10^4.

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* *Transactions of the American I.E.E.*, 1916, vol. 35, p. 99.

DETAILED CONSIDERATION OF THE ACTION OF THE PEAK VOLTMETER.

The necessary conditions for the peak voltmeter accurately to record the peak value of a periodic voltage wave, assuming that the charge on the measuring arm of the divider is destroyed, are:—

(1) There should be no capacity across the valve.

(2) The electrostatic voltmeter with its associated condenser should have perfect insulation.

(3) The plate-voltage/plate-current characteristic of the rectifying valve should be such that with no voltage between the plate and the negative end of the filament no plate current should flow, and for negative voltages between plate and filament no reverse current should flow.

Condition (1). *Effect of Valve Capacity, and Consideration of Values of Divider and Peak-Voltmeter Capacities.*—The capacity between the valve electrodes is negligibly small, but to one side are connected a filament battery and leads to the peak voltmeter and the peak condenser, and to the other a lead to the condenser divider. Thus the effective capacity across the valve may be appreciable and its effect must be considered.

Let K be the value of this capacity,

C_1 and C_2 the capacities of the high- and low-voltage arms of the condenser divider,

C_3 the capacity of the peak condenser,

V the applied voltage,

V_1, V_2, V_3 and V_K the instantaneous voltages on C_1, C_2, C_3, and K respectively, and

V_m, etc., the maximum values of V, etc.

When equilibrium is established the valve will no longer pass current at any time (neglecting any small current due to leakage on the peak condenser), and the various capacity currents will be those produced by the alternating voltage V in the capacity network C_1, C_2, C_3, K. Thus the voltage on C_2 will be

$$\frac{VC_1}{C_1 + C_2 + (C_3K/C_3 + K)}$$

provided that no charge is allowed to collect on C_2.

The total charge on the connected plates of C_3 and K must be constant, giving the relation

$$V_3C_3 - V_KK = (V_3)_mC_3$$

or, substituting $V_2 - V_3$ for V_K,

$$\begin{aligned} V_3(C_3 + K) &= (V_3)_mC_3 + V_2K \\ &= (V_2)_mC_3 + V_2K \end{aligned}$$

Squaring and taking mean values we obtain

$$[V_3^2]\,(C_3 + K)^2 = \left\{(V_2)_mC_3\right\}^2\left(1 + \frac{[V_2^2]}{(V_2)_m{}^2}\cdot\frac{K^2}{C_3^2}\right)$$

where the mean value is indicated by the square brackets.

Taking the square root and neglecting second-order quantities, this reduces to

$$\begin{aligned} \sqrt{[V_3^2]} &= \frac{(V_2)_mC_3}{C_3 + K} \\ &= V_m\frac{C_1C_3}{(C_3 + K)\left(C_1 + C_2 + \dfrac{C_3K}{C_3 + K}\right)} \\ &= \frac{V_mC_1}{C_1 + C_2}\left[\frac{C_3}{(C_3 + K)\left\{1 + \dfrac{C_3K}{(C_3 + K)(C_1 + C_2)}\right\}}\right] \\ &= \frac{V_mC_1}{C_1 + C_2}\left(1 - \frac{K}{C_3} - \frac{K}{C_1 + C_2}\right) \end{aligned}$$

This is the value obtained from the voltmeter reading and it shows that the use of the simple formula $V_mC_1/(C_1 + C_2)$ would involve two errors, which may be made negligible by giving the divider and peak-voltmeter capacities sufficiently large values.

TABLE 2.

Plate voltage	Plate current	
	Mullard DU.5	Osram DEP.240
volts	μA	μA
0	33·0	0·70
− 100	− 0·2	− 0·01
− 200	− 0·7	− 0·03

The two errors were investigated experimentally with various values of K, C_2 and C_3, with results closely agreeing with the formula.

If C_1 be infinite, the formula becomes $V_m\{1 - (K/C_3)\}$ and is applicable to the rectification of the whole voltage. This is in accordance with the conclusions of Paterson and Campbell.*

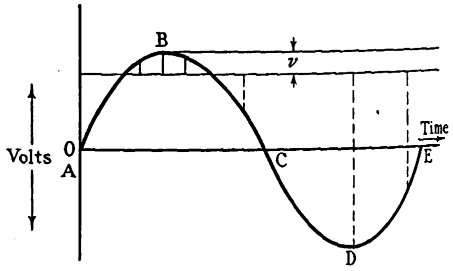

FIG. 4.—Voltage wave applied to measuring arm of capacity divider.

Conditions (2) *and* (3). *Effects of the Valve Characteristic and of the Imperfect Insulation of the Peak Condenser.*—In practice the insulation of the peak condenser is not perfect. Consequently when the peak voltmeter receives a charge a current which tends to discharge the voltmeter flows through the resistance associated with the voltmeter and its condenser.

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* *Philosophical Magazine*, 1919, vol. 37 p. 301.

Further, the behaviour of the valve does not fulfil condition (3) above. The characteristics of two valves were investigated and the results are given in Table 2.

The characteristics of the DEP.240 valve approach more closely to the ideals required, and this valve was used for subsequent work.

When the voltmeter indicates a steady value V the net quantity of electricity passed by the valve in a cycle equals the charge dissipated via the leak across the voltmeter. If R be the value of the leak, this quantity equals $360V/R$ ampere electrical degrees (abbreviated to ampere-degrees). This equilibrium current V/R flows through the resistance R′, say, which is connected across the condenser C_2, the measuring arm of the divider. The measuring arm consequently acquires a direct voltage $(V/R)R'$ which depresses the whole of the applied voltage-wave by this amount, leading to an error of this value on the peak-voltmeter reading. The value of the resistance R' should be as small as is consistent with the expression $1/2[\omega R'(C_1 + C_2)]^2$ being negligible.

The effect on the peak-voltmeter reading of supplying the quantity 360 V/R ampere-degrees per cycle may be investigated in the following way. Let ABCDE, Fig. 4, represent the voltage wave applied to the measuring arm of the divider. Assume that the error on the peak voltmeter due to the passage of electricity through the valve is $-v$, so that the voltage on the valve at the peak of the wave is $+v$. The voltage on the valve at any other instant in the cycle can either be determined from the equation of the curve ABCDE, or graphically. From this voltage the current passing through the valve at any instant can be determined. In the figure the vertical lines indicate the voltages on the valves at different instants; the broken lines represent negative, the unbroken, positive values. A current/time curve for the valve over a period of a cycle can now be constructed, and by measuring the area of this curve the net quantity of electricity passed by the valve in a cycle can be determined. The quantity so determined is passed for an error $-v$. By repeating this process for different values of error, a curve relating the error to the quantity passed by the valve can be constructed. This relation between quantity and error for a particular rectifier is illustrated by the curves in Fig. 5 (*d*) for the case of a sinusoidal voltage-wave having maxima of 50, 100 and 200 volts, respectively.

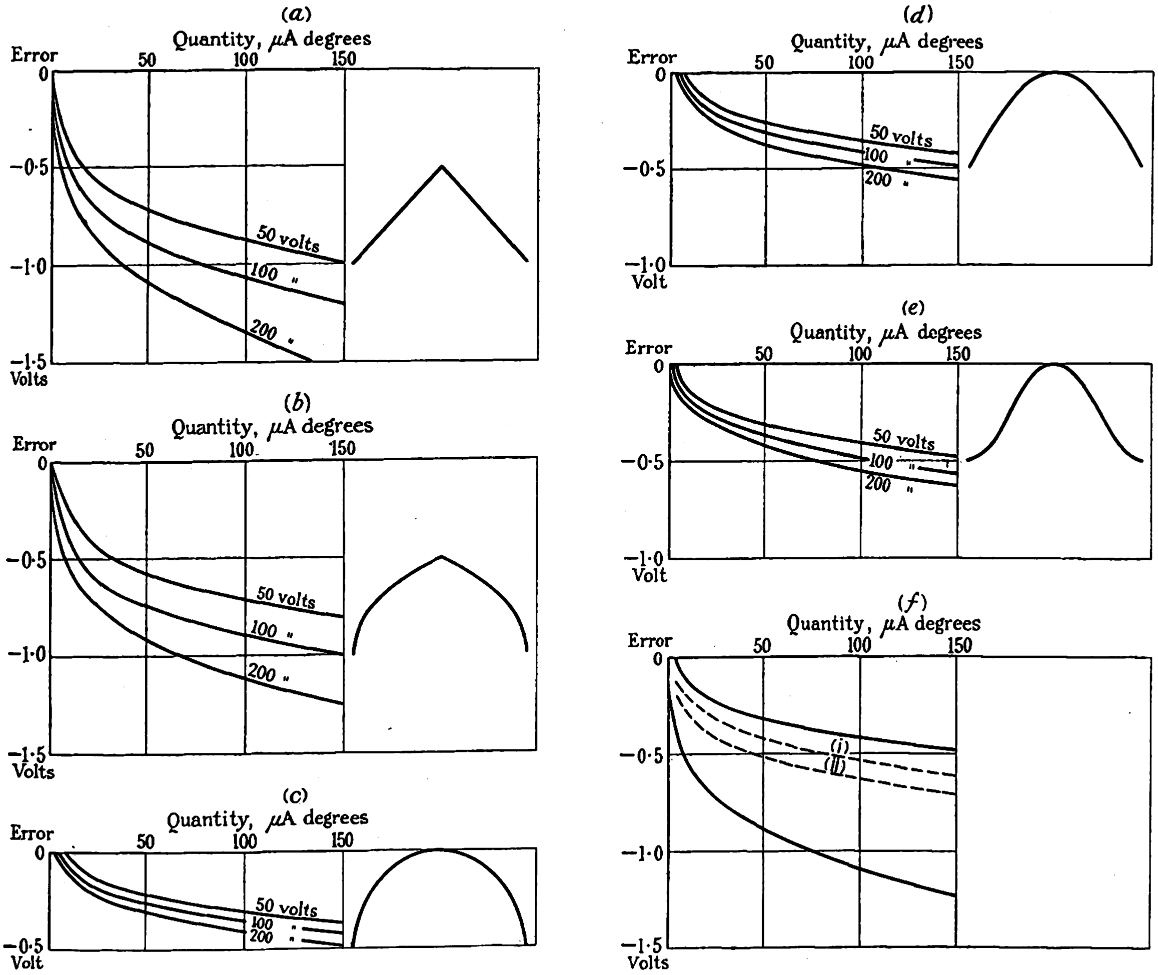

FIG. 5.—" Quantity/error " curves for a rectifier, obtained by applying various voltage waves.

In determining the quantity for different errors the quantity of electricity passed in the reverse direction has been neglected. This quantity was estimated to be about 5 microampere-degrees for an applied sinusoidal wave with a maximum of 100 volts. The effect of this constant error on the "quantity/error" curve is negligible. Further, in determining the voltage on the valve at any instant in the cycle the effect of the increase in the voltage on the peak condenser, due to the acquisition of a charge during the period of positive conduction of the valve, is negligible.

EXPERIMENTAL INVESTIGATION OF THE RELATION BETWEEN ERROR AND PEAK-CONDENSER LEAKAGE.

An Osram 3-electrode valve working at a filament current of 0·4 ampere (the condition under which the valve was calibrated) was used in the tests. The plate and the grid of the valve were connected, and the plate voltage was applied between the plate and the negative end of the filament. The circuit diagram is illustrated in Fig. 3 (*b*). The condensers C_1, C_2 and C_3 were of nominal capacities, 1·0, 1·0 and 2·0 μF, respectively. The value of the resistance *R′* was 0·1 megohm, and the error on the divider due to this resistance was less than 2 in 10^4. R consisted of sealed liquid resistances which were constant in value for voltages up to 1 000.

TABLE 3.

V_2	V_3	R	$360\frac{V_3}{R}$	Error due to quantity $360\frac{V_3}{R}$	Error $\frac{V_3}{R}R'$	E_2
volts	volts	megohms				volts
69·25	100·5	5 500	6·6	0	0	100·5
69·25	99·5	63	570	−0·8	−0·2	100·5
69·25	99·4	46	780	−0·9	−0·2	100·5
69·25	99·2	35	1 020	−1·0	−0·3	100·5
69·25	98·8	22	1 616	−1·2	−0·5	100·5
69·25	98·5	14	2 530	−1·4	−0·7	100·6
69·25	97·5	7	5 015	−1·8	−1·4	100·7

The peak voltage of a supply, the wave-form of which approximated to a sine curve, was determined for different quantities of electricity passed by the valve per cycle. The variation in the quantity was obtained by varying the value of *R*. Let V_3 be the equilibrium voltage on the peak voltmeter. On removing the supply voltage the peak condenser begins to discharge via the resistance R. By timing the rate of loss of charge the value of *R* can be determined by the well-known condenser leak method. Then the quantity of electricity passed per cycle by the valve is $360\ V_3/R$ microampere-degrees, where V_3 is in volts and *R* in megohms. The error for this quantity can then be determined from one of the curves in Fig. 5, or by interpolating between two of the curves if the maximum of the wave under examination lies between 100 and 200 volts or between 50 and 100 volts.

The error due to the direct-current charge on the condenser divider is $-\ (V_3/R)R'$.

The results obtained are given in Table 3, where

V_2 = R.M.S. voltage on condenser C_2 (volts),
V_3 = peak voltmeter reading (volts),
R = resistance in parallel with C_3 (megohms),
R' = 0·1 megohm,
E_2 = corrected peak voltage.

The agreement as shown in the last column is sufficiently close to justify the considerations on which the corrections are based. They would also indicate that the errors given in the fifth column apply closely to waves which are not accurately sine waves. The ratio of the peak value to the R.M.S. value, for the wave-form used in the test, works out to be $1{\cdot}45_0$ instead of 1·414—the value of this ratio for a sine curve. Further consideration will be given to the question of wave-form in the next section.

EFFECT OF WAVE-FORM.

The relation between the quantity of electricity passed by the rectifier and the error in the peak-voltage reading has been theoretically determined for the following voltage waves, which are illustrated in Fig. 5:—

$$(a)\ \begin{cases} e=E\left(\frac{4}{T}\right)t \text{ from } t=0 \text{ to } t=\frac{1}{4}T \\ e=E\left(\frac{4}{T}\right)\left(\frac{T}{2}-t\right) \text{ from } t=\frac{1}{4}T \text{ to } t=\frac{1}{2}T \end{cases} \qquad \frac{E}{V}=1{\cdot}732$$

$$(b)\ \begin{cases} e=E\left(\frac{4}{T}\right)^{\frac{1}{2}}t^{\frac{1}{2}} \text{ from } t=0 \text{ to } t=\frac{1}{4}T \\ e=E\left(\frac{4}{T}\right)^{\frac{1}{2}}\left(\frac{T}{2}-t\right)^{\frac{1}{2}} \text{ from } t=\frac{1}{4}T \text{ to } t=\frac{1}{2}T \end{cases} \qquad \frac{E}{V}=1{\cdot}414$$

$$(c)\ e=E\sin^{\frac{1}{2}}\frac{2\pi}{T}\cdot t \qquad \frac{E}{V}=1{\cdot}252$$

$$(d)\ e=E\sin\frac{2\pi}{T}\cdot t \qquad \frac{E}{V}=1{\cdot}414$$

$$(e)\ e=E\sin^2\frac{2\pi}{T}\cdot t \qquad \frac{E}{V}=1{\cdot}633$$

in which

e = instantaneous value of the voltage,
V = R.M.S. value of the voltage,
E = maximum value of the voltage,
t = time,
T = periodic time.

The negative half of the wave is supposed to be similar to the positive half.

The quantity/error curves have been constructed for values of *E* of 50, 100 and 200 volts, respectively. These are illustrated by the curves in Fig. 5. The shape of the wave has been illustrated in each case.

From these curves Table 4 has been constructed showing the relation between the leak across the peak condenser and the error in the peak-voltmeter reading, for the voltage waves given by equations (*a*) to (*e*).

Table 4 shows that when the leakage resistance across the condenser is high (5 000 megohms or more) the error in the worst case is only about 0·5 per cent. In practice it will be almost impossible to realize this worst possible case—that of a triangular wave with a definite point at the peak. Excluding this case, therefore, the uncertainty in the peak-voltmeter reading is only of the order of 0·2 per cent for the family of curves dealt with above.

In the case of wave-shapes which are irregular the shape near the crest alone is of importance. Thus, for waves with subsidiary peaks, these peaks will not affect the error appreciably unless they are within 0·5 per cent of the maximum of the highest peak, for otherwise they occur in that portion of the cycle when the valve is non-conducting.

For any given voltage wave a curve connecting quantity and peak-voltmeter reading can be determined experimentally. By comparing the shape of this curve with that of the quantity/error curves in Figs. 5 (*a*) to 5 (*e*), and by comparing an oscillogram with the corresponding wave-forms, it is possible with some reliability to convert the experimental curve into a quantity/error curve. An illustration of this is given in Fig. 5 (*f*). Curves (i) and (ii) are experimental ones inserted between curves for a sine wave and a triangular wave. Figs. 6 (*a*) and 6 (*b*) are oscillograms of the corresponding voltage wave-forms. The errors appear to be nowhere more than 0·2 per cent different from those associated with a sine wave-form. For a sharp but rounded peak the shape of a sine wave with the time scale reduced 20 times the errors would be approximately the same as for a triangular wave. Thus most voltage supplies should be measurable to 0·5 per cent and, with sufficient care, to 0·1 or 0·2 per cent.

TABLE 4.

Leakage resistance	Maximum voltage	Error for the voltage wave given by equation:—				
		(*a*)	(*b*)	(*c*)	(*d*)	(*e*)
megohms	volts					
10 000	50	−0·2	−0·1	+0·1	+0·1	+0·1
	100	−0·4	−0·2	0·0	0·0	−0·1
	200	−0·6	−0·5	−0·1	−0·1	−0·2
5 000	50	−0·3	−0·1	+0·1	0·0	0·0
	100	−0·5	−0·3	−0·1	−0·1	−0·1
	200	−0·7	−0·6	−0·2	−0·2	−0·3
2 500	50	−0·4	−0·2	0·0	0·0	−0·1
	100	−0·6	−0·5	−0·1	−0·2	−0·2
	200	−0·9	−0·8	−0·2	−0·3	−0·3

SUMMARY OF ERRORS IN THE CONDENSER-DIVIDER METHOD OF MEASURING PEAK VOLTAGE.

Using the nomenclature of Fig. 3 (*b*) and calling the peak-voltmeter reading V_3, the following are the errors in the peak-voltmeter reading:—

(1) The shunting effect of R' on C_2 introduces an error

$$-V_3\frac{1}{2[R'\omega(C_1+C_2)]^2}$$

(2) The capacity (K) across the valve introduces errors

$$\text{(i)}\ -V_3\cdot\frac{K}{C_1+C_2}\quad\text{and}\quad\text{(ii)}\ -V_3\cdot\frac{K}{C_3}$$

(3) The leakage resistance (R) across the peak condenser introduces

(i) an error $-V_3\cdot\dfrac{R'}{R}$

and (ii) an error depending on V_3, on the valve characteristic and on the wave-form of the supply voltage.

All these errors can be determined when accurate measurements are required, or the circuit may be so arranged that most of them are negligible.

For satisfactory working R must not be too large, or the peak voltmeter will not respond to a drop in the supply voltage. The response depends on the product RC_3. To reduce errors 2 (ii) and 3 (i), however, it is desirable to have both R and C_3 large. If the various errors are each to be limited to, say, 1 part in 1 000 then C_3 must be 1 000K, $C_1 + C_2$ must be 1 000K, R' must be 1 000R, and $2[R'\omega(C_1 + C_2)]^2$ must be 1 000. These conditions dispose of all the errors except that depending on the valve characteristic. The Osram DEP.240 has been found to be a satisfactory type of valve, but from the curves in Fig. 5 it may be seen that, if the leakage resistance R is not sufficiently high, there may be an appreciable error. For example, if V_3 be 50 volts and R be 120 megohms (corresponding to 150 microampere-degrees), this error is 0·8 per cent.

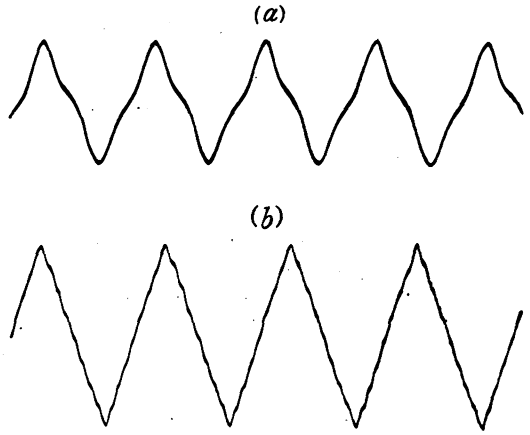

FIG. 6.

The results of some measurements at high voltages by the two methods described in this paper are compared later. In the voltage rectification method the values of C_1, C_2, etc., were C_1 = from 10 to 45 $\mu\mu$F, $C_2 = 0{\cdot}2\ \mu$F, $C_3 = 0{\cdot}2\ \mu$F, K = (about) 100 $\mu\mu$F, R = 6 000 megohms, and R' = 1 megohm.

Here the error involving the valve characteristic was only about 1 in 1 000. All the other errors together came to a similar amount.

THE MEASUREMENT OF PEAK VOLTAGE BY RECTIFICATION OF A CONDENSER CURRENT.

In this method of measuring peak voltage, which was described by Chubb and Fortescue,* the voltage is applied to a condenser in series with a pair of diode rectifiers connected in parallel. The rectifiers are so arranged that one of them carries the positive, and the other the negative portion of the current. A d.c. microammeter or galvanometer measures the current flowing through either of the rectifiers. The circuit is illustrated in Fig. 7, where the switch S may be connected to either terminal of the microammeter A.

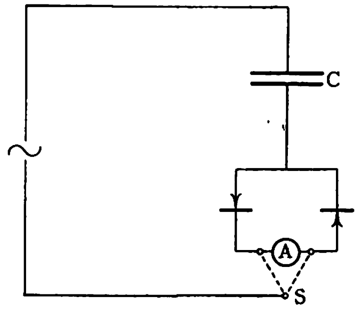

FIG. 7.

If the impedance of the rectifiers be small compared with that of the condenser the current i is given by the equation $i = C(de/dt)$, where e is the instantaneous circuit voltage and C is the capacity of the condenser.

Then in a cycle the total charge flowing through each rectifier is $\int idt = C\int de$, where the integration is carried out over that part of the cycle for which de/dt is positive in the case of one rectifier, and negative in the case of the other. For a sine wave of voltage in which $e = E \sin 2\pi ft$, f being the frequency, the charge flowing through each rectifier in a cycle is $2\pi fCE\int_{3/(4f)}^{1/(4f)} \cos 2\pi ft\,.\,dt$, which equals $2CE$. The mean current at a frequency f is consequently $2CEf$.

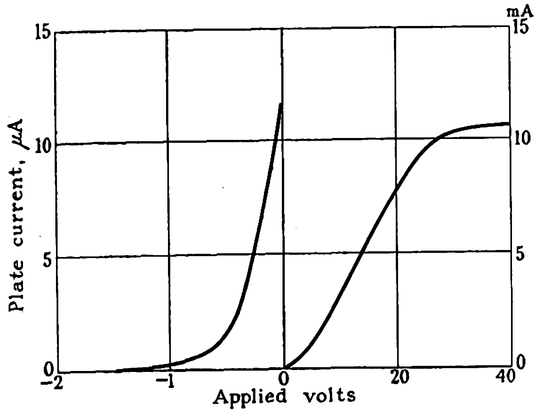

FIG. 8.—Characteristics of rectifying valves.

For a sine wave of voltage the method will give the true peak voltage provided that:—

(1) The impedance of the rectifier is negligible compared with that of the condenser.

(2) All the positive current passes through one rectifier and all the negative through the other.

(3) The measuring instrument (ammeter or galvanometer) correctly indicates the mean current.

The conditions (1) and (2) are controlled by the characteristics of the rectifying valves. These are illustrated by the curves in Fig. 8, where the current and voltage scales are magnified for negative values of applied voltage in order to reveal the point on the characteristic at which the valves were used. Three-electrode valves were used, and the grid and plate were connected together.

At the instant when the condenser current is zero, the voltage on the valve is zero, for which voltage the rectifier current is 11 μA. Consequently the valve will pass a quantity of electricity greater than that passed by the condenser. The error due to this can be reduced to negligible proportions by so arranging the circuit that at zero condenser-current the voltage on the valves shall be negative and not zero. For the present tests the connections to the filament circuits of the valves were made at points 1 volt negative with respect to the negative ends of the filaments.

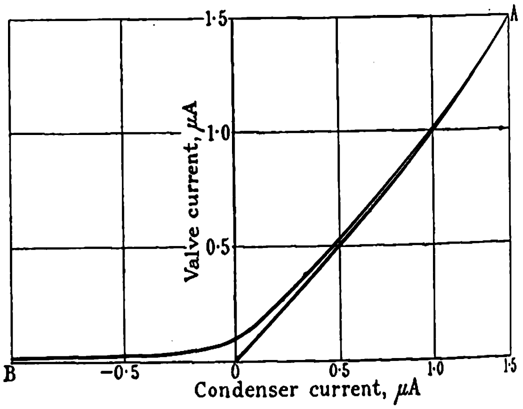

FIG. 9.—Curve showing relation between current through one valve and condenser current.

From the valve characteristic a curve showing the relation between the current through one valve and the condenser current can be derived. This is illustrated in Fig. 9. Condition (2) assumes that the relation is represented by the lines OA and OB. Only the region near zero condenser-current is drawn, for as the condenser current increases the excess of the valve current over the condenser current gets smaller. From a value of about 1 μA up to about 10 mA, which is the saturation current of the valve, the difference between the two is indistinguishable. The error introduced in the case of a sine wave of condenser current can be determined quantitatively as follows:—

Let $i = I \sin \theta$ represent the condenser current. When i is small

$$i = I\theta$$

---

* *Transactions of the American I.E.E.*, 1913, vol. 32, p. 739.

Let i_1 = the excess current through the galvanometer at any instant.

The total excess in a cycle = $\int i_1 d\theta$, where the integration is carried out over the cycle.

$$\int i_1 \,.\, d\theta = \frac{1}{I} \int i_1 \,.\, di$$

The value of $\int i_1 \,.\, di$ as determined from the valve characteristic was equal to 0·14 (microamperes)^2.

$$\text{The true quantity} = \int_0^\pi I \sin \theta d\theta = 2I.$$

Hence the error = $0 \cdot 14/(2I^2)$, where I is in microamperes.

For an error of 1 in 1 000, I equals 8·4 μA, which is equivalent to a mean current in the galvanometer of 2·7 μA, a low value which can easily be exceeded in practice. For example, 10^6 volts will supply, through 1 $\mu\mu$F, about 140 μA at 50 cycles.

The impedance of the rectifiers is of the order of 10^4 ohms, so that for a current of 200 μA the voltage-drop on the rectifiers is 2. As this is in quadrature with the voltage on the condenser, for a voltage of 50 on the latter the error due to the valve impedance is less than 1 in 1 000.

The microammeter used was a moving-coil instrument of the pointer type and was calibrated with direct current. A similar instrument was calibrated with rectified alternating-current by comparison with measurements made with a potentiometer and a differential galvanometer.* In no case did the calibration differ from that on direct current—even when the frequency was raised to 4 000 cycles per second—by more than 1 part in 1 000. Consequently condition (3) may be regarded as being accurately fulfilled. In some later measurements the current was measured on a potentiometer instead of the microammeter, in order to obtain greater sensitivity.

THE EFFECT OF WAVE-FORM.

Since the charge flowing through the rectifier equals $\int C \,.\, de$, where the integration is taken during the cycle when de/dt has one sign only (positive for one rectifier and negative for the other), the average current in the galvanometer for the wave-shape of applied voltage illustrated in Fig. 10 (*a*) would be proportional to $E_1 + E_2$, and for the wave-shape illustrated in Fig. 10 (*b*) it would be proportional to $E_1 + E_2 + E_1' + E_2'$. Therefore for wave-shapes having different positive and negative peaks this method would only give the average. For waves with subsidiary peaks, since the method gives only one relation between the quantities E_1, E_2, E_1', E_2', it will not avail to determine E_1 and E_2.

It is concluded that the method of measuring peak voltage by the valve rectification of a condenser current is satisfactory for all wave-shapes with the exception of (1) wave-shapes with different positive and negative maxima, and (2) wave-shapes with more than one peak in each half-cycle.

To ascertain whether the peak value of a given voltage wave can be determined by this method the wave-shape can be examined visually by means of oscillograms. The electrostatic oscillograph has been found useful for this purpose.

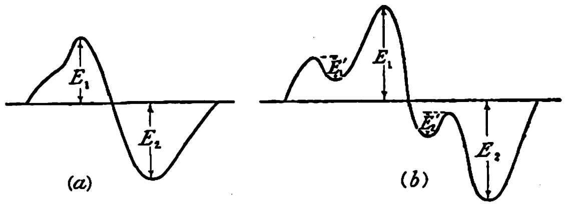

FIG. 10.—Wave-shapes of applied voltage.

COMPARISON OF RESULTS OBTAINED BY THE TWO METHODS.

Tests were made to compare the results obtained by the two methods described in the previous sections. The condenser used in the current rectification method constituted the high-voltage arm of the divider, so that any uncertainty in the absolute value of the capacity was common to the two methods. The apparatus was so arranged that by means of a switch the low-voltage plate of this condenser could be connected either to the low-voltage arm of the divider or to the current-rectifying apparatus. This connecting lead was shielded, and its capacity together with that of the electrostatic voltmeter across the low-voltage arm of the divider, etc., was taken into account in determining the capacity of this arm. The current in the current-rectification method was measured on a potentiometer.

The results obtained by the two methods are given in Table 5.

TABLE 5.

Capacity of high-voltage condenser	Capacity of low-voltage condenser	Peak voltage by:—	
		Voltage rectification	Current rectification
$\mu\mu$F	μF	kV	kV
45·30	0·2011	$213\cdot_{2}$	$213\cdot_{4}$
29·91	0·2011	$279\cdot_{0}$	$278\cdot_{5}$
25·51	0·2011	$426\cdot_{3}$	$426\cdot_{5}$
18·52	0·2011	$694\cdot_{5}$	$695\cdot_{0}$
10·07	0·2011	101_{9}	101_{9}
10·07	0·2011	118_{4}	118_{1}

Peak-condenser capacity = 0·2 μF.

Table 5 shows that the agreement between the methods is of the order of 0·2 per cent. This agreement is very satisfactory as important sources of error in the current rectification method would tend to make the reading high, whereas the errors in the other method would generally tend to make the reading low. It does not, however, necessarily signify a corresponding accuracy in the absolute values of the peak voltage measured, as the high-voltage condenser used was incompletely shielded and was affected by the stray capacitance to high-voltage conductors, etc., in the building.

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* G. W. BOWDLER: *Journal of Scientific Instruments*, 1930, vol. 7, p. 151.

CONCLUSION.

The result of the work shows that under suitable conditions and with proper precautions an accuracy of the order of 1 or 2 parts in 1 000 is obtainable in the measurement of peak voltages up to 10^6, by the rectification of voltage from a condenser divider or by the rectification of the charging current of a condenser.

The authors wish to thank Dr. E. H. Rayner, M.A., D.Sc., Member, for the interest which he has taken in the work.

DISCUSSION ON

"SUMMARY (TO 1925) OF EUROPEAN AND AMERICAN DATA ON INTERFERENCE BETWEEN POWER AND COMMUNICATION CIRCUITS.*

Mr. R. K. Honaman (*communicated*): In the discussion of acoustic shocks, notably on page 590 and again on page 599, it is pointed out that acoustic shock arises when only one of the two voltage discharge-gaps associated with a metallic circuit is operated by induction, or when one of the two discharge-gaps operates in advance of the other. While such a condition would undoubtedly result in acoustic shock, it would be of interest to point out that the occurrence of acoustic shock does not necessarily require this difference in time of initiation of the discharges on the two sides of the line. The protectors used on telephone lines in the United States are air discharge-gaps between carbon electrodes. Even if the discharge of these gaps takes place at the same instant—and in most cases this is true at least within an extremely small fraction of a second—nevertheless the discharge characteristics of the gaps on the two sides of the line are not symmetrical, that is, there is a difference in the impedance of the discharge path while currents are passing. This dissymmetry in the discharge impedances gives rise to the voltage between wires which most commonly causes acoustic shock. Inasmuch as this dissymmetry lasts during the entire interval while the discharge is taking place, the acoustic shock also lasts for the same interval. Contrary to a belief commonly held, the effect of this time on the intensity of acoustic shock is important. While the so-called "initial crack" is usually very severe, the prolonged effect of the shock through the interval while the gaps are discharging is also very important. Much effort has been expended in an endeavour to provide spark-gaps which would combine adequate protection for the circuits with features providing for symmetry of discharge of two units. It has not been found practicable, however, up to the present time to modify the gaps in any way to reduce substantially this dissymmetry in the discharge impedances, without at the same time making unjustifiable sacrifices in the protective characteristics of the over-voltage protectors.

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* E.R.A. Technical Report Ref. M/T3 (see p. 587).

PROCEEDINGS OF THE INSTITUTION.

797TH ORDINARY MEETING, 9TH JANUARY, 1930.

Colonel Sir Thomas F. Purves, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 19th December, 1929, were taken as read and were confirmed and signed.

The President announced that the Council had elected Sir Richard T. Glazebrook, K.C.B., D.Sc., F.R.S., Past-President, an Honorary Member of the Institution.

The following list of donors to the Library was taken as read, and the thanks of the meeting were accorded to the donors.

Donors to the Library.—American Institute of Electrical Engineers; American Telegraph and Telephone Co.; The Astronomer Royal; Messrs. Blackie and Son, Ltd.; D. J. Bolton, M.Sc.; British Engineering Standards Association; British Insulated Cables, Ltd.; Cable Research; Cambridge University Press; Canadian Engineering Standards Association; Central Electricity Board; Messrs. Crosby Lockwood and Son; Department of the Interior, Canada; A. T. Dover; Captain P. P. Eckersley; Electricity Commissioners; J. J. Fahie; The Fanfare Press; Franklin Institute; E. Garcke; B. Hague, D.Sc., Ph.D.; Industrial Transport Publications, Ltd.; Prof. A. E. Kennelly, D.Sc.; G. H. Lake; Librairie Payot et Cie; Lincoln Engineering Society; London and Home Counties Joint Electricity Authority; Messrs. P. Lund, Humphries and Co., Ltd.; Prof. E. Mallett, D.Sc.(Eng.); H. G. Massingham; Mines Department; Captain W. Morecombe, R.E., B.Sc.(Eng.), National Illumination Committee of Great Britain; W. H. Patchell; O. Pedersen; Messrs. Sir Isaac Pitman and Sons, Ltd.; St. G. Lane Fox Pitt; A. R. Rubin; Safety in Mines Research Board; Schweizerischer Elektrotechnischer Verein; E. Kilburn Scott; Siemens-Schuckert-Werke, G.m.b.H.; Prof. S. Parker Smith, D.Sc.; W. Hanneford Smith, F.R.S.E.; G. W. Stubbings, B.Sc.; Surveyor-General of India; Prof. W. M. Thornton, O.B.E., D.Sc., D.Eng.; S. Velander; Verein Deutscher Ingenieure-Verlag; R. A. Watson Watt; W. J. White; "World Power."

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

The President announced that, during the month of December, 35 donations and subscriptions to the Benevolent Fund had been received, amounting in the aggregate to £120. A vote of thanks was accorded to the donors.

A paper by Messrs. T. W. Ross and H. G. Bell, M.Sc. Tech., Associate Members, entitled "Recent Developments in the Protection of Three-Phase Transmission Lines and Feeders" (see page 801), was read and discussed.

The meeting terminated at 8 p.m. with a vote of thanks to the authors, which was moved by the President and carried with acclamation.

798TH ORDINARY MEETING, 23RD JANUARY, 1930.

Colonel Sir Thomas F. Purves, O.B.E., President, took the chair at 6 p.m.

The President having reported the death of Dr. S. Z. de Ferranti, F.R.S., Honorary Member, who held the office of President of the Institution from 1910 to 1912, and was awarded the Faraday Medal in 1924, the members rose in silence as a mark of their sympathy and regret.

The minutes of the Ordinary Meeting held on the 9th January, 1930, were taken as read and were confirmed and signed.

The President announced that the Council had made the ninth award of the Faraday Medal to Sir Ernest Rutherford, O.M., F.R.S.

Messrs. H. W. Hartridge and A. E. Kennard were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the President reported that the members whose names appeared on the lists (see page 522) had been duly elected and transferred.

A paper by Mr. L. C. Grant, Member, entitled "The Breaking Performance of High-Power Switchgear and of a New Form of Quenched-Arc Switch" (see page 1089), was read and discussed.

The meeting terminated at 7.50 p.m. with a vote of thanks to the author, which was moved by the President and carried with acclamation.

799TH ORDINARY MEETING, 13TH FEBRUARY, 1930.

Colonel Sir Thomas F. Purves, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 23rd January, 1930, were taken as read and were confirmed and signed.

Messrs. H. J. Neill and H. C. Wilkinson were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the President reported that the members whose names appeared on the lists (see page 655) had been duly elected and transferred.

The President announced that, during the month of January, 2 327 donations and subscriptions to the Benevolent Fund had been received, amounting in the aggregate to £1 344. A vote of thanks was accorded to the donors.

A paper by Prof. J. Hartmann, Dr.Tech., Member, entitled "The Jet-Wave Rectifier: the Experimental and Theoretical Basis of its Design" (see page 945), was read and discussed. The paper was illustrated by a cinematograph film.

The meeting terminated at 7.50 p.m. with a vote of thanks to the author, which was moved by the President and carried with acclamation.

INSTITUTION NOTES.

National Certificates and Diplomas in Electrical Engineering (England and Wales).

The undermentioned colleges have been approved under the scheme drawn up by the Board of Education and the Institution:—

Approved for Ordinary Grade Certificates (Senior Part-time Course).

West Ham Municipal College.

Approved for Higher Grade Certificates (Advanced Part-time Course).

Acton Technical Institute.
Bournemouth Municipal College.
West Ham Municipal College.

Graduateship Examination Results: May, 1930.

SUPPLEMENTARY LIST.*

Passed.

Aggarwala, H. (India).
Ashthana, R. P. (India).
Bedwell, A. V. (New Zealand).
Colaco, J. A. (India).
Dev, M. (India).
Dixon, G. S. (New Zealand).
Dodd, J. H. (Straits Settlements).
Hamid, M. A. (India).
Jarvis, J. R. (H.M.S. " Suffolk ").
Jones, R. T. (South Africa).
Khan, G. S. (India).
Khosla, D. S. N. (India).
Kinra, K. N. (India).
Macdougall, W. P. (New Zealand).
McKenzie, E. F. (New Zealand).
Raine, J. C. (South Africa).
Ray, F. R. (China).
Richardson, W. E. (South Africa).
Richmond, B. M. (New Zealand).
Robertson, E. S. (China).
Rogers, J. T. (China).
Row, L. F. (New Zealand).
Singh, Hardial (India).
Smith, J. A. (Australia).
Veitch, R. D. (New Zealand).

Passed Part I only.

Bhattacherjee, B. N. (India).
Kapur, V. P. (India).
Sarup, S. (India).
Sethi, H. A. (India).

Passed Part II only.

Wilkinson, A. B. (China).

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* See page 1086.

The Benevolent Fund.

On the last page of the cover of this issue of the *Journal* will be found particulars of certain publications, etc., which are on sale on behalf of the Fund.

Proceedings of the Meter and Instrument Section.

11TH MEETING OF THE METER AND INSTRUMENT SECTION, 21ST MARCH, 1930.

Mr. E. W. Hill, Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 7th March, 1930, were taken as read and were confirmed and signed.

The Chairman drew the attention of the members to the arrangements which had been made for the holding of a Summer Meeting at Leamington Spa on the 24th May.

An informal discussion then took place, the subjects being as follows:—

(1) " To Meter or not to Meter " (opened by Mr. A. J. Gibbons).
(2) " Whether or not Prepayment Meters should be Earthed " (opened by Mr. C. B. Green).
(3) " Whether or not Prepayment Meters should be Stamped and Sealed " (opened by Mr. W. Lawson).
(4) " The Use of 1-amp. Secondaries in Current Transformers in special circumstances, as against 5-amp. Secondaries " (opened by Mr. E. Fawssett).
(5) " Formula for the Merit-Factor of a Meter " (opened by Mr. G. F. Shotter).
(6) The Chairman also raised two minor points which had been submitted in writing by Mr. S. Garbutt.

The meeting terminated at 9.42 p.m. with a vote of thanks to those members who had introduced the subjects for discussion.

12TH MEETING OF THE METER AND INSTRUMENT SECTION, 4TH APRIL, 1930.

Mr. E. W. Hill, Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 21st March, 1930, were taken as read and were confirmed and signed.

A paper by Messrs. E. H. Rayner, M.A., Sc.D., Member, W. G. Standring, M.A., R. Davis, M.Sc., and G. W. Bowdler, M.Sc., entitled " Low Power-Factor Measurements at High Voltages " (see page 1132), was read and discussed.

The meeting terminated at 9.8 p.m. with a vote of thanks to the authors, which was moved by the Chairman and carried with acclamation.

THE STEAM AND ELECTRIC POWER PLANT OF IMPERIAL CHEMICAL INDUSTRIES, LTD., AT BILLINGHAM.

By H. A. Humphrey, Member, D. M. Buist, Member, and J. W. Bansall, Associate Member.

(*Paper first received* 18*th November*, 1929, *and in final form* 29*th January*, 1930; *read before* The Institution 13*th March*, *before the* North-Eastern Centre 24*th March*, *before the* North Midland Centre 25*th March*, *before the* North-Western Centre 1*st April*, *before the* Tees-side Sub-Centre 2*nd April*, *before the* Scottish Centre 8*th April*, *and before the* South Midland Centre 14*th April*, 1930.)

Summary.

This paper describes a large pulverized-fuel, high-pressure, high-temperature, industrial power plant erected by Imperial Chemical Industries, Ltd., for the supply of steam and electrical energy to the Billingham-on-Tees factory of Synthetic Ammonia and Nitrates, Ltd.

Apart from its size, this plant possesses the following features, and these features alone are described, all reference to standard boiler and power plant practice being omitted wherever possible:—

(1) A maximum pressure of 800 lb. per sq. in. gauge and a maximum temperature of 856° F.
(2) The world's largest high-pressure pulverized-fuel boiler plant, containing special constructional features for the high pressure and temperature.
(3) An unusually large distillation plant.
(4) A 7-stage feed-heating system, with feed-pumps specially designed for high pressure and temperature.
(5) High-pressure pass-out turbines of unique design.
(6) The first system of its kind of automatic frequency control, automatic steam-pressure control, and automatic feed-pump regulation, together with automatic synchronizing.
(7) Unusual lay-out features for the accommodation of pipework and cables.

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Introduction.

The conditions governing the design of the power plant described in this paper differ essentially from those relating to a public electricity supply station.

The extension programme of Synthetic Ammonia and Nitrates, Ltd., at Billingham, called for 6 930 tonnes * of steam per day delivered for process purposes, and 37 500 kW distributed as electrical energy to the works. The quantity of steam in the first item is approximately double the amount of steam required to generate the electrical energy of the second item, and so the boiler-plant capacity is three times that of a purely electric power station.

Then again, the load factor of a chemical works approaches closely to 100 per cent, and continuity of supply is of the utmost importance. A cessation of power supply not only causes loss of output but disorganizes the steady conditions of temperatures and pressures upon the maintenance of which satisfactory operation depends throughout a very complicated process. The power station, therefore, must have sufficient stand-by plant and means of bringing such plant rapidly into operation, whilst, further, the lay-out, methods of control, size of units, etc., must all be considered on the lines of "safety first."

In designing a plant for an annual output as great as that of the largest electricity station in the country, great attention must be paid to all possibilities for securing economy in generating costs. The balance has to be struck between simplicity and reliability on the one side, and maximum attainable economy on the other. Unproved designs involving apparatus of an experimental nature had to be avoided, and the consulting engineer had to steer his way through some rather conflicting considerations in order to obtain the best *commercial* results.

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* One tonne = 1 000 kg = 2 204 lb.

Another matter influencing design was the existence of a large powdered-fuel-fired boiler plant and also the fact that a contract for a bulk supply at 11 000 volts, 40 periods, from the adjacent North Tees power station continues until 1941.

(*a*) *Boiler Plant.*—The existing boiler plant provides the steam used in the factory at 290 lb. absolute * and 653° F., and the necessity of paralleling with these conditions made their adoption for the new plant almost imperative. The first problem, therefore, was how best to raise steam at some higher pressure so that after some of its energy had been converted to electrical energy it could be passed on as steam to process. Calculations showed that if steam were raised at such a pressure that it entered the primary turbines at 645 lb. per sq. in. and 833° F. its expansion down to 290 lb. would provide steam at 653° F., these being the steam conditions of the existing boiler plant.

A study of the superheater problem showed that, to gain the economy due to high velocity of flow in the superheater tubes, a large resistance pressure-drop had to be faced, and the normal working pressure at the boilers therefore became 715 lb. and was finally fixed at 815 lb. as a maximum.

By adopting still higher pressures a slightly greater calculated efficiency would have been possible, but in view of the fact that 856° F. was considered to be the highest safe temperature for ordinary steel superheaters, and that such high temperatures have a greater influence on economy than super-high pressures, any temptation to adopt still higher pressures was readily rejected. Especially was such a decision made easy because a pressure of 1 200 lb. per sq. in., for example, would have entailed reheating the steam after expansion, in order to reach existing boiler-plant conditions, and the small additional economy was not worth the added complication and expense thus involved. Further, we have yet to learn a great deal about creep stresses at 856° F., and such stresses are proportional to pressure. Considerations of safety after prolonged use therefore suggested the wisdom of not exceeding the 815 lb. maximum boiler pressure adopted.

High-pressure boilers must have distilled-water feed. Unfortunately, only 60 per cent of the steam would be condensed and returned from process, and so 2 512 tonnes per day of raw water, obtained from Billingham Beck, had to be distilled and the distillate added to the "make-up" feed. This involved the erection of an unusually large distillation plant, with its attendant de-aerators.

(*b*) *Turbo-Alternators.*—Careful consideration of the possible degree of economy to be obtained by progressive feed-heating led to the adoption of separate feed-heating turbines from which the steam is bled to heat the feed water. Here, again, a commercial maximum economy, rather than a theoretical maximum, was aimed at, and no attempt was made to bleed the primary turbines. These unusual pieces of apparatus were advisedly kept simple and comparatively small, and the consulting engineer insisted, in the interests of flexibility, on their being mechanically independent of other units.

By passing all the steam required as such, plus that required for conversion to electrical energy, through two primary turbines, 23 800 kW would be obtained, so that two units of 12 500 kW each would provide the working units and one was to be added as a spare. A corresponding set of feed-heating turbines would give 9 500 kW output for two units working, and these were fixed at 6 000 kW each on the generator side.

Lastly, condensing sets had to be provided because the proportion of steam energy to electrical energy distributed to the works was liable to vary, and condensing sets were necessary to meet such variation within the required limits and to make up the balance of the electrical output. One working condensing set to produce 10 200 kW would meet the then known conditions, another machine being kept as spare. These were made capable of 12 500 kW each in view of unknown requirements, and provision was made for a third set, should this be required in the future.

Naturally, some complicated calculations were involved in correlating the output and input of all the plant units, and in the end the steam to be raised by the new boilers was found to be 11 700 tonnes per day, and the electrical energy required was augmented to 43 500 kW in order to cover all the internal requirements of the plant plus the outside load.

(*c*) *Costs.*—In granting the authors permission to read this paper, the directors of Imperial Chemical Industries, Ltd., have reserved from publication all questions of cost, but it may be stated that the estimated cost of electric energy at the busbars of the station is well below the unit cost of any electric generating station in the world depending on coal as fuel. This is due to the use of high-pressure and high-temperature steam, to the use of primary turbines passing a greater quantity of steam than would be available in an ordinary central station, to the low cost of coal in the locality, to the high load factor, to the abundant supply of cooling water, and to the many economies which have been introduced into the designs.

(*d*) *Erection.*—The station was erected in record time. Tenders were invited in December 1927, contracts were placed in February 1928, excavations were commenced in May 1928 and by February 1929 the station was erected with sufficient plant to commence operation and give an external supply to the factory.

(*e*) *Lay-out.*—The general lay-out of the power plant was the subject of quick decisions, made even before contracts were placed and adhered to during the subsequent settlement of details with the main contractors. In reviewing the lay-out now that the plant is built, no radical improvement therein can be suggested. The governing decisions were:—

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* Except where otherwise stated, all subsequent pressures mentioned in this paper are absolute pressures.

(1) To dispose the plant so that the flow from boilers to high-pressure turbines, thence to the feed-heating and the distillation plants and finally back to the boilers, constituted a simple ring with a tee-off to the condensing sets and one to the factory for process purposes.

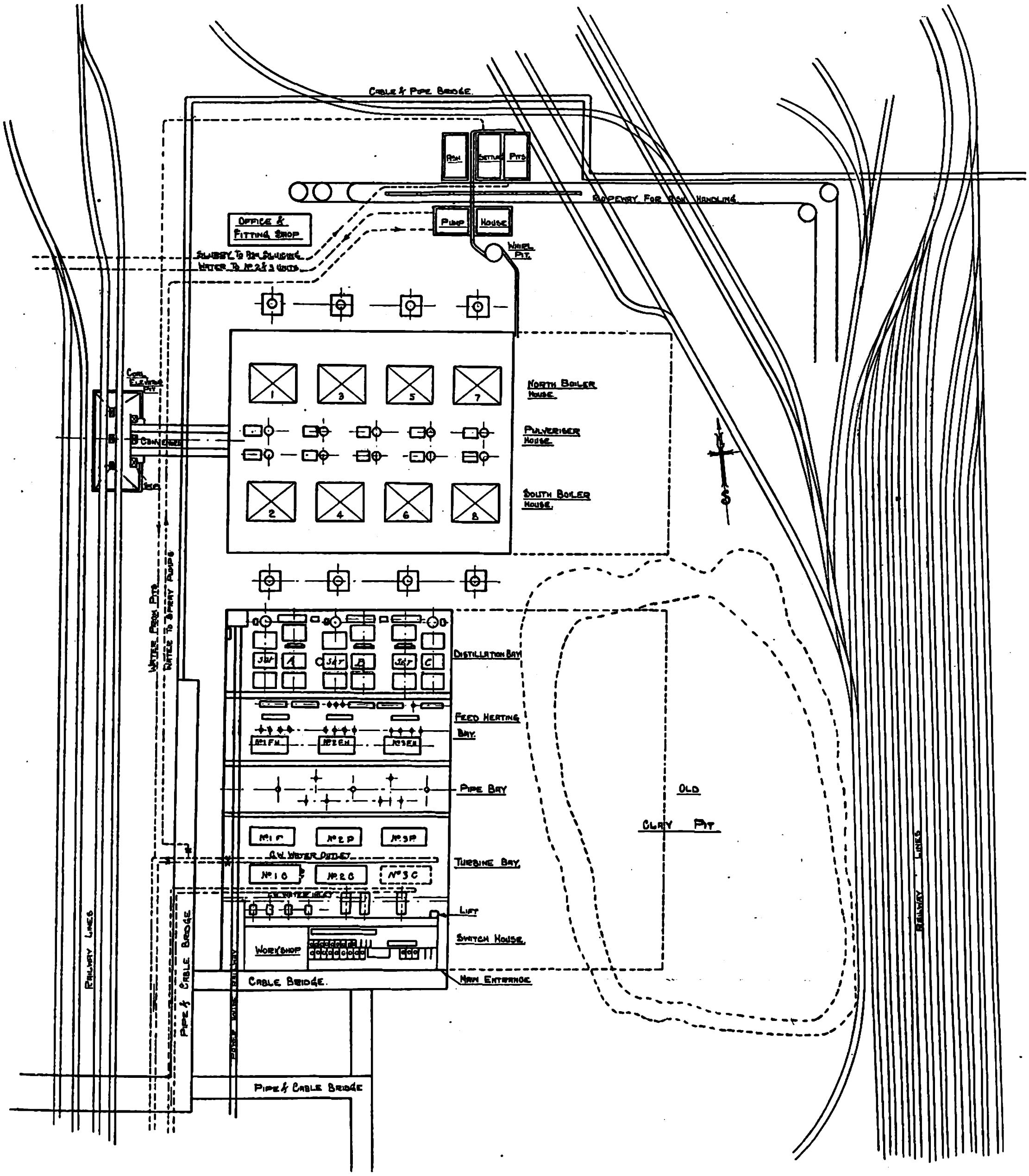

Cable & Pipe Bridge.
Ash
Settling
Pits
Ropeway for Ash Handling
Office & Fitting Shop
Pump
House
Whirl Pit.
Sludge To Ash Sluicing
Water To Nos. 2 & 3 Units
Coal Elevator Pit
Conveyor
North Boiler House.
Pulveriser House.
South Boiler House.
1
3
5
7
2
4
6
8
N
S
Water From Pits
Water To Spray Pumps
Distillation Bay
A
B
C
Feed Heating Bay.
No. 1 F.H.
No. 2 F.H.
No. 3 F.H.
Pipe Bay
No. 1 P
No. 2 P
No. 3 P
C.W. Water Outlet
Turbine Bay.
No. 1 C
No. 2 C
No. 3 C
Lift
Switch House.
Workshop
Cable Bridge.
Main Entrance
Pipe & Cable Bridge
Old Clay Pit
Railway Lines
Railway Lines
Pipe & Cable Bridge

Fig. 1.—Site plan.

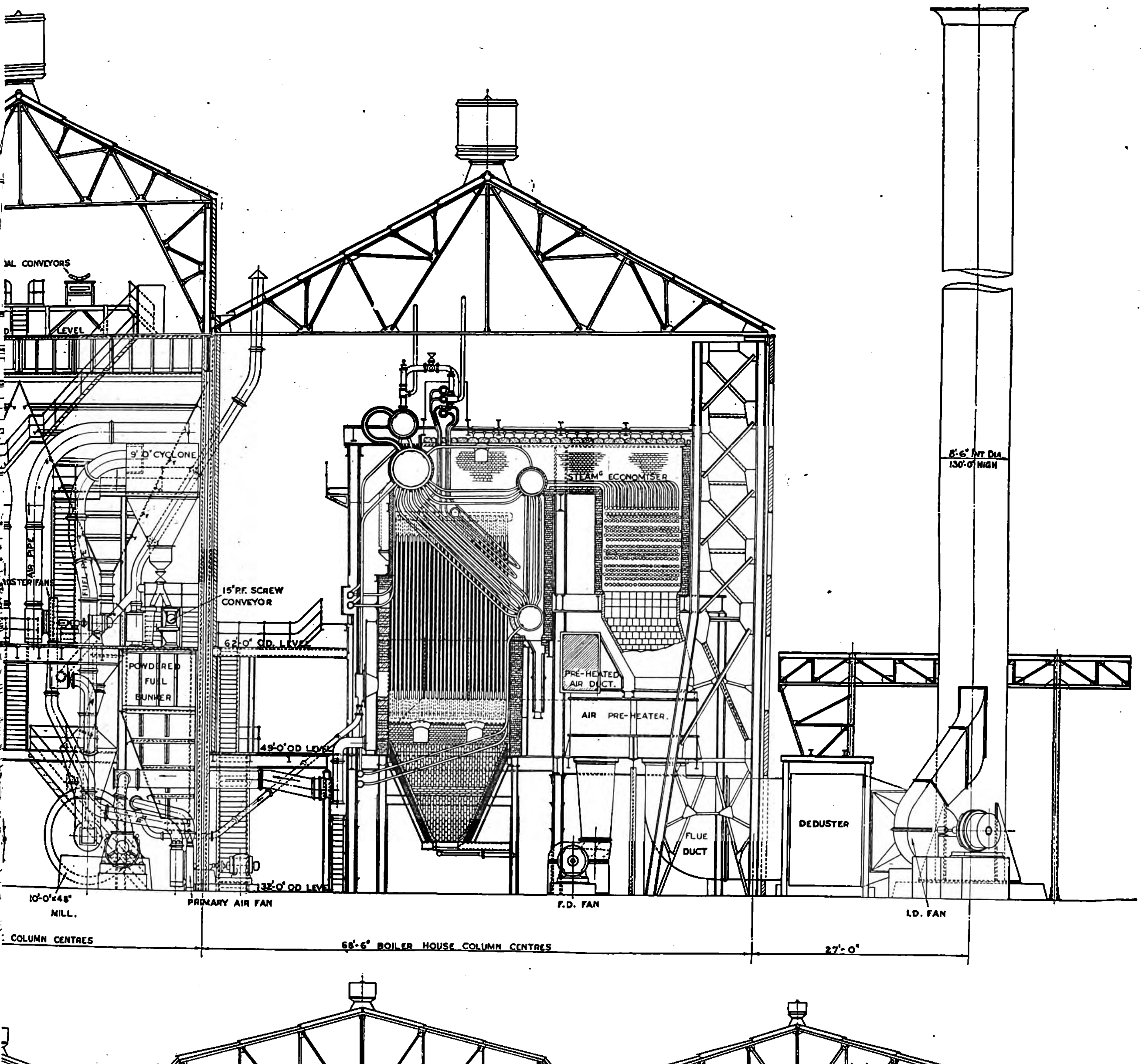
(2) To make the distillation and feed-heating bays duplicates in height, width and design of the turbine and switch bays respectively.

(3) To keep all large sets in one bay under a 40-ton crane.

(4) To place the feed-heating sets with all heaters and pumps in one bay, under a 20-ton crane, this bay to adjoin the distillation bay and both bays to be next to the boiler plant.

(5) To place the condensing sets at that end of the plant where the 48-in. circulating water inlet and outlet pipes could most conveniently and cheaply be brought into the building.

(6) To include a separate bay for the accommodation of high-pressure steam receivers, de-superheaters, reducing valves, all interconnecting pipework and valves (in short a control centre, analogous to an electrical control room) for all high-pressure and low-pressure steam distribution.



AL CONVEYORS
LEVEL
9'-0" CYCLONE
AIR PIPE
FUEL PIPE
USTER FANS
15" P.F. SCREW CONVEYOR
62'-0" O.D. LEVEL
POWDERED FUEL BUNKER
49'-0" O.D. LEVEL
13'-0" O.D. LEVEL
10'-0" × 48" MILL.
PRIMARY AIR FAN
STEAM ECONOMISER
PRE-HEATED AIR DUCT
AIR PRE-HEATER
F.D. FAN
FLUE DUCT
DEDUSTER
I.D. FAN
8'-6" INT DIA. 130'-0" HIGH
COLUMN CENTRES
68'-6" BOILER HOUSE COLUMN CENTRES
27'-0"
BAY
TURBINE BAY
SWITCH HOUSE

FIG. 2 (*cont.*).

(7) To provide on the electrical side, as on the steam side, a separate bay in the switch house for all cables, consisting of a vertical gallery fed from the basement and feeding two horizontal steel-floored races under the main switchgear and under the control room respectively.

(8) To place the majority of the generating plant next to the switch house for convenience and economy of heavy cable runs.

(9) To place the switch house external to the main buildings to facilitate exit of the large number of feeders; and, for the same reason, to place the main switchgear on a level with the cable bridges.

The above short introduction gives an outline of the plant, the details of which the engineering staff of Synthetic Ammonia and Nitrates, Ltd., had to work out with the co-operation of the contractors. The great care applied to the many problems involved renders the detailed solutions worthy of study, and it is felt that the members of the Institution would welcome, as a model, the most complete data ever published concerning a modern power station.

This preliminary review will enable members to appreciate the leading features now to be described in detail.

Section (1). GENERAL ARRANGEMENT OF THE PLANT.

(*a*) *General Lay-out.*—The power station is situated adjacent to the River Tees, from which an ample supply of cooling water is obtained from a large pump house on the riverside containing four 36-in. pumps driven by 2 200-b.h.p. 6 600-volt motors. This pump house is one of two built for the general factory supply. Excellent railway facilities for the supply of coal were already in existence for the general requirements of the factory. As will be seen from the site plan (Fig. 1) the boiler and power plants are separated by a chimney bay. The boiler plant consists of a north and a south boiler house between which lies the pulverizer house, the general arrangement being clearly shown in the end elevation in Fig. 2.

The power plant is accommodated in the following five bays: Distillation bay; feed-heating bay; pipe bay; turbine bay; and switch house. The last named has several floors and accommodates house transformers, motor-convertors, reactances, switchgear, control room and various offices. The power plant is further divided into three complete units, which are interconnected at various points on the steam and on the electrical side, each unit extending across the entire five bays. The general arrangement of the power plant will be seen from the end elevation in Fig. 2, which also shows the type of steel structure employed, the construction being similar to that of the other plant buildings throughout the factory. The structural steelwork throughout both plants weighs 6 500 tons.

(*b*) *Boiler and Pulverizer Houses.*—The schematic arrangement of the boiler and pulverizer plants is depicted diagrammatically in Fig. 3. The north and south boiler houses each contain four multi-drum boilers normally generating 215 000 lb. of steam per hour at 715 lb. per sq. in. The intervening pulverizer house contains six 15-ton roller mills and four 15-ton ball mills together with their attendant bunkers, conveyors, cyclones, exhausters, feeders, etc.

Raw coal is brought in by rail and dropped into underground bunkers from which it is raised by skip hoists to overhead belt conveyors which carry it past magnetic separators to overhead steel bunkers (lined with concrete applied by means of compressed air) in the pulverizer house. The raw coal falls through chutes to the weighers and from there to the mill hoppers.

From the mills the pulverized coal is carried to an overhead cyclone separator by an air stream circulated by exhauster fans. From the cyclones the pulverized coal drops through rotary air locks to screw conveyors, which distribute it to the pulverized-coal bunkers of which there is one to each boiler. From these bunkers the powder passes through feeders driven by variable-speed motors, from which it is picked up by the air stream from the primary air fans and fed to the burners. The air for combustion is supplied by forced-draught fans, being first of all brought to a temperature of about 500° F. by air preheaters.

The flue gas is discharged into the stacks by induced-draught fans which draw the gas through economizers, air preheaters and de-dusters, the grit, together with the ash from the combustion chamber, being discharged into ash sluices along which it is washed into a slurry whirl pit. A centrifugal slurry pump raises the ash and water to an ash settling pit where the water drains off from the ash. An overhead grab raises the ash and drops it through a chute into buckets on an aerial ropeway by which the ash is conveyed to barges at the riverside for dumping at sea.

(*c*) *Distillation Bay.*—The distillation bay (Fig. 4) comprises three complete sets of feed-heating distillation plants, two of which are normally working, the remaining set being spare.

Each set consists of a range of four evaporators, a feed-water heater (2nd stage feed-heater), a raw-water heater, a condensate de-aerator (1st stage feed-heater), a raw-water de-aerator, an air ejector and four flash boxes. The steam-and-water-flow through the distillation plant will be seen from the detailed flow sheet (Fig. 13). The three condensate storage tanks and the two raw-water storage tanks are mounted on the north wall of the distillation bay, the reserve in the former being sufficient to maintain the normal feed-water supply for nearly three hours if one of the distillation plants should fail.

(*d*) *Feed-Heating Bay.*—The feed-heating bay (Fig. 5) contains the three 6 000-kW feed-heating turbines, exhausting into their respective distillation plants, together with their attendant feed-heaters, feed-pumps and extraction pumps, arranged on the separate drain-pump system. Each set of bleeder heaters (3rd-, 4th-, 5th- and 6th-stage feed-heaters) is adjacent to its turbine to facilitate operation. The three final-stage heaters are grouped together in line with the final boiler feed-pumps, whilst the intermediate feed-pumps are accommodated in a line between the latter and the feed-heating turbines.

The emergency heater and feed-pumps are situated

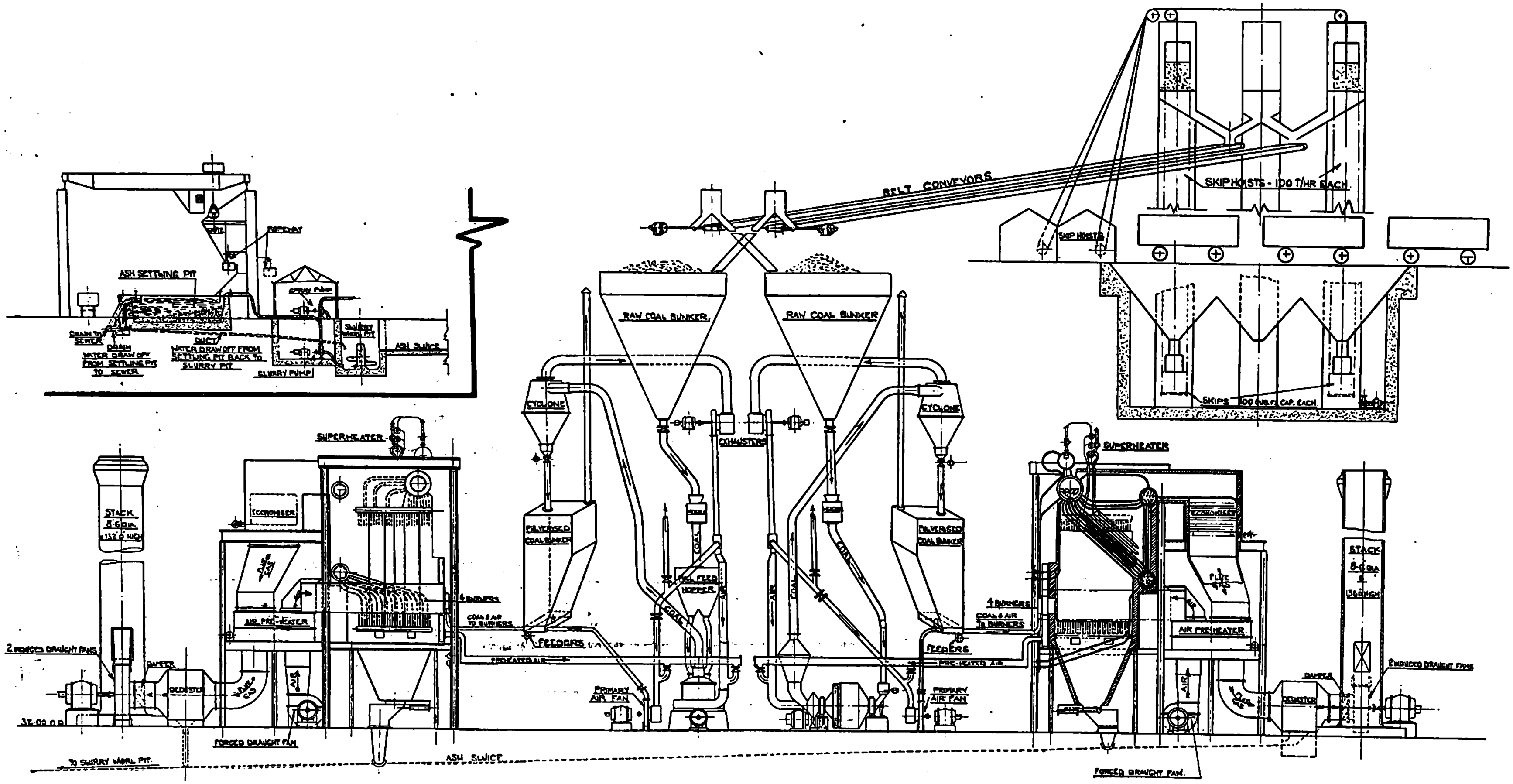

ASH SETTLING PIT
ROPEWAY
SPRAY PUMP
SLURRY WHIRL PIT
ASH SLUICE
DRAIN TO SEWER
DRAIN
WATER DRAW OFF FROM SETTLING PIT TO SEWER
DUCT
WATER DRAW OFF FROM SETTLING PIT BACK TO SLURRY PIT
SLURRY PUMP
BELT CONVEYORS
SKIP HOISTS - 100 T/HR EACH
SKIP HOISTS
SKIPS 100 CUB. FT. CAP. EACH
RAW COAL BUNKER
RAW COAL BUNKER
CYCLONE
CYCLONE
EXHAUSTERS
PULVERISED COAL BUNKER
PULVERISED COAL BUNKER
COAL
AIR
MILL FEED HOPPER
FEEDERS
FEEDERS
PRE-HEATED AIR
PRE-HEATED AIR
PRIMARY AIR FAN
PRIMARY AIR FAN
COAL & AIR TO BURNERS
COAL & AIR TO BURNERS
4 BURNERS
4 BURNERS
SUPERHEATER
SUPERHEATER
ECONOMISER
ECONOMISER
AIR PRE-HEATER
AIR PRE-HEATER
FLUE GAS
AIR
FORCED DRAUGHT FAN
FORCED DRAUGHT FAN
DEDUSTER
DEDUSTER
DAMPER
DAMPER
2 INDUCED DRAUGHT FANS
2 INDUCED DRAUGHT FANS
STACK 8-6 DIA. 132-0 HIGH
STACK 8-6 DIA. & 130-0 HIGH
32-00 O.D.
TO SLURRY WHIRL PIT
ASH SLUICE

Fig. 3.—Pictorial flow-sheet of boiler plant.

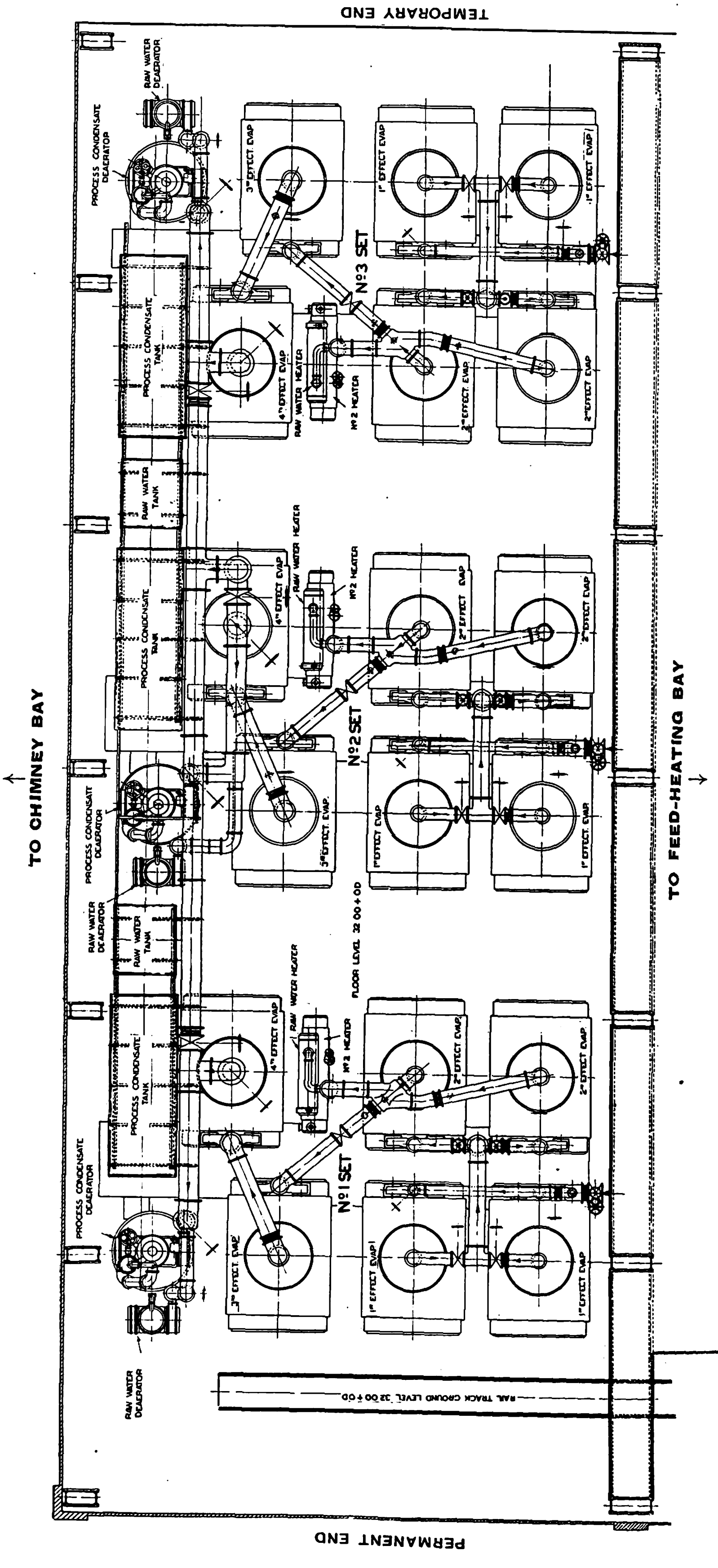

TEMPORARY END
PERMANENT END
TO CHIMNEY BAY
TO FEED-HEATING BAY
RAW WATER DEAERATOR
PROCESS CONDENSATE DEAERATOR
PROCESS CONDENSATE TANK
RAW WATER TANK
3RD EFFECT EVAP
4TH EFFECT EVAP
1ST EFFECT EVAP
2ND EFFECT EVAP
RAW WATER HEATER
Nº2 HEATER
Nº3 SET
Nº2 SET
Nº1 SET
FLOOR LEVEL 32 00 + 0D
RAIL TRACK GROUND LEVEL 32 00 + 0D

FIG. 4.—Plan of distillation bay.

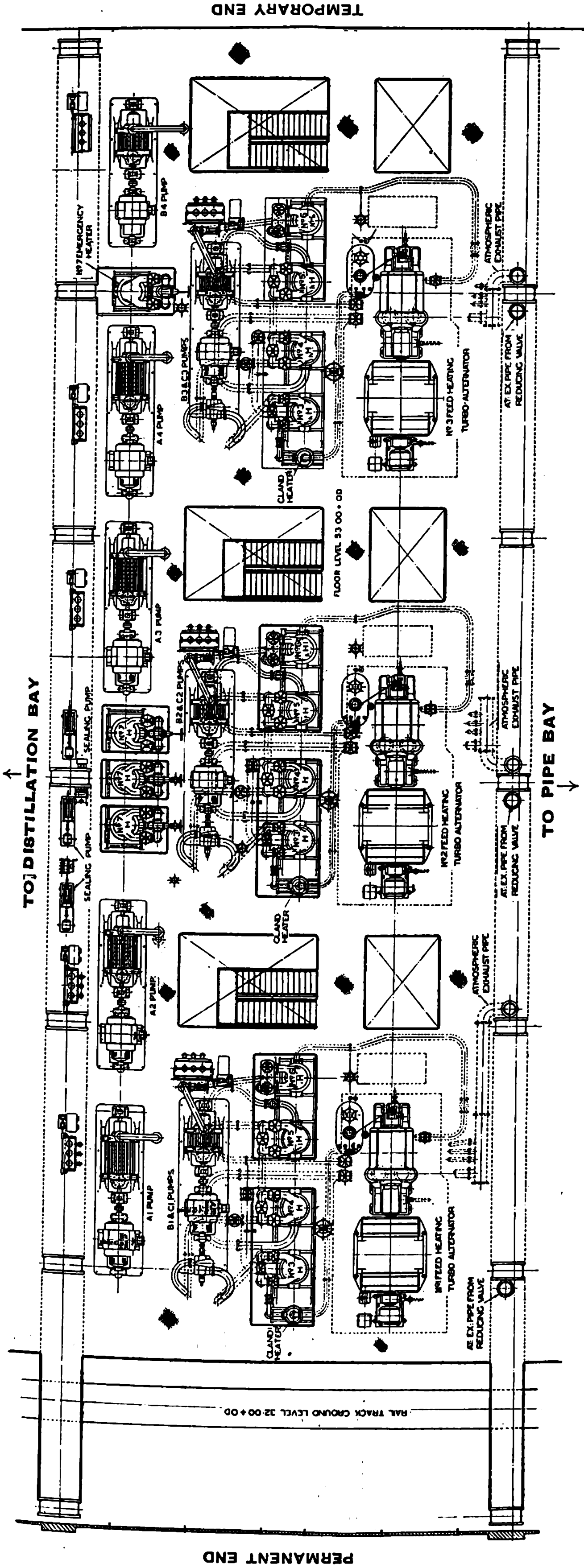

TEMPORARY END
PERMANENT END
TO DISTILLATION BAY
TO PIPE BAY
No 2 EMERGENCY HEATER
B4 PUMP
A4 PUMP
A3 PUMP
A2 PUMP
A1 PUMP
B3 & C3 PUMPS
B2 & C2 PUMPS
B1 & C1 PUMPS
SEALING PUMP
SEALING PUMP
GLAND HEATER
GLAND HEATER
GLAND HEATER
No 3 FEED HEATING TURBO-ALTERNATOR
No 2 FEED HEATING TURBO ALTERNATOR
No 1 FEED HEATING TURBO ALTERNATOR
ATMOSPHERIC EXHAUST PIPE
AT. EX. PIPE FROM REDUCING VALVE
FLOOR LEVEL 53·00+00
RAIL TRACK GROUND LEVEL 32·00+00

FIG. 5.—Plan of feed-heating bay.

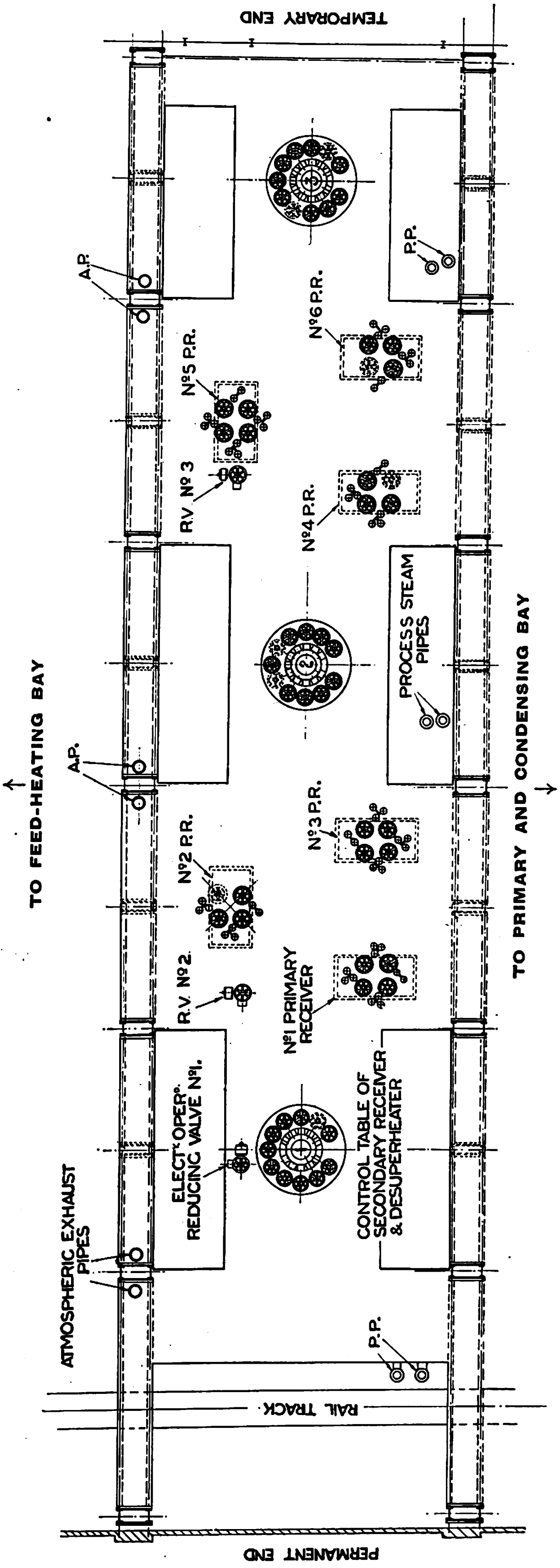

TEMPORARY END
PERMANENT END
TO FEED-HEATING BAY
TO PRIMARY AND CONDENSING BAY
A.P.
A.P.
P.P.
P.P.
P.P.
No 6 P.R.
No 5 P.R.
RV No 3
No 4 P.R.
PROCESS STEAM PIPES
No 3 P.R.
No 2 P.R.
RV No 2
No 1 PRIMARY RECEIVER
ELECTo OPERo REDUCING VALVE No 1
CONTROL TABLE OF SECONDARY RECEIVER & DESUPERHEATER
ATMOSPHERIC EXHAUST PIPES
RAIL TRACK

FIG. 6.—Plan of pipe bay.

in the north-east corner of the distillation bay, from which the auxiliary boiler feed-line passes across the distillation bay to the boiler plant. All heater extraction pumps are on the ground floor below their respective heaters.

The sealing pumps, supplying gland-sealing water to all pumps in the distillation and feed-heating bays, are also on the turbine floor behind the centre main feed-pump (see Fig. 5).

(*e*) *Pipe Bay*.—Between the feed-heating and the turbine bays is situated the pipe bay (Fig. 6) which contains the high-pressure (primary) receivers, desuperheaters (secondary receivers) and reducing valves, together with the entire collecting and distributing system of high- and intermediate-pressure pipework.

The accommodation of the pipework in one bay around a symmetrically placed receiver system facilitates control of the steam flow by means of valve tables mounted on the turbine floor-level, immediately above the receivers. The lay-out of the pipework associated with this compact arrangement gives complete flexibility, as will be seen from Fig. 16.

All valves are provided with extended spindles for hand operation, with the exception of the three motor-operated reducing valves on the turbine floor-level. The latter can also be operated by hand.

(*f*) *Turbine Bay*.—This bay (Fig. 7) contains the main generating units—three 12 500-kW high-pressure, pass-out, or primary, turbines and two 12 500-kW intermediate-pressure condensing turbines. Provision has been made for a third condensing machine should this be required at a future date. The turbines run at 2 400 r.p.m. and are direct-coupled to 13 750-kVA alternators generating 3-phase, 40-cycle current at a pressure of 6 600 volts.

The condensing machines are provided with duplicate extraction pumps driven by a.c. and d.c. motors respectively, the former operating normally. In the event of a failure of the a.c. supply the d.c. motor-driven pump automatically starts up.

(*g*) *Switch House*.—As will be seen from Fig. 2, the switch house has a top floor, above the turbine floor-level, which accommodates the control room, battery room, battery booster room, model room and various offices. The general arrangement of this floor is shown in Fig. 8.

The first floor (Fig. 9) houses all the main e.h.t. switchgear and the auxiliary 400-volt a.c. and 460-volt d.c. switchgear. These two boards are both arranged for hand operation and are accordingly placed in a gallery facing the main turbine room, immediately over the transformers and convertors respectively.

On the ground floor (Fig. 10) are placed the four 1 500-kVA station transformers, from which the 400-volt auxiliary a.c. supply is derived; the three 2 000-kW motor-convertors, which provide the 460-volt auxiliary d.c. supply; and the bus-section reactors, station-feeder reactors and the auxiliary e.h.t. switchgear and neutral-earthing switchgear. Provision has also been made for a workshop on this floor, adjacent to the railway entrance to the building.

Below the ground floor there is a cable basement extending underneath the main turbine bay and terminating in three cable ducts leading under the pipe bay to the feed-heating turbo-alternators. In addition, vertical and horizontal cable galleries are provided in the switch house which allow of clean unimpeded cable-runs to the various portions of the switchgear and to the control room. This unorthodox feature is clearly revealed in Fig. 2. The extra building cost incurred was amply recovered in the consequent facility of erection, quite apart from the simplicity and the neatness of the runs and the accessibility afforded for speedy repairs. Furthermore, it permitted the erection of a bay the exact duplicate of the feed-heating bay in width, height and design of structural steelwork.

Section (2). FLOW SHEET.

Fig. 11 illustrates in simple diagrammatic form the feed-heating cycle and steam distribution.

The general heat-flow in the boiler and power plants is illustrated diagrammatically in Fig. 12, while the complete quantitative flow sheet is given in detail in Fig. 13.

Steam is normally generated at a pressure of 715 lb. per sq. in., the maximum working pressure being 815 lb. per sq. in. and the temperature 856° F. On leaving the superheaters the steam passes into the high-pressure steam receivers (primary receivers), where its pressure is in the neighbourhood of 650 lb. per sq. in. As will be described later, in Section 3 (*b*), these receivers function as equalizers and distributors.

The high-pressure steam from the primary receiver system is distributed to the reducing valves and the primary turbines, being admitted to the latter at 645 lb. per sq. in. and 833° F. Under normal operating conditions the reducing valves remain closed while each of the two high-pressure turbines running takes some 244 tonnes of steam per hour and generates 11 900 kW at an overall efficiency of 74 per cent. Steam exhausts at 290 lb. per sq. in. from the primary turbines into the de-superheaters or secondary receivers where the superheat is maintained constant at 243° F., corresponding to a total temperature of 653° F., by means of a thermally-regulated water spray. Under certain conditions of steam load and electrical load, steam is automatically diverted from the high-pressure turbines and passes from the primary to the secondary steam receiver system through one or more of the reducing valves. From the secondary receiver system the steam is distributed to the following points: Process plants; condensing turbines; feed-heating turbines; 7th-stage feed-water heaters; and distillation plant air ejectors and soot-blowers.

The process plants normally consume 6 930 tonnes of steam per day, which represents very nearly 60 per cent of the boiler output. Of this quantity 3 994 tonnes per day are returned in the form of condensate to the feed-water storage tanks in the power station, so that the net consumption to be replaced by distillate amounts to 2 936 tonnes per day, or 42 per cent of the total quantity delivered by the three outgoing steam mains.

The condensing turbine under normal operating conditions takes 1 130 tonnes of steam per day and gives an output of 10 200 kW at an overall efficiency

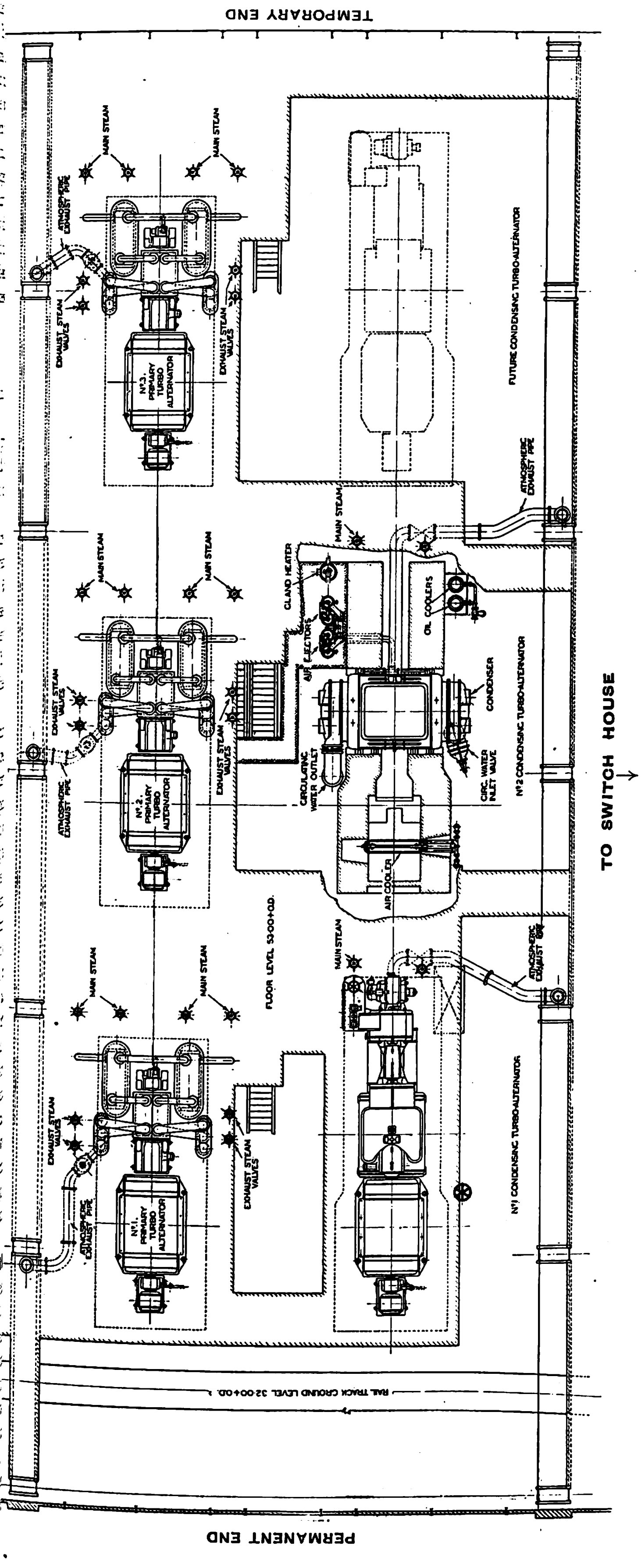

TEMPORARY END
PERMANENT END
MAIN STEAM
ATMOSPHERIC EXHAUST PIPE
EXHAUST STEAM VALVES
Nº 3. PRIMARY TURBO ALTERNATOR
Nº 2. PRIMARY TURBO ALTERNATOR
Nº 1. PRIMARY TURBO ALTERNATOR
FUTURE CONDENSING TURBO-ALTERNATOR
Nº 2 CONDENSING TURBO-ALTERNATOR
Nº 1 CONDENSING TURBO-ALTERNATOR
GLAND HEATER
AIR EJECTOR
OIL COOLERS
CONDENSER
CIRC. WATER INLET VALVE
CIRCULATING WATER OUTLET
AIR COOLER
FLOOR LEVEL 53·00+O.D.
RAIL TRACK GROUND LEVEL 32·00+O.D.
TO SWITCH HOUSE

FIG. 7.—Plan of turbine bay.

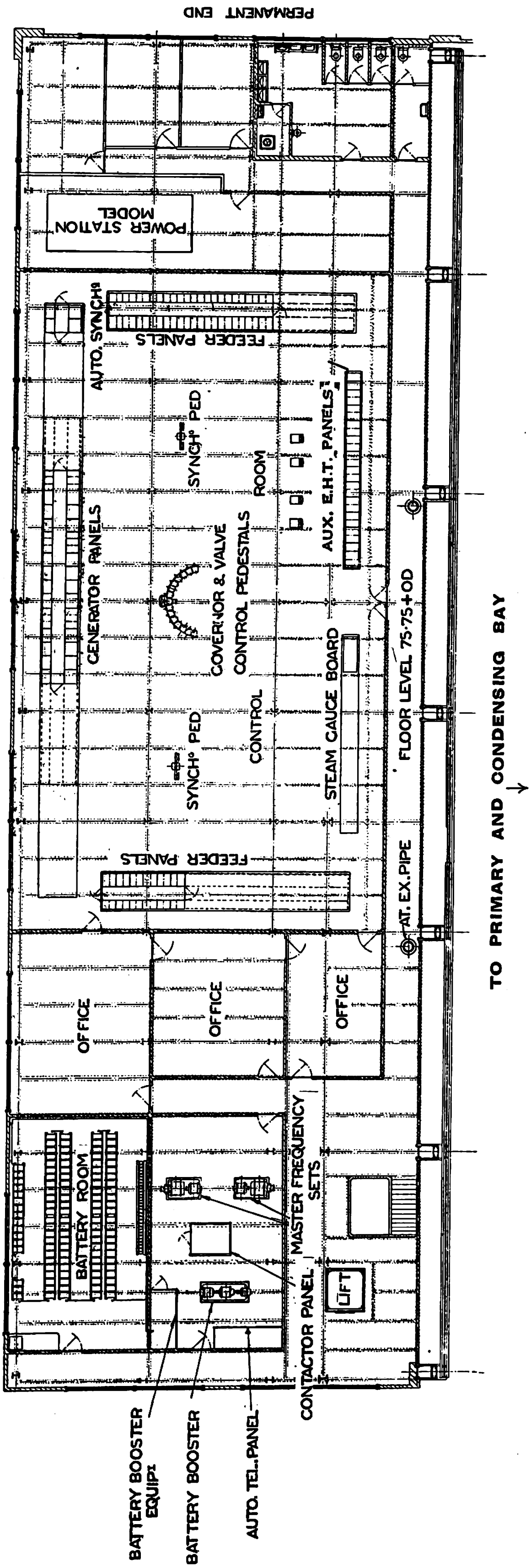

PERMANENT END
POWER STATION MODEL
AUTO. SYNCHS
FEEDER PANELS
SYNCHº PED
GENERATOR PANELS
GOVERNOR & VALVE CONTROL PEDESTALS
CONTROL ROOM
AUX. E.H.T. PANELS
STEAM GAUGE BOARD
FLOOR LEVEL 75·75+OD
AT. EX. PIPE
OFFICE
OFFICE
OFFICE
BATTERY ROOM
MASTER FREQUENCY SETS
CONTACTOR PANEL
LIFT
BATTERY BOOSTER EQUIPT
BATTERY BOOSTER
AUTO. TEL. PANEL
TO PRIMARY AND CONDENSING BAY

FIG. 8.—Plan of switch house (top floor).

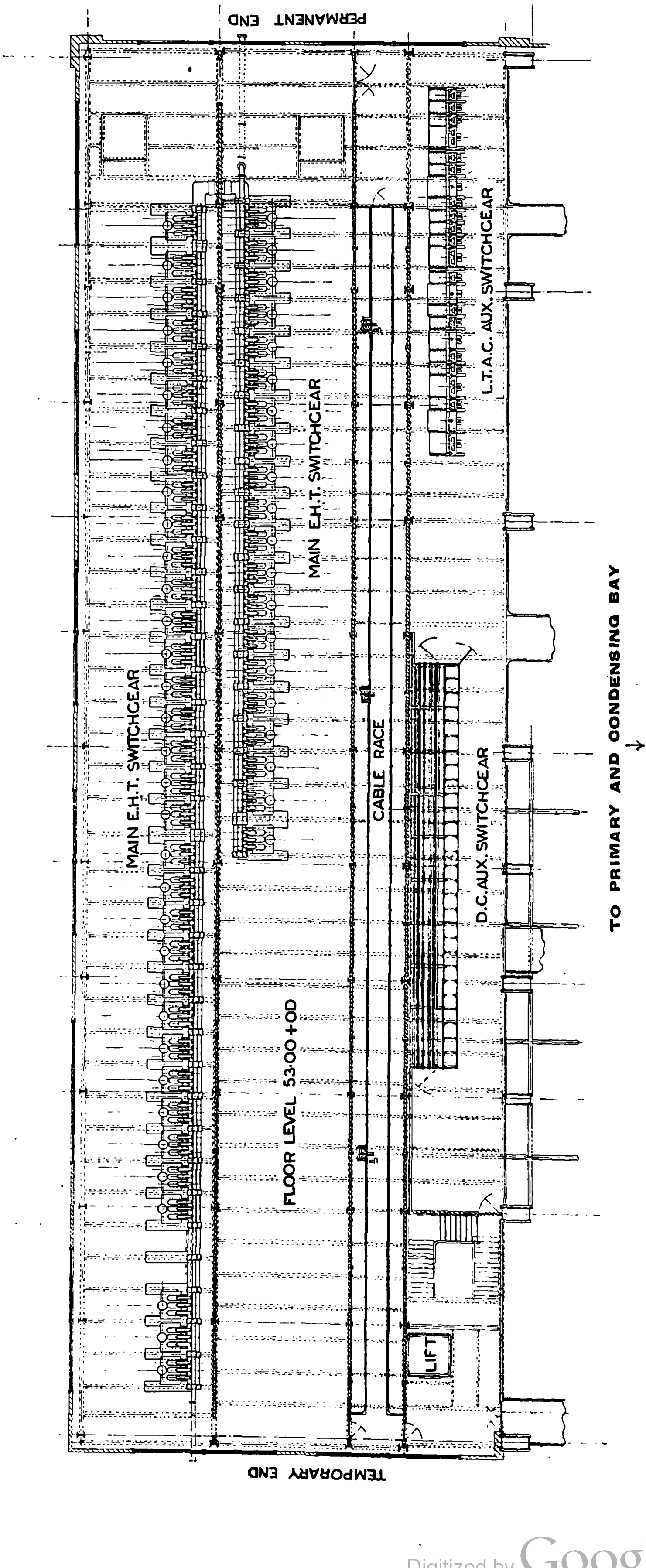

PERMANENT END
MAIN E.H.T. SWITCHGEAR
MAIN E.H.T. SWITCHGEAR
L.T.A.C. AUX. SWITCHGEAR
CABLE RACE
D.C. AUX. SWITCHGEAR
FLOOR LEVEL 53·00+OD
LIFT
TEMPORARY END
TO PRIMARY AND CONDENSING BAY

Fig. 9.—Plan of switch house (first floor).

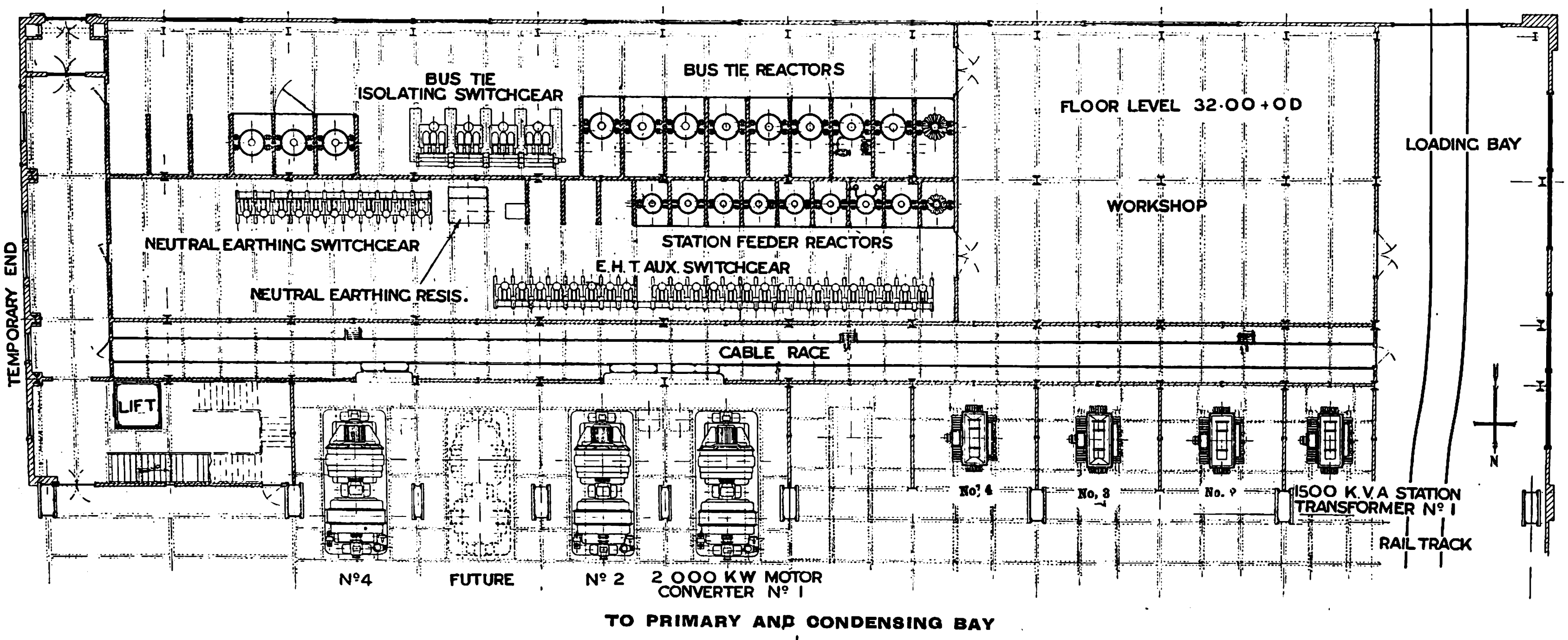

BUS TIE ISOLATING SWITCHGEAR
BUS TIE REACTORS
FLOOR LEVEL 32·00 + OD
LOADING BAY
WORKSHOP
PERMANENT END
TEMPORARY END
NEUTRAL EARTHING SWITCHGEAR
NEUTRAL EARTHING RESIS.
STATION FEEDER REACTORS
E.H.T. AUX. SWITCHGEAR
CABLE RACE
LIFT
N
No. 4
No. 3
No. 2
1500 K.V.A STATION TRANSFORMER Nº 1
RAIL TRACK
Nº 4
FUTURE
Nº 2
2 000 KW MOTOR CONVERTER Nº 1
TO PRIMARY AND CONDENSING BAY

Fig. 10.—Plan of switch house (ground floor).

of 76 per cent. It exhausts to its condenser at 0·58 lb. per sq. in. or a vacuum of 28·82 in. of mercury, corresponding to a condensate temperature of 84° F. with a cooling water inlet temperature of 59° F. and outlet 79° F.

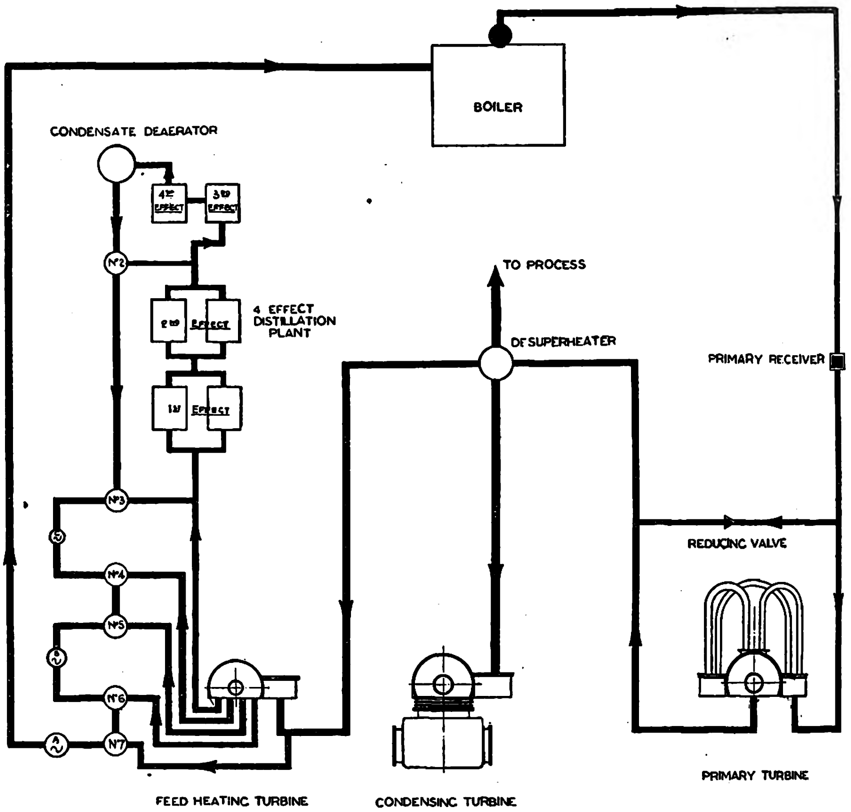

BOILER
CONDENSATE DEAERATOR
4TH EFFECT
3RD EFFECT
Nº2
2ND EFFECT
4 EFFECT DISTILLATION PLANT
1ST EFFECT
TO PROCESS
DESUPERHEATER
PRIMARY RECEIVER
Nº3
Nº4
Nº5
Nº6
Nº7
REDUCING VALVE
FEED HEATING TURBINE
CONDENSING TURBINE
PRIMARY TURBINE

Fig. 11.—Feed-heating cycle and steam distribution.

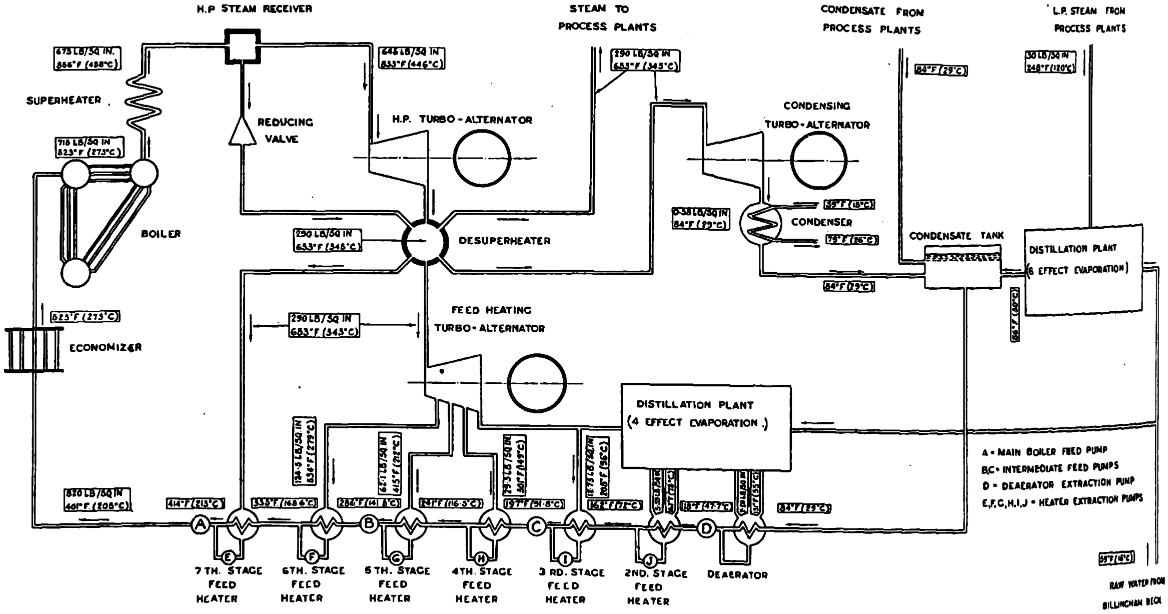

H.P STEAM RECEIVER
STEAM TO PROCESS PLANTS
CONDENSATE FROM PROCESS PLANTS
L.P. STEAM FROM PROCESS PLANTS
675 LB/SQ IN. 886°F (488°C)
645 LB/SQ IN 833°F (446°C)
290 LB/SQ IN 653°F (345°C)
84°F (29°C)
30 LB/SQ IN 248°F (120°C)
SUPERHEATER
REDUCING VALVE
H.P. TURBO-ALTERNATOR
CONDENSING TURBO-ALTERNATOR
718 LB/SQ IN 523°F (273°C)
BOILER
290 LB/SQ IN 653°F (345°C)
DESUPERHEATER
0·58 LB/SQ IN 84°F (29°C)
59°F (15°C)
CONDENSER
79°F (26°C)
CONDENSATE TANK
DISTILLATION PLANT (6 EFFECT EVAPORATION)
84°F (29°C)
176°F (80°C)
523°F (273°C)
ECONOMIZER
290 LB/SQ IN 653°F (345°C)
FEED HEATING TURBO-ALTERNATOR
DISTILLATION PLANT (4 EFFECT EVAPORATION.)
124·5 LB/SQ IN 534°F (279°C)
62·1 LB/SQ IN 415°F (213°C)
29·3 LB/SQ IN 301°F (149°C)
12·73 LB/SQ IN 205°F (96°C)
820 LB/SQ IN 401°F (205°C)
414°F (213°C)
335°F (168·6°C)
286°F (141·8°C)
241°F (116·5°C)
197°F (91·8°C)
162°F (72°C)
118°F (47·7°C)
84°F (29°C)
A
B
C
D
E
F
G
H
I
J
7 TH. STAGE FEED HEATER
6TH. STAGE FEED HEATER
5 TH. STAGE FEED HEATER
4TH. STAGE FEED HEATER
3 RD. STAGE FEED HEATER
2ND. STAGE FEED HEATER
DEAERATOR
A = MAIN BOILER FEED PUMP
B,C = INTERMEDIATE FEED PUMPS
D = DEAERATOR EXTRACTION PUMP
E,F,G,H,I,J = HEATER EXTRACTION PUMPS
59°F (15°C)
RAW WATER FROM BILLINGHAM BECK

Fig. 12.—Diagrammatic flow sheet.

The regenerative feed-heating system comprises 7 stages, the feed water being progressively heated from the initial temperature of 84° F., at which it leaves the storage tanks, to a final temperature of 401° F. Steam for the first two heaters is derived from raw water evaporated in the quadruple-effect distillation plant, the latter virtually functioning as a condenser for the

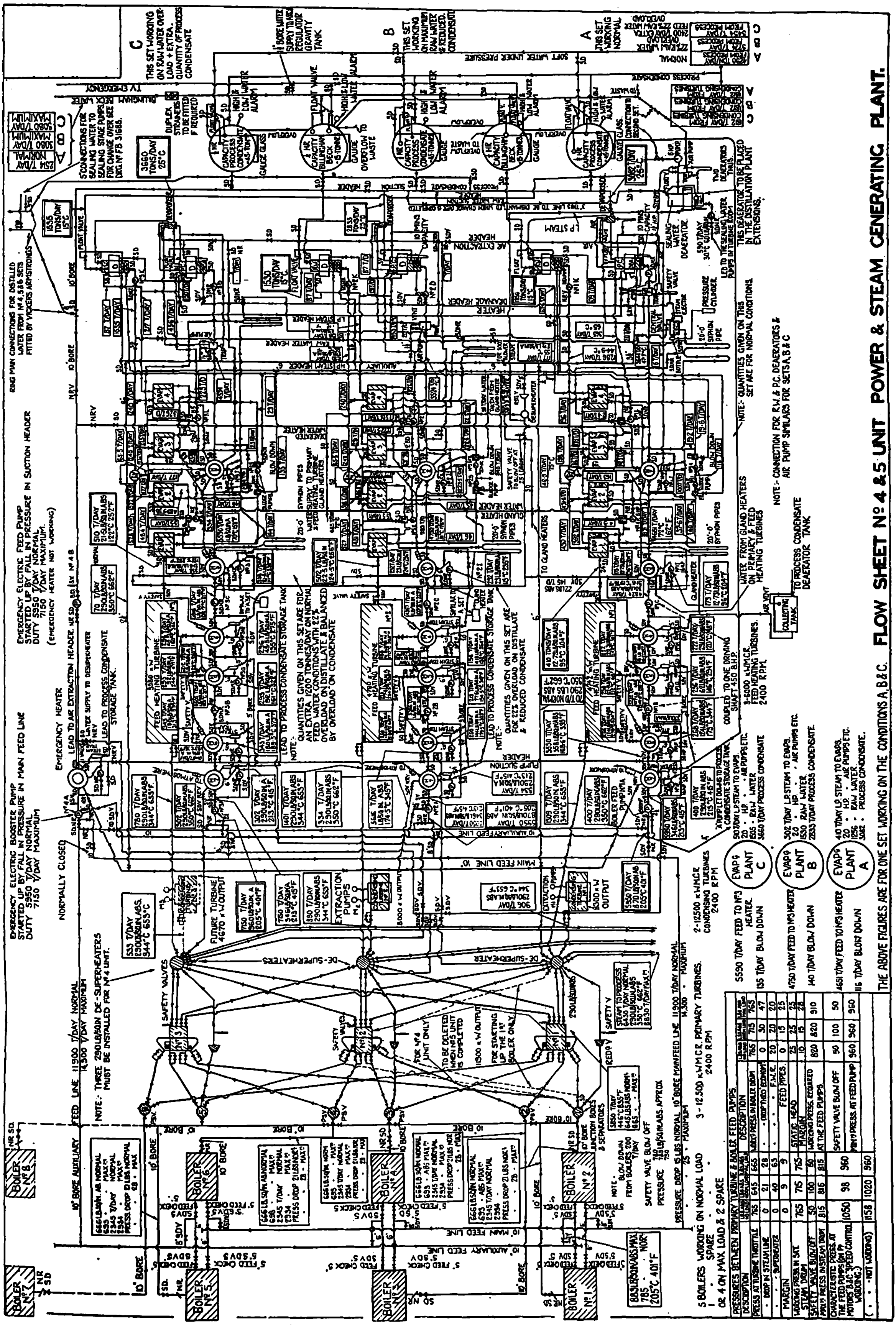

FLOW SHEET No 4 & 5 UNIT POWER & STEAM GENERATING PLANT.
THE ABOVE FIGURES ARE FOR ONE SET WORKING ON THE CONDITIONS A, B & C.
BOILER No 1
BOILER No 2
BOILER No 3
BOILER No 4
BOILER No 5
BOILER No 6
BOILER No 7
BOILER No 8
MAIN FEED LINE 10"
10" AUXILIARY FEED LINE
DE-SUPERHEATERS
SAFETY VALVES
FUTURE TURBINE
EXTRACTION PUMPS
EMERGENCY HEATER
EMERGENCY ELECTRIC FEED PUMP
EMERGENCY ELECTRIC BOOSTER PUMP
NORMALLY CLOSED
PUMP SUCTION HEADER
FEED HEATING TURBINE
GLAND HEATERS
AIR EXTRACTION HEADER
DEARATOR
EVAPg PLANT A
EVAPg PLANT B
EVAPg PLANT C
5 BOILERS WORKING ON NORMAL LOAD 1 SPARE OR 4 ON MAX LOAD & 2 SPARE
3 - 12,500 KW M.C.R. PRIMARY TURBINES. 2400 R.P.M.
2 - 12,500 KW M.C.R. CONDENSING TURBINES 2400 RPM
3 - 6000 KW M.C.R. FEED HEATING TURBINES. 2400 R.P.M.
PRESSURES BETWEEN PRIMARY TURBINE & BOILER FEED PUMPS
LP STEAM
SOFT WATER UNDER PRESSURE
PROCESS CONDENSATE
BILLINGHAM BECK WATER

Fig. 13.—Quantitative flow sheet.

feed-heating turbines. The steam for the next four heaters is bled from the feed-heating turbines, the bleeding points occurring immediately after the 6th, 12th, 18th and 24th (exhaust) stages of each machine. The last heater in the feed-water heating system is supplied with live steam direct from the secondary receivers, so that accurate adjustment of the final feed-water temperature may be obtained once the feed-heating turbine and its attendant distillation plant and heaters have settled down to steady operating conditions. This being the case, the two feed-heating turbines (normally running) each take 1 310 tonnes of steam per day from the secondary receiver system, whilst their corresponding final-stage feed-heaters each account for a further 400 tonnes per day from the same source. Under these conditions each turbine generates 4 750 kW at an overall efficiency of 70 per cent, exhausting to its distillation plant at a pressure of 12·73 lb. per sq. in. and a temperature of 205° F., whilst the net quantity of raw water distilled and passed into the feed line as "make-up" feed-water then amounts to 1 138 tonnes per day from each of the two distillation plants.

An examination of the steam and water quantities so far given reveals that the amount of distillate gained from the two feed-heating distillation sets is insufficient to compensate for the steam consumed by the process plants and for boiler blow-down losses and gland leakage in the high-pressure turbines. It was, therefore, necessary to install three further distillation sets deriving their steam supply from the factory's low-pressure steam main. Two of these sets can make up the deficit of 860 tonnes per day by the evaporation of raw water. The final resultant steam and water balance is shown in Table 1.

Table 1.

Steam and Water Balance.

Steam consumed (tonnes per day)		Steam and water returned (tonnes per day)	
		Condensate from:—	
Process plants	6 930	(1) Process plants	3 994
Condensing turbine	1 130	(2) Condensing turbine	1 130
		Condensate from:—	
7th-stage feed-heaters	800	(3) 7th-stage feed-heaters	800
Feed-heating turbines	2 620	(4) 6th-stage feed-heaters	538
		(5) 5th-stage feed-heaters	472
		(6) 4th-stage feed-heaters	444
		(7) 3rd-stage feed-heaters	346
		(8) 2nd-stage feed-heaters	820
Air ejectors (in feed-heating distillation plants)	40	(9) Air ejectors	40
		Gained distillate entering from feed-heating distillation sets:—	
		(1) 2nd-stage feed-heaters	1 194
		(2) De-aerators	1 082
		Condensate from:—	
Air ejectors (in extra distillation plants)	20	(10) Air ejectors	20
Total	11 540	L.P. steam from:—	
Gland leakage (h.p. turbines)	160	Process plants	160
		Gained distillate from:—	
Primary (h.p.) turbines	11 700	(3) Extra distillation sets	860
Boiler blow-down loss	200		
Total consumed at boilers	11 900	Total feed water to boilers	11 900

The power balance is given in Table 2, whilst from the figures in Table 3 it will be seen that the anticipated overall thermal efficiency of the power station is 24·2 per cent. Table 4 shows the increase in thermal efficiency due to raising the pressure and temperature of the steam at the turbine stop-valves and also that due to the adoption of regenerative feed-heating.

The calculations involved in the determination of the quantities in Tables 3 and 4 are detailed in Appendices 1 and 2 respectively, whilst Appendix 3 contains general data relating to the various parts of the installation.

TABLE 2.

Electrical Power Balance.

Total kW installed	Power generated (kilowatts)		Power consumed (kilowatts)	
37 500	2 primary turbo-alternators at 95·2 per cent M.C.R.*	23 800	Feed and extraction pumps	2 200
25 000	1 condensing turbo-alternator at 81·6 per cent M.C.R.	10 200	Boiler, pulverizer and power plant auxiliaries	3 800
18 000	2 feed-heating turbo-alternators at at 79·2 per cent M.C.R.	9 500	Plants at outgoing feeders	37 500
80 500	Total	43 500	Total	43 500

* Maximum continuous rating.

TABLE 3.

Thermal Efficiency.

	Boiler plant		Power plant	
Power supplied ..	Heat power in coal ..	409 500 kW	Steam power to turbo-alternators	59 150 kW
Power available ..	Power in steam to plants and turbo-alternators ..	141 700 kW	Electrical power at station busbars	41 300 kW
Efficiency of conversion	Boiler plant efficiency (on above basis) $\left(=\frac{141\ 700}{409\ 500}\right)$	34·6 per cent	Power plant efficiency $\left(=\frac{41\ 300}{59\ 150}\right)$	70 per cent
Overall efficiency ..	Overall thermal efficiency of power station $=\frac{34\cdot6\times70}{100}=24\cdot2$ per cent			

TABLE 4.

Effect of Feed-Heating and Increased Pressure and Temperature upon Thermal Efficiency.

Steam conditions at turbine inlet		Theoretical steam power available	Heat in coal converted into available steam energy	Heat in coal converted into electrical power with an efficiency of conversion from steam to electricity of 70 per cent	Remarks	Gain in efficiency over steam generation at 290 lb./sq. in. abs. and 653° F. with no feed-heating
lb./sq. in. abs. (kg/cm²)	° F. (° C.)					
		kW	per cent	per cent		per cent
290 (20·4)	653 (345)	113 600	27·7	19·39	No feed-heating	—
290 (20·4)	653 (345)	118 400	29·0	20·30	Single-stage feed-heating to 176° F. (80° C.)	4·7
645 (45·3)	833 (446)	128 100	31·3	21·91	No feed-heating	13·0
645 (45·3)	833 (446)	141 700	34·6	24·22	Seven-stage feed-heating to 401° F. (205° C.)	24·9

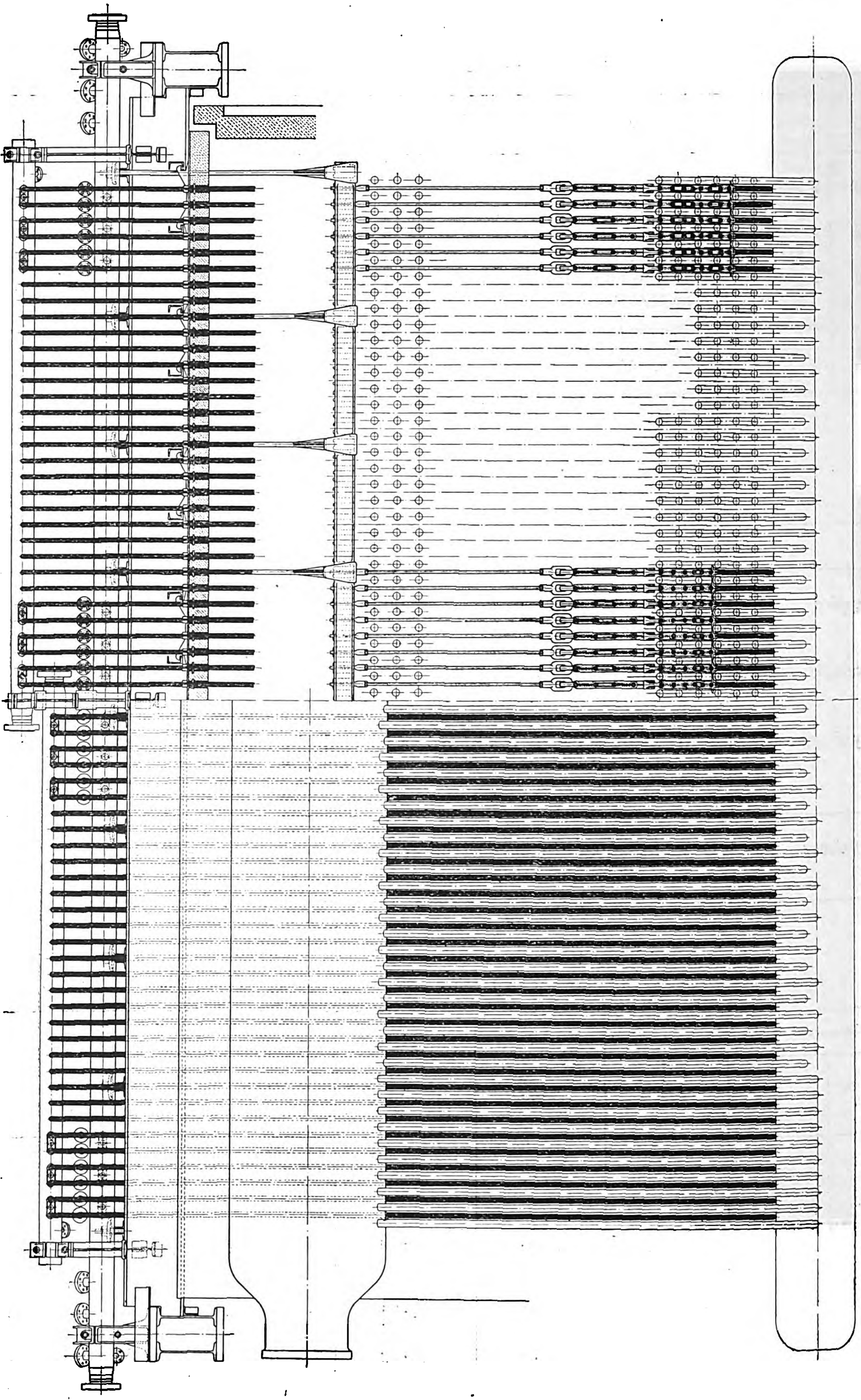


FIG. 14.—Method of boiler drum suspension.

Section (3). DESCRIPTION OF INDIVIDUAL PARTS OF THE PLANT.

(a) *Boiler Plant.*

The general arrangement of the boiler plant has already been described in Section (1) in conjunction with the pictorial flow-sheet of Fig. 3. Space precludes a detailed description of the entire plant, but mention will be made of its more important features and of certain details in which it differs from usual high-pressure boiler-plant practice.

In the first place it is noteworthy that the two boiler houses are isolated from the pulverizer house by means of brick walls, whilst the raw-coal bunker floor at the top of the pulverizer house (Fig. 2) has been made dust-tight to keep the lower floors clean. In addition, the symmetrical location of the 10 pulverizing mills permits the coal dust from the vents of the mill systems to be discharged into the boiler combustion chambers by means of the primary air fans. This feature eliminates a great deal of the dust nuisance from the pulverizer house.

The flue gas de-dusting equipment consists of two falling-water-film type units to each boiler. River water from the condenser circulating-water outlet main is pumped to the de-dusters and to a number of sluice channels in the boiler-house floor which convey the ash and water to settling pits, via slurry pumps.

Boilers.—The steam-generating plant consists of 8 multi-drum boilers, each having a normal rating of 215 000 lb. per hour and a maximum rating of 270 000 lb. per hour.

The general construction of the boilers is clearly illustrated in the end elevation of the plant given in Fig. 2. The main upper drums are both suspended from the boiler structure, whilst the boiler as a whole is largely dependent upon the tubes for its support (Fig. 14).

A considerable portion (about 30 per cent) of the boiler heating surface is exposed to the radiant heat of the combustion chamber. The available heating surface in the combustion chamber is 3 000 sq. ft., which includes the fin-tube water walls, water screens and front rows of boiler tubes, whilst the convection tubes of the boiler account for 7 000 sq. ft., which makes a total of 10 000 sq. ft. for the boiler heating surface. The evaporation obtained averages from 22 to 28 lb. per sq. ft. per hour, exclusive of the steam which is generated by the cast-iron gilled steel-tube economizer. It has been calculated that the latter will generate about 30 per cent of the total steam when operating under normal load conditions. This reduces the average amount of steam generated by the boiler tubes to approximately 17 lb. per sq. ft. of heating surface per hour, an effective evaporation which is very much in excess of that obtaining in average practice to-day.

Boiler Drums.—The manufacture of these drums was entirely outside the scope of the ordinary boiler shops and presented quite a problem to large forging makers. When it was realized that 32 drums were required and that each drum would take more than 6 months to complete, it was clear that if any trouble were experienced in obtaining satisfactory and uniform forgings at regular intervals the completion of the plant would be seriously delayed.

The question of choosing a suitable type of boiler was one of considerable difficulty in view of the many new conditions which had to be faced. In December 1927 it was decided that high-pressure boilers should be installed. Early in 1928 the design work was commenced, and after the size of the plant and the capacity of the boiler units had been determined it was obvious that the design and manufacture of the large 800-lb. pressure, forged-steel boiler drums would require careful consideration to ensure perfect forgings and to obtain them in time to meet the steam demands.

After due consideration of all the factors involved it was decided not to adopt the lighter alloy-steel forgings but to use ordinary mild steel having an ultimate tensile strength of little more than 26 tons per sq. in. and a yield stress of not less than 13 tons per sq. in. The length of the main steam drums is 43 ft., the internal diameter 4 ft. 6 in. and the shell thickness 4½ in. The finished drum weighs 56 tons and was machined from a 150-ton ingot. Allowing for the following stresses:—

Hoop stress due to pressure;
Longitudinal stress due to pressure;
Radial stress due to pressure; and
Longitudinal stress due to the bending moment resulting from concentrated and uniformly distributed loads, which amount to over 200 tons in the case of the main steam drums,

and using a formula combining the results of each separate stress, the drum thicknesses were obtained by limiting the working stresses in the forgings to 5·2 tons per sq. in., which gives a safety factor of 2·5 on the yield stress.

Superheaters.—Special precautions had also to be taken in the design of the superheaters, on account of the very high normal superheat temperature of 850° F., whilst during periods of fluctuating load this figure might be exceeded so that temperatures lying within the region of low limiting creep stress might be reached in the tube walls. At the time the superheaters were being designed, several classes of special alloy-steel appeared to be suitable from the point of view of withstanding the high temperature; but when other factors were taken into account it was found that the most satisfactory material was mild steel of exceptionally good quality, with a very low sulphur content. This material was decided upon after very careful consideration of both cost and reliability.

In each boiler the superheater is suspended between the tubes (Fig. 15) and is partly exposed to the radiant heat of the furnace. The weight of the whole superheater is carried from the boiler structure in such a way that none of the weight of the elements is imposed upon any of the pressure parts of the boiler.

The superheaters are of the locomotive return-bend type, the saturated steam inlet flanges and superheated steam outlet flanges being at opposite sides so that there is an even distribution of steam flow throughout the superheater.

In each superheater the headers, four in number, are turned from solid mild-steel forgings, being left blank at one end and provided with heavy steel flanges at the other end. The superheater elements are made from solid-drawn steel tubing, the material for which has received special attention through all the stages of its manufacture. The finished material has a tensile strength of from 21 to 23 tons per sq. in. and an elongation of not less than 28 per cent. Each superheater element is made in two sections and provides a total length of steam path of approximately 200 ft. between the saturated and superheated steam headers. Each complete superheater is divided into two halves, there being two inlets and two outlets for each boiler. To ensure the necessary protection to the superheater elements a reasonably high steam velocity is essential; this was provided for by designing the superheaters for a pressure-drop of 40 lb. per sq. in. at normal evaporation.

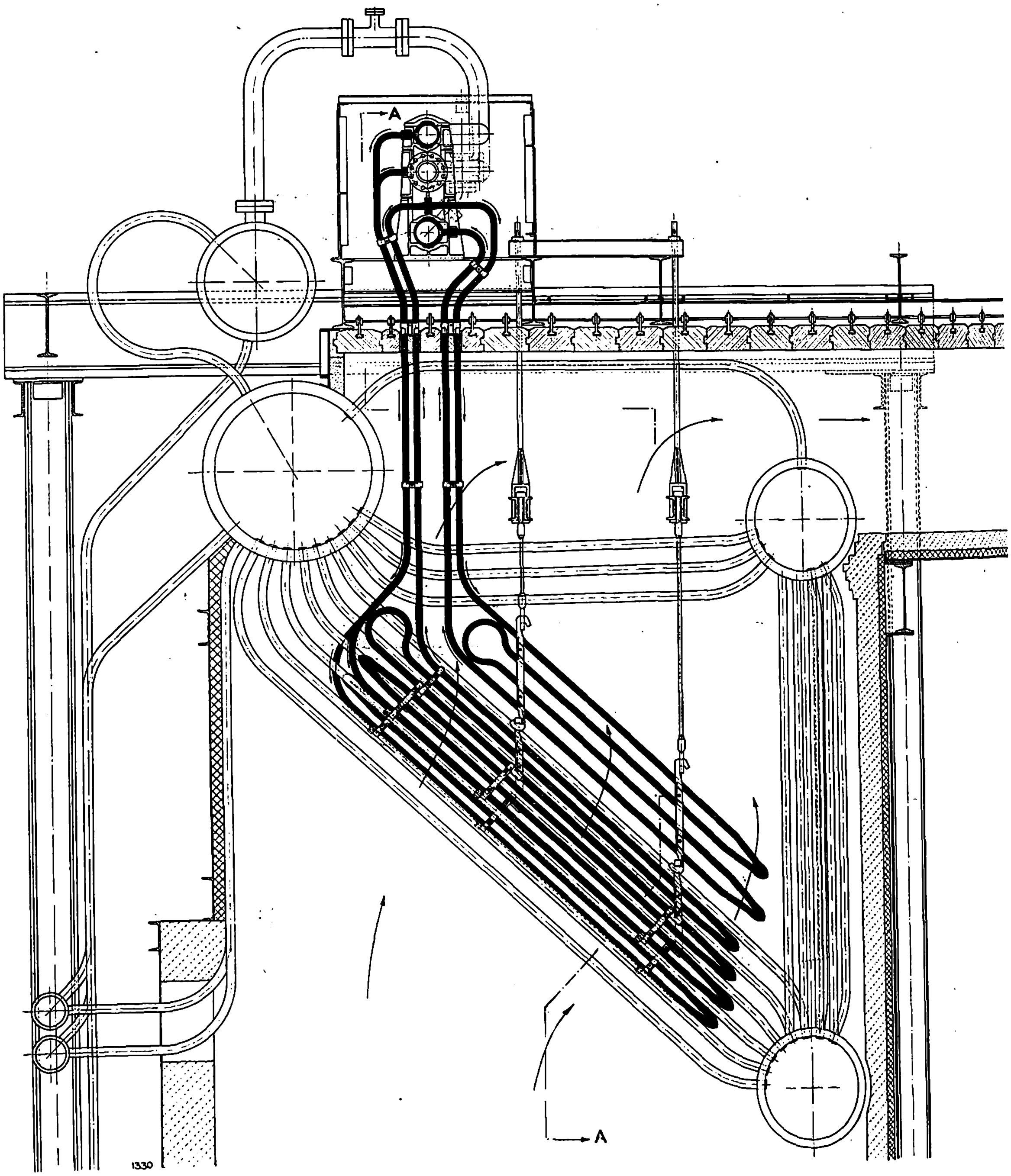


FIG. 15.—Superheater.

Economizers.—A highly interesting feature of the boiler plant is the so-called steaming economizer. The economizers can be seen at the rear of the boilers in Fig. 2. The advantages of steaming over non-steaming economizers are a saving in space and the elimination of baffles in the boiler, with a consequent reduction in draught loss and fan power.

Each economizer has a heating surface of 23 000 sq. ft. and is connected to the boiler by means of a number of bent tubes, a mixture of steam and water entering these tubes at a temperature of 524° F., the feed-water temperature at the economizer inlet being 401° F. The corresponding flue-gas inlet and outlet temperatures are 1 150° F. and 600° F. respectively.

Burners and Air Preheaters.—The horizontal burners, of which there are four to each boiler, are located at the front of the combustion chamber. These burners are of the new short-flame, turbulent type and are each capable of burning more than 4 tons of coal per hour.

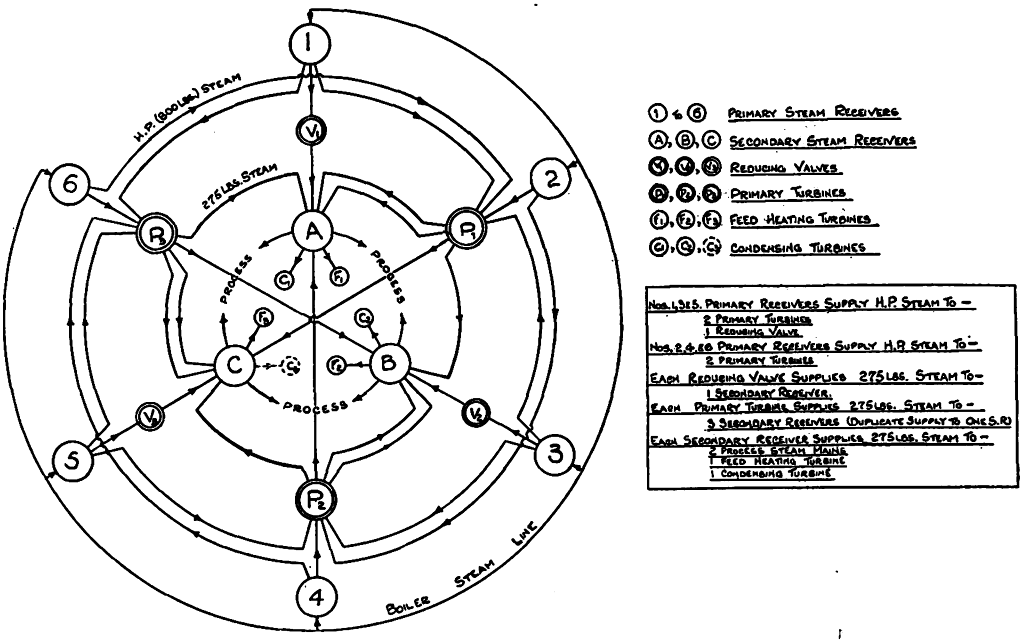

1
2
3
4
5
6
V₁
V₂
V₃
P₁
P₂
P₃
A
B
C
F₁
F₂
F₃
C₁
C₂
C₃
H.P. (800 LBS.) STEAM
275 LBS. STEAM
PROCESS
PROCESS
PROCESS
BOILER STEAM LINE
① to ⑥ PRIMARY STEAM RECEIVERS
Ⓐ, Ⓑ, Ⓒ SECONDARY STEAM RECEIVERS
V₁, V₂, V₃ REDUCING VALVES
P₁, P₂, P₃ PRIMARY TURBINES
F₁, F₂, F₃ FEED HEATING TURBINES
C₁, C₂, C₃ CONDENSING TURBINES
NOS. 1, 3 & 5. PRIMARY RECEIVERS SUPPLY H.P. STEAM TO –
2 PRIMARY TURBINES
1 REDUCING VALVE
NOS. 2, 4 & 6 PRIMARY RECEIVERS SUPPLY H.P. STEAM TO –
2 PRIMARY TURBINES
EACH REDUCING VALVE SUPPLIES 275 LBS. STEAM TO –
1 SECONDARY RECEIVER.
EACH PRIMARY TURBINE SUPPLIES 275 LBS. STEAM TO –
3 SECONDARY RECEIVERS (DUPLICATE SUPPLY TO ONE S.R.)
EACH SECONDARY RECEIVER SUPPLIES 275 LBS. STEAM TO –
2 PROCESS STEAM MAINS
1 FEED HEATING TURBINE
1 CONDENSING TURBINE

FIG. 16.—Diagram showing symmetrical lay-out of pipework.

The air preheaters are of a well-known rotary type and present no special features, except in regard to size. Each preheater has a heating surface of 37 000 sq. ft. and raises the temperature of some 3½ million cub. ft. of air per hour from 60° F. to 500° F.

Control of Boiler Auxiliaries.—The boiler auxiliaries are driven by d.c. motors, the distribution being so arranged that each pair of boilers forms a complete and independent system. The distribution boards in the boiler plant are each fed by two cables in parallel from the d.c. board in the switch house and are interconnected, thus ensuring that the worst possible steam restriction is that due to the opening of the breaker supplying one induced-draught and the forced-draught fan on one boiler, under which condition 75 per cent output of the pair of boilers can be maintained. Two fuel feeders and one primary air fan for each boiler are fed from each distribution board in order to keep half the burners in operation until the interconnecting links can be closed in the event of an interruption of the supply to either board.

Contactor-type startors are installed for each motor, and the remote controls are grouped on a central board in front of each boiler together with the other boiler control instruments and gauges. An interlock is provided to ensure that the forced-draught fans, primary air fans and fuel feeders cannot be run without one of the induced-draught fans being in commission.

The raw-coal handling plant includes two vertical automatic skip hoists and two belt conveyors with travelling trippers.

Visible and audible warning signals are installed on each mill system and on the pulverized-fuel conveyors to draw attention to any departure from the correct sequence of operation or failure of any of the drives concerned.

There are 75 a.c. motors and 92 d.c. motors of the totally enclosed type in the boiler and pulverizer plants, 44 of these motors being equipped with water-cooling on a system specially designed for the purpose by the staff of Synthetic Ammonia and Nitrates, Ltd. The largest motors are the 350-b.h.p. mill motors.

(*b*) *Pipework and Receiver System.*

Lay-out.—In the design of the station the accommodation of about 30 000 ft. of steam and water piping and nearly 2 500 valves of all sorts and sizes presented a problem of no mean order. The unusual feature, therefore, of a separate bay for pipework was decided upon and incorporated in the lay-out.

In order to arrive at a satisfactory arrangement of the maze of pipework resulting from the accommodation of some 50 distinct pipe ranges in a comparatively small space, it was found essential to construct and make frequent use of a scale model. This principle was also applied to the pipework in the feed-heating bay, and eventually the model was extended to include the boiler plant as well as the entire power plant.

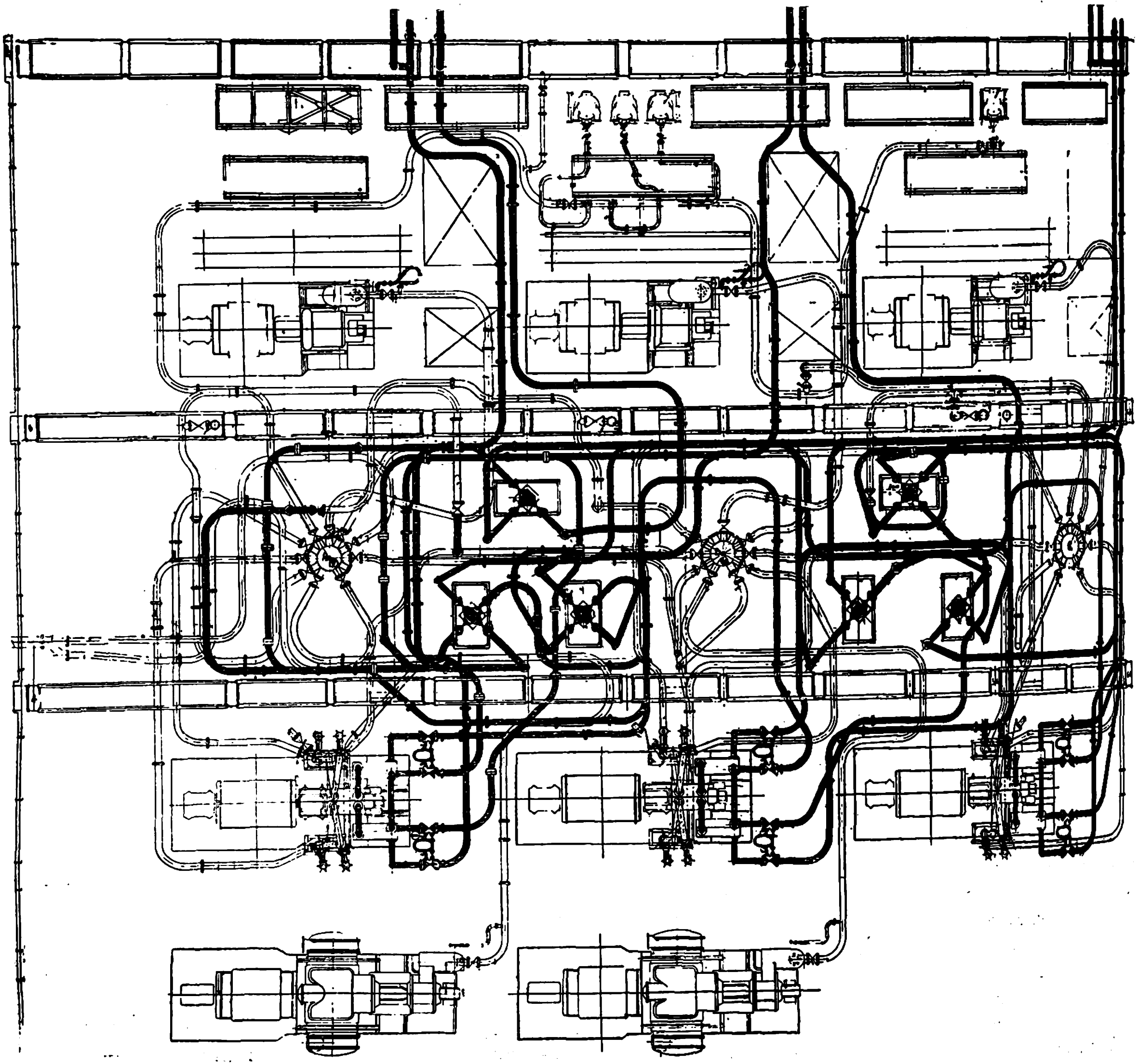


Fig. 17.—Arrangement of steam pipework (high-pressure pipes shown solid).

The pipe bay contains 6 high-pressure receivers and 3 low-pressure receivers or de-superheaters which, with all pipework, are below turbine floor-level. The spindles of all valves are extended up to this level, and consequently on the operating floor are erected three circular valve tables above the de-superheaters, with pressure and temperature gauges mounted above them, the valve wheels on these tables being neatly labelled and the surface of each table bearing a diagram similar to an electrical control diagram. The high-pressure valve wheels are grouped above each high-pressure receiver, forming six symmetrically disposed groups in all. The three electrically operated reducing valves are also situated in this floor.

A plan view of the pipe-bay control floor is shown in Fig. 6, while the general arrangement of the pipework is given in Fig. 17.

Design Conditions.

High-pressure steam pipes and valves, 815 lb./sq. in. and 850° F.

Intermediate-pressure steam pipes and valves, 290 lb./sq. in. and 650° F.

High-pressure feed pipes and valves, 1 150 lb./sq. in. and 400° F.

The same standard of piping, valves and joints, etc., was adopted for both the high-pressure steam piping and the high-pressure feed piping.

Practice Adopted.—After consideration of the various factors involved it was decided to adopt the following practice:—

(1) High-pressure steam and feed pipes not to exceed 10 in. bore.

(2) Intermediate-pressure steam and feed pipes not to exceed 12 in. bore.

(3) All high-pressure pipes to be solid-drawn.
(4) Pipes to be manufactured in as long lengths as possible.
(5) High-pressure steam ranges to be pulled up on erection by an amount equal to the full expansion between the anchorages under working temperature.
(6) High-pressure feed and also intermediate-pressure steam ranges to be pulled up on erection by an amount equal to half the maximum expansion between the anchorages under working temperature.
(7) The maximum thrust of any anchorage not to exceed 7 cwt.
(8) The flexibility of the pipework to be such that the thrust on the steam chests of the primary turbines did not exceed 6 cwt. per pipe line.
(9) The pipes to be run as far as possible from the line between anchorages, in order to minimize thrust thereon and also pipe bending stresses.
(10) To arrange that any boiler could supply any h.p. turbine.
(11) To adopt spring-cushioned pipe hangers with ball sockets, permitting movement in any direction.

TABLE 5.

Particulars of Main Piping.

	Number of ranges	Bore of pipes	Thickness	Location
		in.	in.	
715 lb. per sq. in.	16	7	0·643	Superheater header to main steam line
	6	10	0·850	Boilers to receivers
	12	9	0·770	Receivers to primary turbines
	3	9	0·770	Receivers to reducing valves
	2	10	0·850	Feed to boilers
290 lb. per sq. in.	12	12½	0·5	Primary turbines to de-superheaters
	3	12½	0·5	Reducing valves to de-superheaters
	3	12½	0·5	De-superheaters to F.H. turbines
	2	12½	0·5	De-superheaters to condensing turbines
	6	12½	0·5	De-superheaters to process
	2	12½	0·5	Between de-superheaters

Particulars of Main Piping.—These are given in Table 5.

Type of Joint.—The research department of Synthetic Ammonia and Nitrates, Ltd., conducted extended experiments, as a result of which it was decided to adopt, for the high-pressure pipes, screwed flanges with spot welding on both sides (Fig. 18), and a compressed asbestos fibre joint ring $\frac{1}{32}$ in. thick. Screwed flanges were finally adopted in preference to welded flanges, chiefly because of the impracticability of satisfactorily welding such thick flanges as were required.

Particulars of the flanges are given in Table 6.

The joints were not "followed up" after putting steam on the ranges. The majority of them have now been in use for several months and no trouble has yet been experienced.

Bolts.—These are made of special alloy steel, with a maximum cold yield of 50 tons per sq. in. To obtain uniform bolt stress around the joint, the bolts were tightened up to a definite elongation measured by micrometer, the bolts being pointed for this purpose.

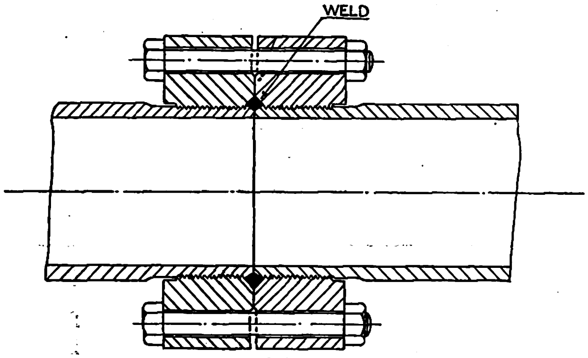


FIG. 18.—Flanged joint for 800 lb. pressure.

These decisions were the result of experiments. The bolt stresses are given in Table 7, the bolts being $9\frac{1}{32}$ in. long and 1½ in. diameter.

TABLE 6.

Flange Particulars.

Duty	Diameter and thickness of flange	Number of bolts
	in.	
10-in. feed pipes	21 in. × 3 in.	16
10-in. steam pipes	21 in. × 6 in.	16
9-in. steam pipes	19 in. × 5¾ in.	14
7-in. steam pipes	15½ in. × 5 in.	12

High-Pressure Receivers.—Six of these vertical receivers are installed, each having one 10-in. inlet connection from the boilers and either two or three 9-in. outlets (see Fig. 16). The receivers are 20½ in. square outside, 18 in. diameter inside and 9·5 ft. high and are hollow steel forgings. A flexible type of vertical plate supports the receivers. The four connections are disposed one on each side and "staggered" in position (see Fig. 19).

Secondary Receivers (De-Superheaters).—Three cylindrical secondary receivers of the vertical type are installed, the dimensions being 4 ft. 2 in. diameter and 19 ft. high (see Fig. 19). Each receiver has four 12-in. inlet branches from its corresponding primary turbines and reducing valve (see Fig. 16), and eight 12-in. bore outlet branches at the top supplying the process plants and the secondary turbines. De-superheater sprays are fitted adjacent to the inlet branches, the water being supplied from the intermediate feed line at 330 lb. per sq. in. and 300° F. These de-superheaters are the largest of their type in existence.

TABLE 7.

Bolt Sizes and Extensions.

Duty	Extension	Stress
	in.	tons/sq. in.
10-in. bore feed pipes	0·008	16
10-in. bore steam pipe	0·010	20
9-in. bore steam pipe	0·009	20
7-in. bore steam pipe	0·007	20

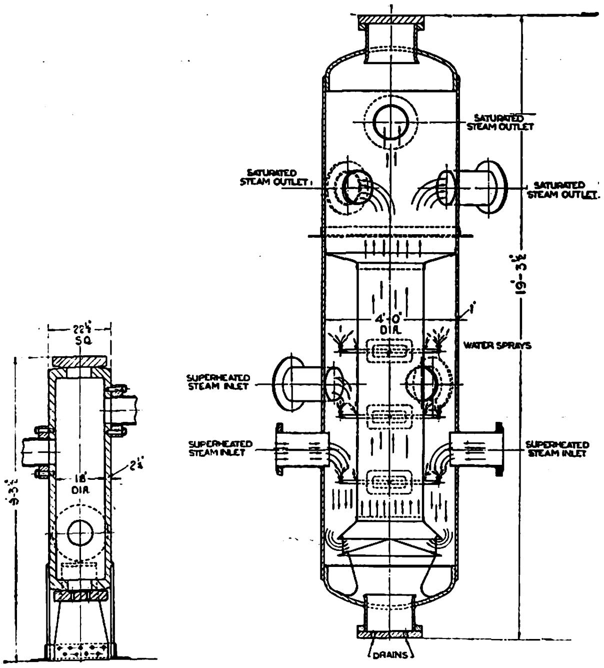


FIG. 19.—Sections of primary and secondary steam receivers.

Valves.—Generally all valves are of the parallel slide type. Up to and including 5-in. bore the valve bodies are of forged steel, and over 5 in. the bodies are of cast steel. As already stated, the spindles of all main stop-valves, valve drains and bypass valves are extended to the operating floor-level. The three electrically-operated reducing valves are of the balanced non-seated type, with 9-in. inlets, 12-in. outlets, 5-in. throats, 3½ in. lift and 2 in. overlap, and are each capable of reducing 437 000 lb. of steam per hour from a maximum pressure of 665 lb. per sq. in. to 290 lb. per sq. in.

Steam-pipe Drainage.—All pipe ranges were designed with a fall of at least 3 in. per 100 ft. towards the receivers. To reduce the cost of traps on the high-pressure steam lines, about four drain-pipes were led to each trap. All traps are provided with strainers and by-passes so that, in the event of a trap sticking, it can be isolated and repaired without shutting down the line.

Lagging.—The economic thickness of high-pressure pipe lagging was determined in the Billingham research department and consists of the following:—

Asbestos	1 in.	Total, 4 in.
Magnesia	2½ in.	
Hard-setting cement ..	½ in.	

Materials and Tests.—The work involved in drafting specifications was immense, especially in the absence of standards for the high pressures and temperatures being considered, and necessitated the closest collaboration with steel-makers and also the various contractors. As a result, the authors desire to stress the urgent need of appropriate British Standard Specifications, owing to the rapid increase in the use of high pressures and temperatures.

The following general information relative to materials and tests will be of interest. The analysis of the high-pressure pipe steel is:—

Carbon, 0·15 to 0·20 max.; silicon, 0·30; manganese, 0·80; sulphur, 0·03; phosphorus, 0·03;

and that of the bolts is:—

Carbon, 0·30; silicon, 0·15; manganese, 0·60; phosphorus, 0·03; sulphur, 0·04; nickel, 2·50; chromium, 0·60; molybdenum, 0·60.

The physical tests are as follows:—

Pipes.—Ultimate tensile stress of 26 to 30 tons per sq. in. with a yield stress of 13 tons per sq. in.; pipe to be flattened cold to one-third outside diameter without cracks, in addition to a temper bend test, and finally each pipe when manufactured to be water-tested to 3 500 lb. per sq. in. abs.

Bolts.—Ultimate tensile stress of 60 to 70 tons per sq. in. with a yield stress of 50 tons per sq. in.; elongation not to exceed 20 per cent and reduction in area 50 per cent. Izod impact value 60 ft.-lb.

In conclusion it may be mentioned that, when delivered, all pipes were "pickled" with a weak nitric acid solution for a few hours, this proving very effective in the removal of scale.

(c) *Turbines.*

High-pressure Turbines.—A sectional view of one of these turbines is given in Fig. 20. They are of the single-cylinder type and have 16 stages. The cylinder and the two steam chests are of forged steel and their manufacture required the exercise of extreme care on the part of the makers.

It is outside the scope of this paper to describe in detail the many specially devised features which had, of necessity, to be incorporated in this unique turbine. It will be of interest, however, to refer briefly to the following outstanding features:—

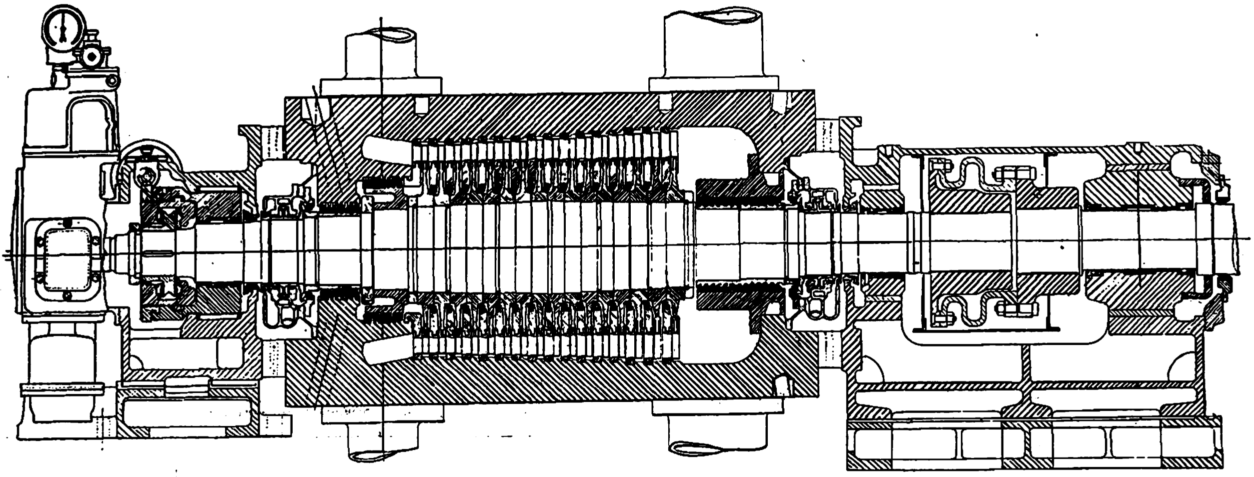


Fig. 20.—Sectional arrangement of high-pressure turbine.

Steam Chests.—The admission of a very large quantity of steam at high pressure and temperature in the case of these turbines necessitated departure from the usual steam-chest practice. Each turbine has two steam chests in parallel, one on each side of the inlet end of the turbine, to which chests the high-pressure steam is supplied via four 9-in. pipes and stop-valves, two per chest. Steam passes from the chests to the turbine admission belt via four 9-in. arched pipes or bends. By this procedure a far greater degree of steam pipe flexibility is obtained than would be possible if one, or even two, connecting pipes of larger diameter were employed. The exhaust end of the turbine is similarly equipped with two steam chests connected to the cylinder by four 12-in. pipes. The arrangement of the various pipes is shown in Figs. 2 and 7, half of them (two inlet and two exhaust) being arched above the turbine, the other half of them being correspondingly arched below the turbine, this arrangement eliminating unbalanced expansion thrusts on the cylinder. The two inlet chests are also interconnected by an arched 8-in. balance pipe. A 12-in. spring-loaded relief valve is attached to one of the exhaust steam chests and is set to operate at about 320 lb. per sq. in.

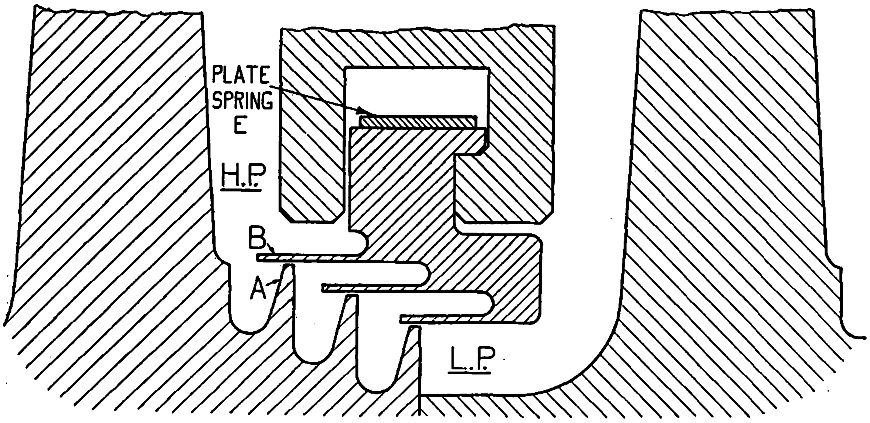


Fig. 20A.—Labyrinth packing.

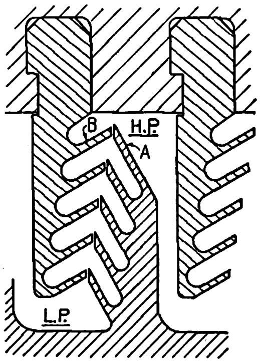


Fig. 20B.—High-pressure gland.

Diaphragms.—The question of expansion throughout these turbines was very exhaustively studied by the makers, and the various devices adopted to allow for such expansions have proved eminently satisfactory. Fig. 20A illustrates the labyrinth packing between the diaphragms. The latter consists of a number of projections " A " cut on the boss of the diaphragms. These projections almost touch a number of projections, " B," on the packing piece " C," which fits into a slot. The clearance space behind " C " is taken up by the spring " E." This device is also one for regulating the clearance and this is accomplished by virtue of the shape taken by the projections during expansion, the diaphragm projections lengthening while the packing-piece projections assume the shape shown in Fig. 20A. The clearance is thus always preserved. One of these packings is placed between each diaphragm, and 8 are placed together at the exhaust end of the turbine.

Glands.—The use of increased steam pressure, particularly in the case of large units, has resulted in radical changes in gland design. The disadvantage of some earlier types of labyrinth glands was that, in the event of rubbing of the faces, the resultant heating, with distortion of the faces, caused wear and decreased the gland efficiency.

The glands employed at both high-pressure and low-pressure ends of the turbines are so designed that, if rubbing should occur, the resultant distortion of the parts in contact causes the clearance to be increased automatically.

The glands at the high-pressure ends are of a special axial clearance type, illustrated in Fig. 20B. The projections "A" were made solid with the sleeve keyed to the main shaft, similar projections being cut on the packing piece "B" fitted into the turbine casing. A clearance is thus always maintained, since the projections on expanding tend to curve outwards from the clearance space, which tends therefore to become larger instead of smaller. This design enables a very large number of throttling joints to be provided in a given gland length, while the fitting of an adjustable thrust block of the Michell type permits the gland clearance to be most accurately adjusted to a working minimum while the set is in operation.

The glands at the low-pressure ends are of the standard radial comb type. External to the labyrinth glands on both h.p. and l.p. ends, water-sealed glands are provided to prevent leakage of steam to the turbine room, these glands also tending to cool the shaft near the bends.

Coupling.—The coupling used in this instance for coupling the turbine to the generator is known as the semi-flexible type. With its use the turbine and generator rotors may be balanced separately and when coupled together the degree of flexibility provided by the coupling allows their perfect individual balance to be maintained in operation. The coupling consists of a solid steel shell of corrugated section provided with flanges at each end for direct coupling to the ends of the turbine and generator shafts.

Steam Consumption.—The steam consumption guarantees of the high-pressure turbines are given in Table 8.

TABLE 8.

Turbine Steam Consumptions.

	Primary	Feed-heating	Condensing
Service rating (kW)	11 900	5 670	8 544
Service rating as a percentage of max. cont. rating	95·2	94·5	68·3
Stop-valve pressure (lb./sq. in. abs.)	644·7	289·7	289·7
Stop-valve temperature (° F.)	833	653	653
Superheat (° F.)	340	243	243
Exhaust pressure (lb./sq. in. abs.)	289·7	12·73	0·526
Exhaust temperature (° F.)	653	205	81·23
Steam flow (tonnes/day)	5 850	1 511	933
Steam flow (lb./hour)	538 000	139 000	86 800
Overall efficiency of turbo-alternator (per cent)	75·0	73·1	75·6
Total steam consumption at unity power factor (lb./kWh) ..	45·07	24·4	10·01

Feed-heating and Condensing Turbines.—These turbines are of standard construction and possess no unusual features. Their steam consumptions are also given in Table 8. The stages at which the former turbines are bled are given in Section 3 (*d*).

Turbine Governors.—The only governors which call for special comment are those controlling the steam admission to the primary turbines. With this class of turbine the inertia of the rotor is small in comparison with the power output, and consequently a heavy duty is imposed on the governor in the event of the alternator suddenly throwing off a heavy load.

For this reason the manufacturers have made these governors much quicker in operation than is usual on the more standard type of turbine; the responsiveness of these governors is about 10 times greater than that of ordinary turbine governors.

It is explained in Section (4) why it was necessary to design the primary governors with a speed regulation of 9 per cent in place of the more usual 3½ per cent. This characteristic necessitated raising the setting of the overspeed device from 10 per cent to 12½ per cent to avoid, as far as possible, the total shutting down of the turbine in the event of the alternator switch opening with the set carrying full load. It was considered that the increased margin of 3½ per cent as against 1 per cent would be sufficient to meet this case, in view of the high speed of operation of the governor itself.

The governor is of the vertical type, and there are no mechanical connections between it and the steam admission valves, the control of the steam admission being effected by means of an oil relay system. A relay valve mounted on the governor spindle controls the admission of oil under pressure to power pistons arranged on the steam admission valves and so controls their opening.

General.—Each alternator is also of standard design, with closed-circuit air-cooling system, and direct-coupled exciter with radial commutator. All turbines have duplicate oil coolers, and the condensing sets have duplicate air-ejector equipments. A complete set of instruments for each machine is grouped in compact systematic formation upon a vertical steel control board adjacent to the governor end of the machine.

(*d*) *Feed-Heating and Distillation Plants.*

(1) *Feed-Heating.*

The 3 single-cylinder 6 000-kW feed-heating turbines are bled after the 6th, 12th and 18th stages, the whole of the remaining steam being used in a lower-stage feed-heater and for the distillation of raw water in the evaporators.

The normal working conditions of these turbines are given in Table 9.

The condition of the steam leaving the turbine at the various stages is given in Table 11 at the end of Appendix 3.

Relief and non-return valves have been installed on all bled-steam connections from the turbine. No pressure regulators, however, have been employed.

Feed-Heaters.—The feed water passes through 7 heaters before entering the economizer. The first two heaters are situated in the distillation bay. The next four heaters are supplied with steam tapped from the feed-heating turbine and are of the vertical type with the tubes expanded into the tube plates at both ends. The last heater in the line (No. 7) is supplied with steam at 290 lb. per sq. in. and 653° F. The temperature of the feed water leaving this heater is 401° F.

Heaters Nos. 3, 4, 5 and 6 are situated as close to the turbines as possible in order to reduce the pressure-drop across the bled-steam pipes, and also to facilitate operation. In the event of the bursting of a tube, any heater can easily be bypassed, and the accumulated water in that case is automatically let down to the condensate tanks.

The heater extraction pumps are arranged on the separate drain-pump system. The steam water from each heater is pumped into the main feed line by its own extraction pump. As already stated, in the event of the bursting of a tube or the failure of the extraction pump or motors, the condensate is returned to the condensate tanks by virtue of the steam pressure in the heater.

The heaters supplied with steam from the turbine have their air vents connected to the preceding turbine bleeder connection. Since the amount of air-venting depends upon the amount of oxygen in the feed water, and as this amounts to only about 0·1 milligramme per litre, the air vents were purposely closed for long periods and then opened, when it was found that under the same steam and water conditions no appreciable temperature-rise across the heaters was to be observed.

Feed-Pumps.—The feed water, after being de-aerated and evaporated, emerges from the distillation plant to the feed-heating bay through No. 3 heater at a pressure of about 50 lb. per sq. in. and 197° F. The water then enters a 2-stage rotary pump " C " which discharges at a pressure of 130 lb. per sq. in. through Nos. 4 and 5 heaters (see Fig. 13). From No. 5 heater the water enters a 5-stage rotary pump " B," the discharge pressure of which is 200 to 450 lb. per sq. in., and the water continues through Nos. 6 and 7 heaters into the suction omnibus-main from which the high-pressure final boiler feed-pumps " A " are supplied. These pumps boost the feed-water pressure up to a normal value of 820 lb. per sq. in. (900 lb. per sq. in. max.). The intermediate feed-pumps (" B " and " C ") are driven by a common 450-b.h.p., 6 600-volt, 1 200-r.p.m., 3-phase motor. The speed of this motor is varied automatically from 400 to 1 200 r.p.m. by a liquid rheostat [see Section 5 (*c*)].

TABLE 9.

Working Conditions of Feed-Heating Turbine.

Steam to turbine	Electrical output	Input of raw water	Gained distillate	Condensate input to No. 3 heater	Condensate to boilers	Steam pressure after governor valve	Steam bypassed
tonnes/day 1 310	kW 4 750	tonnes/day 1 256	tonnes/day 1 138	tonnes/day 4 650	tonnes/day 5 950	lb./sq. in. abs. 220	tonnes/day nil

The high-pressure boiler feed-pumps " A " are 8-stage rotary pumps, driven by 900-b.h.p., 6 600-volt, 1 200-r.p.m., 3-phase motors. Each pump is capable of delivering 660 000 lb. of water per hour. As these pumps had to deal with water at 401° F., large clearances were necessary. Differential expansion of the various component parts of the pump was the subject of careful consideration. The cross-section of this pump shown in Fig. 21 reveals details of the means adopted to allow for expansion.

The bearings of the " A," " B " and " C " pumps are of the pedestal type with oiler-rings, all bearings and glands being water-cooled.

Two 6-stage sealing water pumps are installed in the feed-heating bay, each being driven by a 60-b.h.p. motor and having a capacity of 25 tonnes per hour. These pumps supply de-aerated water at 95° F. to the suction and delivery end sleeves and bushes of all feed and extraction pumps, the sealing water being returned to the process condensate tanks in the distillation bay.

Owing to the large amount of feed and ancillary piping in the feed-heating bay, and also because of the desire to place all main feed-pumps on the turbine floor-level, it was necessary to support these pumps by individual steel structures. To mitigate as far as possible all vibration troubles the foundations for these structures were isolated from the concrete basement

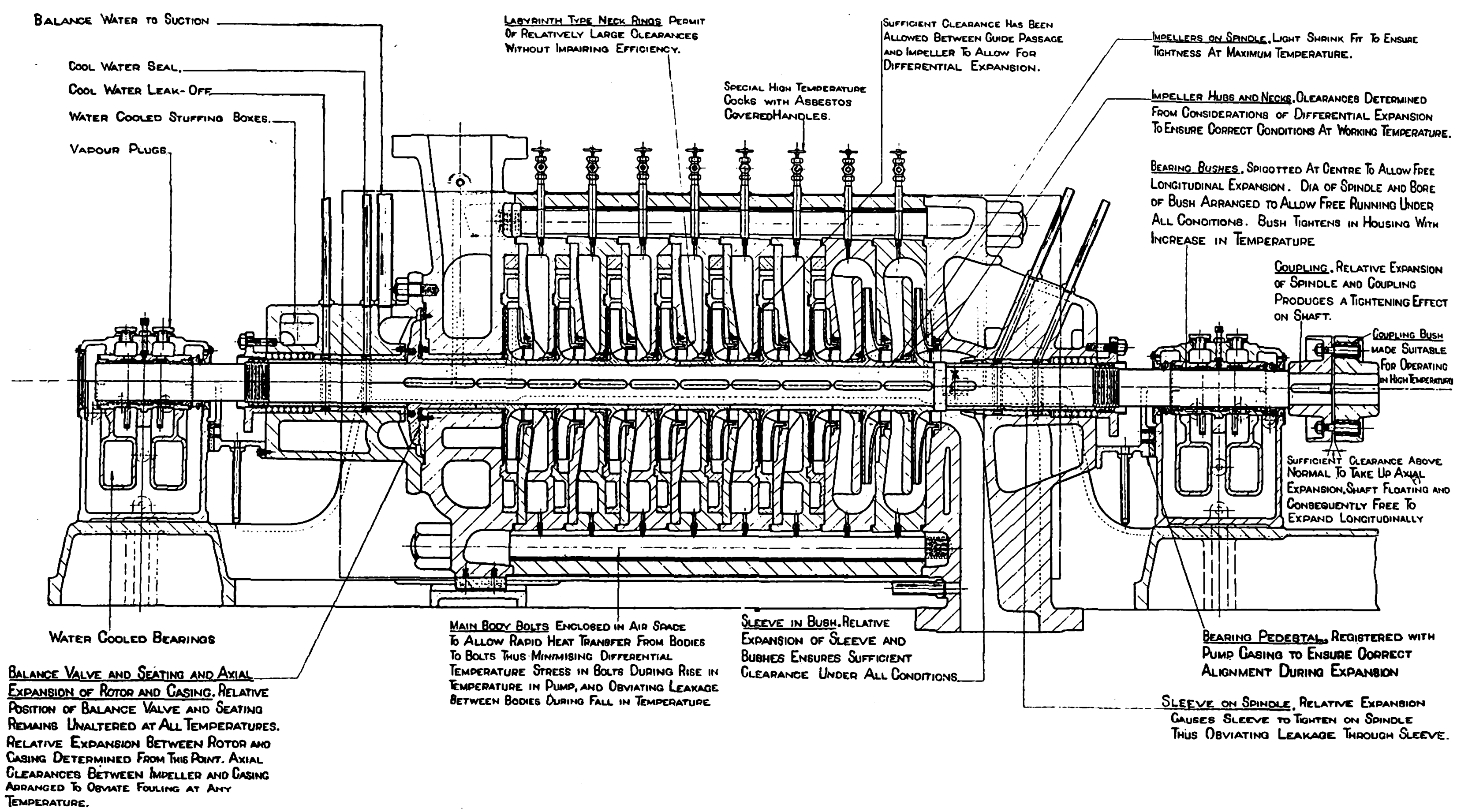

Balance Water to Suction
Cool Water Seal.
Cool Water Leak-Off.
Water Cooled Stuffing Boxes.
Vapour Plugs.
Labyrinth Type Neck Rings Permit Of Relatively Large Clearances Without Impairing Efficiency.
Special High Temperature Cocks with Asbestos Covered Handles.
Sufficient Clearance Has Been Allowed Between Guide Passage and Impeller To Allow For Differential Expansion.
Impellers on Spindle. Light Shrink Fit To Ensure Tightness At Maximum Temperature.
Impeller Hubs and Necks. Clearances Determined From Considerations of Differential Expansion To Ensure Correct Conditions At Working Temperature.
Bearing Bushes. Spigotted At Centre To Allow Free Longitudinal Expansion. Dia of Spindle and Bore of Bush Arranged to Allow Free Running Under All Conditions. Bush Tightens in Housing With Increase in Temperature.
Coupling. Relative Expansion of Spindle and Coupling Produces a Tightening Effect on Shaft.
Coupling Bush made Suitable For Operating in High Temperature
Sufficient Clearance Above Normal To Take Up Axial Expansion, Shaft Floating and Consequently Free To Expand Longitudinally
Water Cooled Bearings
Balance Valve and Seating and Axial Expansion of Rotor and Casing. Relative Position of Balance Valve and Seating Remains Unaltered at All Temperatures. Relative Expansion Between Rotor and Casing Determined From This Point. Axial Clearances Between Impeller and Casing Arranged To Obviate Fouling at Any Temperature.
Main Body Bolts Enclosed in Air Space To Allow Rapid Heat Transfer From Bodies To Bolts Thus Minimising Differential Temperature Stress in Bolts During Rise in Temperature in Pump, and Obviating Leakage Between Bodies During Fall in Temperature
Sleeve in Bush. Relative Expansion of Sleeve and Bushes Ensures Sufficient Clearance Under All Conditions.
Bearing Pedestal. Registered with Pump Casing to Ensure Correct Alignment During Expansion
Sleeve on Spindle. Relative Expansion Causes Sleeve to Tighten on Spindle Thus Obviating Leakage Through Sleeve.

FIG. 21.—Section of boiler feed-pump for 1 150 lb. pressure.

floor by an insertion of tar-macadam about 2 in. thick.

The axial thrust on the "A" and "B" pumps is taken by an hydraulically balanced sleeve. The jointing material between the middle bodies and the partition plates of these pumps consists of compressed asbestos fibre 0·008 in. thick.

A plan of the feed-heating bay is given in Fig. 5, this bay, together with the distillation bay, containing a total of 46 pumps.

(2) *Distillation.*

As already stated in the introductory remarks, about two-thirds of the total steam output from the boiler plant is passed out to the chemical plant for process purposes. About 60 per cent of the steam to process is returned to the process condensate tanks, and therefore it is necessary to "make up" the remaining 40 per cent. In order to keep the solids in the feed water down to 3 parts in 100 000 it was necessary to erect a distillation plant capable of evaporating the required amount of "make-up," approximately 3 000 tonnes per day under normal operating conditions. Of this quantity three-quarters is obtained from the quadruple-effect distillation sets, and the remainder from the sextuple-effect distillation sets.

Under conditions of maximum boiler load the output capacity of the entire distillation plant is between 7 000 and 8 000 tonnes per day, a figure which has probably never yet been exceeded in any boiler feed-water distillation plant.

The steam for this purpose is obtained from the feed-heating turbines. The raw water is obtained from a reservoir specially constructed on Billingham Beck, a small tributary of the River Tees. This reservoir is situated about ½ mile from the power plant, and two rotary pumps each capable of pumping 225 tonnes of water per hour, driven by 60-b.h.p. motors, are installed in a pump-house at the reservoir.

Each quadruple-effect distillation plant consists of six evaporators, two evaporators forming the first-effect, two forming the second-effect and the two remaining evaporators constituting the third- and fourth-effects respectively. Exhaust steam from the feed-heating turbine passes into the first-effect, heating the raw water supplied thereto. The vapour produced in this effect passes to the steam space of the next effect, where the process is continued in a similar manner.

Some of the vapour from the second-effect passes to the raw-water heater which heats the raw water before it enters the first- and second-effects. Another portion of the vapour from the second-effect goes to the process condensate (No. 2) heater and raises the temperature of the feed water to a predetermined value. The remainder of the vapour passes to the third-effect where the process is continued.

The vapour from the fourth—and last—effect goes to the raw-water de-aerator and to the process condensate de-aerator where the heat in the vapour is utilized in raising the temperatures of both the raw water supplied to the evaporators and the process condensate, or boiler feed, which passes into the feed-water system.

Each evaporator is fitted with a condensate drain from the steam header, this drainage water being flashed back to either the process condensate heater or de-aerator (see Fig. 13) from two flashing chambers or flash-boxes. A blow-down sludge-box is provided for each two evaporators, the sludge being discharged to waste whilst the vapour is led to the raw-water de-aerator.

The evaporators are of the horizontal-tube type, steam passing on the inside of the copper tubes and raw water on the outside. Large stuffing boxes are provided in one end tube-plate of each evaporator to allow the tubes to be withdrawn for the removal of scale.

The raw-water supply to the distillation plant is stored in two tanks having a combined capacity of 30 tonnes. The raw water flows by gravity through a preliminary heater incorporated in the raw-water de-aerator. When the water reaches the heating surface of the de-aerator it is heated to the boiling point equivalent to the pressure maintained in the water space and is then pumped to the evaporators.

The returned condensate from the factory and from the condensing turbines in the power plant is stored in three tanks having a combined capacity of 135 tonnes, which quantity can maintain the normal feed-water supply for nearly 3 hours. All the condensate is first de-aerated and then passes to No. 2 heater and then via Nos. 3, 4, 5, 6 and 7 heaters and the final feed pumps ("A") to the economizers.

The evaporators, etc., comprising the sextuple-effect distillation plant are similar to those in the quadruple-effect plant. When the first quadruple-effect plants were started up the demands for make-up water for the boiler feed were very heavy, and the plants while in operation were used continuously for prolonged periods. As this occurred in a very dry summer the quality of water supply was such that it was found expedient to change over to the supply from the district water board (Tees Valley) in order to maintain continuous maximum operation.

Investigations have been carried out in connection with pre-treatment of the raw water, whilst a method has been tried out, and found to be successful, whereby the plant can be expeditiously cleaned when required. As a result of these investigations it is expected that a return to the use of Billingham Beck water will shortly be made.

(*e*) *Switchgear.*

The arrangement of the main switchgear and reactors, the auxiliary e.h.t. and l.t. switchgear, and the auxiliary d.c. switchgear is depicted in diagrammatic form in Fig. 22.

(1) *Main Switchgear.*

This is situated on the same level as the turbines (Fig. 9) and consists of 56 panels of the metal-clad, compound-filled, double-busbar type, rated at 11 000 volts and remote-controlled electrically from the control room on the floor above. There are at present three sections, erected back to back, with a brick dividing-wall between, two sections being in the outer gallery, and the third section, with space for a fourth, being in the inner gallery. There is ample room between the back of the switchgear and the dividing wall, and the gallery floors slope gently downwards to a gravel-filled duct running along the foot of the outer wall of each gallery for the absorption of accidental oil leakage. The oil-vent bus-pipes terminate outside the building at each end and are also provided with drain cocks at suitable positions. The trifurcating boxes are mounted beneath the floor (i.e. on the roof of the 6-ft. high main cable race, Fig. 2) and are of the right-angle type, thus permitting a direct and very neat lead-away, horizontally, of the large number of heavy feeder cables out through the switch-house wall on to a steel bridge running the entire length of the switch house, at the same level as the emerging cables. All cables and pipes are carried on such bridges throughout the factory, buried cables being impracticable on such a congested site, quite apart from liability to attack by leakage of chemicals into the ground.

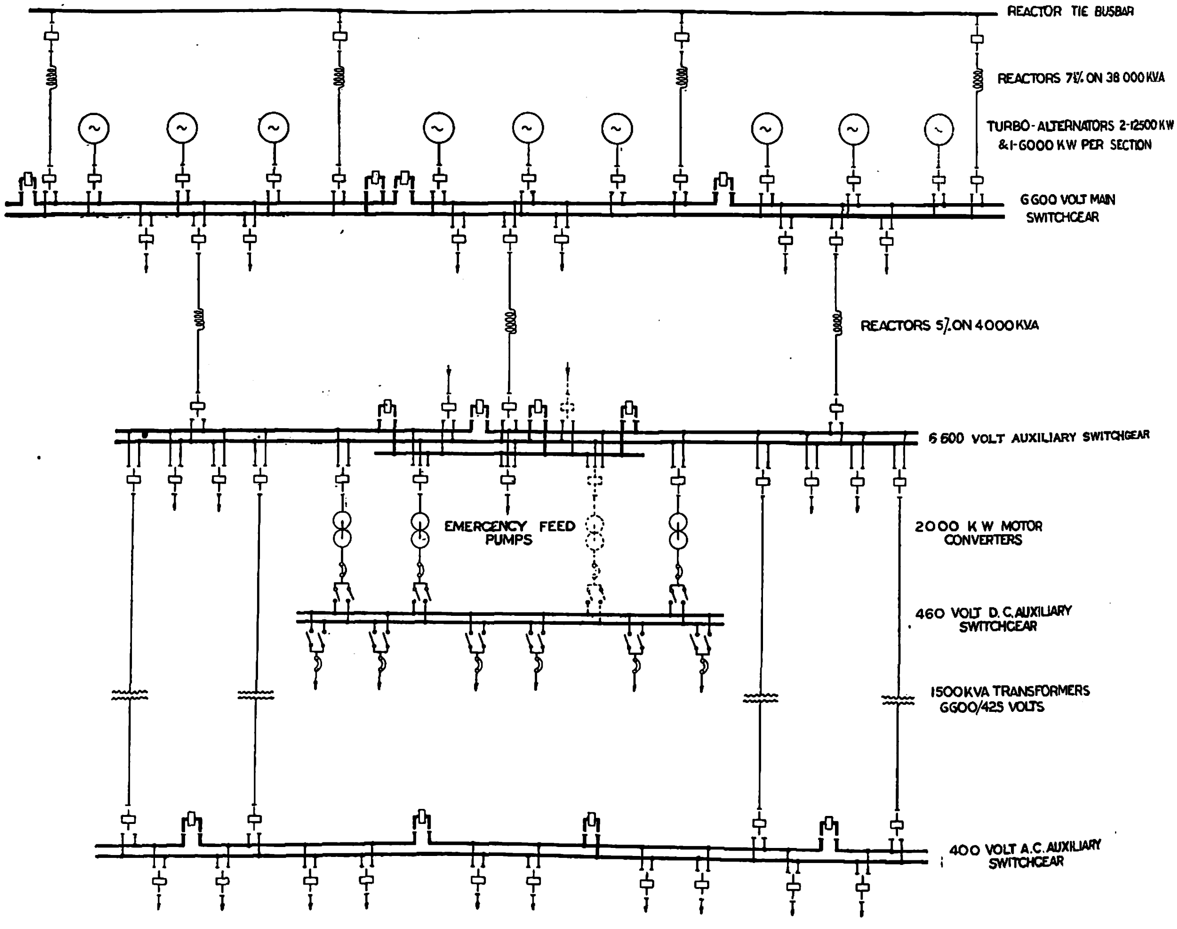

REACTOR TIE BUSBAR
REACTORS 7½% ON 38 000 KVA
TURBO-ALTERNATORS 2-12500 KW & 1-6000 KW PER SECTION
6600 VOLT MAIN SWITCHGEAR
REACTORS 5% ON 4000 KVA
6600 VOLT AUXILIARY SWITCHGEAR
EMERGENCY FEED PUMPS
2000 KW MOTOR CONVERTERS
460 VOLT D.C. AUXILIARY SWITCHGEAR
1500 KVA TRANSFORMERS 6600/425 VOLTS
400 VOLT A.C. AUXILIARY SWITCHGEAR

FIG. 22.—Arrangement of main and auxiliary switchgear.

The switchgear galleries extend over the railway running inside one end of the building, thus allowing switchgear to be lifted directly out of the trucks and up through a square opening in the floor of each gallery.

Each of the three sections is supplied by one primary set, one condensing set and one feed-heating set, totalling 31 000 kW at 6 600 volts, 40 cycles. The double-busbar switchgear in each substation is also divided into three sections, and is fed on the radial-feeder system by three feeders, any two of which are amply capable of carrying the full load of the substation continuously.

The main oil circuit-breakers have a rupturing capacity of 500 000 kVA, any fault being limited to this value by reactors between the sections, which are normally indirectly connected via these reactors and a common reactor tie busbar, but which can also be directly connected by section switches, overload-protected, in the event of the failure of a reactor. These main reactors consist of 3 single-phase open-type reactors of value $7\frac{1}{2}$ per cent on 38 000 kVA. They are mounted separately in brick cubicles, adjacent to the tie busbar switchgear, and occupy the whole of the outer gallery on the ground floor, the inner gallery containing the house-feeder reactors, the e.h.t. auxiliary switchgear and the neutral earthing resistance and its switchgear (see Fig. 10).

(2) *Auxiliary E.H.T. Supply* (6 600 *Volts*).

The auxiliary e.h.t. switchgear is also provided with duplicate busbars and is supplied from the main switchgear by three feeders, one on each section, through single-phase reactors, having a value of 5 per cent on 4 000 kVA, and of the same type and make as the main reactors.

The busbars are arranged in two sections with a transfer busbar common to both. In addition a third busbar, also common to both sections, is provided which is supplied direct from the Newcastle-upon-Tyne Electric Supply Co.'s 11 000-volt network through a 11 000/6 600-volt transformer as described in Section 5 (*a*). In this way an alternative supply is always available for the more important auxiliaries in the power station.

The auxiliary e.h.t. switchgear supplies, direct, the 6 600-volt motors driving the main and intermediate feed-pumps; the auxiliary l.t. switchgear through four 1 500-kVA, 6 600/400-volt transformers; and the auxiliary d.c. switchgear through three 2 000-kW 6 600/460-volt motor-convertors. It is situated on the ground floor of the switch house (Fig. 10) and is of the metal-clad, compound-filled, horizontal draw-out type. The oil circuit-breakers have a rupturing capacity of 100 000 kVA and are electrically operated from the control room.

(3) *Auxiliary L.T. Supply* (400 *Volts*).

The auxiliary l.t. switchgear is erected in a gallery on the turbine floor-level in the switch house, open to the main turbine room (Fig. 9) and immediately above the transformers from which it is supplied (Fig. 10). It is provided with duplicate busbars, the normal busbar being divided into four sections, one section to each transformer, whilst the transfer busbar is common to all sections. The outgoing feeders supply the various auxiliary distribution in the boiler and power plants. This switchgear is also of the metal-clad, compound-filled, horizontal draw-out type and is arranged for hand operation.

(4) *Auxiliary D.C. Supply* (460/230 *Volts*).

In order to cater for the more important auxiliary drives and particularly those requiring variable speed, e.g. the forced-draught fans, both primary and secondary, the induced-draught fans and the coal feeders, three 2 000-kW 460-volt motor-convertors are installed, space being reserved for a fourth.

These sets operate at the relatively high speed of 480 r.p.m., the current per brush arm being approximately 1 450 amperes. Normally, two convertors are running, one being fed from the auxiliary e.h.t. busbars and the other from the Newcastle Electric Supply Co.'s mains, both machines running in parallel on the d.c. side [see Section 5 (*a*)].

Protection is afforded by means of fuse time-limit overload and reverse-current trips which are so set as to ensure continuity of supply in the event of a sudden failure on either e.h.t. system. Operating experience has so far indicated that this forms a reliable and satisfactory arrangement, provided the loads on the machine are not exceptionally light, in which case variations in a.c. supply voltage are apt occasionally to cause a machine to trip out under the action of the reverse-current protection.

Control is effected from pedestals in the control room, on which are mounted a complete set of instruments and push-buttons. The closing of the main circuit-breaker causes the set to start up and synchronize, the operation being made visible in the control room by the provision of a voltmeter connected to the slip-rings, together with indicating lamps. Paralleling with the d.c. busbars is similarly effected by push-button operation, by which means the d.c. voltage is previously adjusted to the correct value.

The auxiliary d.c. switchgear is placed in line with, and in the same gallery as, the auxiliary low-tension a.c. switchgear (Fig. 9) and is situated immediately over the motor-convertors on the ground floor (Fig. 10). The positive and negative busbars are in duplicate and are mounted above and to the rear of the switchboard, with an insulated barrier between the positive and negative bars. An earthed neutral bar is also provided so that a 230-volt supply may be obtained for battery charging, switch operation, and emergency lighting.

This switchboard is of the "dead front" type with hinged sheet-metal panels and is arranged for hand operation. All circuit breakers, switches, isolating links and other live parts are mounted on a suitable structure behind the front panels, which carry the necessary instruments. A non-automatic indicating diagram is erected above the board.

(5) *Control Room.*

As may be seen from Fig. 8, the main control panels are arranged in three groups, the generator panels being distinct from the feeder panels. The three sections of the former are accommodated along the south wall of the control room, whilst the feeder panels are arranged along the east and west walls. The auxiliary e.h.t. control panels are placed along the north wall, the motor-convertor control pedestals being immediately in front of their corresponding switchgear control panels.

The generator and reducing-valve control pedestals are arranged in a semicircle in the centre of the room, around the operator's desk, and facing the generator control board. The pedestals are arranged in three groups of four each, controlling respectively a primary set, a reducing valve, a condensing set and a feed-heating set.

All control panels are of the double sheet-steel cubicle type. A gangway down the centre of the cubicles permits of easy access to all connections and is closed at each end by a sheet-steel door. This arrangement of control panels presents a very neat and simple appearance and occupies a minimum of space. On the front panel facing the operator are mounted only the indicating instruments, the red and green indicating lamps and the master control switch, all recording instruments, Merz-Price and overload relays, time-limit fuse boxes, testing terminals, integrating meters, voltage and other regulators and other such apparatus being mounted on the duplicate cubicles at the back. Thus on a feeder panel there are only an ammeter, two lamps and a switch facing the operator, with the operating diagram above, and consequently his attention is not distracted by a mass of other instruments and relays not essential for frequent reference. Along the top of the four control boards is placed a system diagram which gives the position of all isolating and selector switches and circuit breakers, these being shown by means of automatically-operated indicating discs.

In addition to the main control boards there is a further board on which are mounted various instruments for indicating and recording the pressure and flow of steam in the secondary receiver system, the water-level in the condensate tanks, etc., together with push-button control of the 48-in. main circulating-water inlet valve.

In a corner of the control room and in line with generator control panels are situated two more panels, one for the automatic frequency-control apparatus and the other for the automatic synchronizing apparatus referred to in Section 5 (*b*). The neutral-earthing switchgear control is described in Section 5 (*c*).

The alternators and transformers are equipped with current-balance Merz-Price protection, the ordinary feeders with voltage-balance Merz-Price and overload protection, the other feeders with split-conductor protection, and the motor-convertors with fuse time-limit overload and reverse-current protection. Voltage regulators are installed for each alternator. The total generated output is summated and recorded on a special recorder which also gives simultaneous records of voltage and sequence of switching operation of the individual generators. All stator temperature indicators are grouped together on the same panel as other instruments common to all machines. The telegraphs are of the electrically-operated pointer-dial type. A complete automatic telephone exchange has been installed, connecting the control room with various parts of the plant and with all substations.

The entire control room is built on the principle of a room within a room, in order to obtain quietness and cleanliness. The main entrance to it opens from the centre of a closed passage running the length of the whole of the top floor and permitting communication between the offices, model room and lavatories at one end of the bay with the offices, battery, booster and automatic telephone exchange rooms at the other end of the bay, at which end are also situated the lift and staircase. All instruments are of the flush type, finished in polished black, no nickel plating being employed anywhere. Above the control room is an internal opaque glass roof (Fig. 2) between which and the outer roof are fitted the electric lights. Any dust percolating through the outer roof settles on this internal glass roof, and gangways extending the length of the bay enable it to be easily brushed off. The steel members supporting the internal glass roof have holes in their vertical faces for exit ventilation. The outer glass roof of all bays and also the windows in the walls can be hosed by warm water supplied from a series of cocks regularly spaced along pipework forming the top handrail of gangways running around the outside of the building at window and roof levels.

Section (4). THE AUTOMATIC REGULATION OF STEAM PRESSURE AND STATION FREQUENCY.

(*a*) *Stability of Operation.*

It has already been pointed out that one of the outstanding features of the station, in fact the main outstanding feature, is the extraction from the station, for process purposes, of roughly two-thirds of the total steam passing through the primary turbines. Such an arrangement inevitably gives rise to many serious problems, not the least of which concerns the stabilizing of the process steam pressure. This problem in its original form presented itself as one of load-sharing between the primary turbines and the other turbines in the station, and it was early recognized that the maintenance of the correct steam pressure essential for process work was entirely dependent upon this factor.

Any changes in the steam load and/or the electrical load would upset conditions in the station, and it therefore became necessary to calculate the precise effects of these changes upon the process steam-supply. In doing this the relative importance of the various factors involved, such as the design of the turbine governors, the electrical frequency and the changes in the rates of steam flow through the turbines for changes in steam conditions, was revealed. It was found that the results could be expressed most conveniently in the form of partial differential equations giving the variations in frequency and process steam-pressure for given changes in steam and electrical loads. In formulating such equations, certain approximations had necessarily to be made and, as would be expected, difficulty arose in attempting to allot numerical values to certain of the partial differential coefficients from turbine-design data.

The general purpose of the analysis, however, was achieved in that it enabled the following general conclusions to be drawn:—

(1) For maximum stability the governors on the primary turbines should be coarser than those on the other turbines, to an extent proportional to the total quantities of steam passing through the two classes of turbines. Under this condition there is practically no change in steam pressure due to a change in electrical load. The same does not, of course, hold good for changes in steam demand.

(2) The greater the proportion of steam extracted from the station, the greater is the tendency towards unstable running.

(3) Instability in the mathematical sense can ensue under certain conditions of loading in combination with certain governor characteristics. These conditions were determined by equating to zero the coefficients of the differentials representing the changes either in pressure or in frequency, the coefficients being actually the same in each case.

As a result of these conclusions, the governors on the primary turbines were designed to produce a rise in speed of 9 per cent when full load is gradually thrown off, this being about 3 times the speed rise in the case of the lower-pressure turbines, the governors of which are of the usual sensitive type. This procedure in effect makes the primary turbines base-load machines and reduces to a minimum the risk of encountering a critical or unstable running condition, both steam and electrical, during the gradual growth of load on the station.

In considering the stability of turbine operation the steadying effect of the existing installation of low-pressure boilers supplying steam direct for process work was not overlooked, but it was felt desirable that the station should be as stable in itself as possible. Apart from this, the stabilizing action, which is virtually akin to a flywheel effect, can only be obtained at the expense of sudden changes in demand on this existing plant which, being of relatively small capacity, is therefore liable to priming. Mention must also be made of the stabilizing effect obtainable from the storage capacity of the large network of low-pressure steam mains supplying steam to the factory, and since the total weight of steam in these pipes amounts to about 6 tons this effect is by no means inconsiderable.

(b) *Co-ordinated Control of the Boiler Plants and Power Plant.*

Having established certain points in connection with the speed regulation of the turbines with a view to obtaining stable operation, the question arose as to which was the most suitable method of controlling the process steam-pressure, and upon this devolved the entire policy to be adopted in the method of operating not only the turbines but also the boilers.

It was finally decided that the existing low-pressure boilers should maintain a constant rate of firing, while the new high-pressure boilers should steam at a constant pressure.

There were, broadly speaking, two courses open, viz.:—

(1) The low-pressure boilers could steam at a constant pressure while the high-pressure boilers maintained a constant output.

(2) The low-pressure boilers could maintain a constant output with pressure control effected by varying the loads on the primary turbines.

The difference between these two courses is, briefly, that in the first case any fluctuations in load are taken up by the smaller boiler plant, while in the second case they are taken up by the main boiler plant which, under these conditions, must steam at a constant pressure.

The disadvantage of the first case is that any sudden large variations in load, such as are likely to occur under emergency conditions in the factory, cannot be so effectively coped with as in the second case, and for this reason, as well as for other subsidiary reasons, the second course was adjudged to be the more logical one to adopt.

It will be seen that this policy entails the control of the process steam-pressure by the power plant operatives. This can be carried out in two ways:—

(1) By altering the steam admission to the primary turbines.

(2) By altering the steam admission to the reducing valves.

The first method alters the frequency of the station as a result of the large speed regulation of the primary turbines and, further, it upsets the loads on the feed-heating turbines.

The second method is the better one as judged from these considerations alone, but on the other hand it will be appreciated that the unnecessary bypassing of steam, with the consequent loss in thermal efficiency, cannot be considered on the score of ease of control alone.

(c) *Mode of Operation of Automatic Scheme.*

In considering the question of pressure control, serious doubts arose as to whether the pressure itself would remain sufficiently stable to enable any variations to be readily followed manually by an operator or whether some form of automatic control would be necessary. It was therefore felt that a scheme which would virtually take charge of the operation of the station in a satisfactory and reliable manner under all conditions would not only ease the burden on the operating staff but would also ensure steadier conditions normally and quicker operation in an emergency.

To decide upon the type of scheme to employ which would satisfactorily meet all requirements appeared at first to be fraught with great difficulty, as at the time there was no such scheme in existence which had been designed to cope with such unusual conditions. The ordinary form of mechanical control as fitted to extraction turbines in which primary and condensing machines are combined in one unit could not be adapted to give the necessary flexibility in the case of machines forming separate units, as at Billingham, and for this reason it was decided to install a system of electrical control.

The scheme * which was finally developed and which is now installed combined a recently developed scheme † for automatic frequency control, with a means of maintaining at the same time correct pressure conditions, and is shown diagrammatically in Fig. 23.

Stated briefly, the control imparts correcting impulses to the primary turbine governor motors and reducing-valve motors in such a way as to maintain the process steam pressure at its correct value of 290 lb. per sq. in., and at the same time imparts similar impulses to the condensing machines in such a way as to maintain the station frequency at its normal value. In each case the number of impulses transmitted in unit time increases as the pressure or frequency error increases, and in this way stable control with an entire absence of any tendency towards hunting is ensured.

The operation of the control system under these conditions is therefore such that the condensing machines take up any changes in load which may be caused either by changes in electrical demand or by re-adjustments in the steam admission either to the primary or to the feed-heating turbines. It will be seen, therefore, that the output generated by these latter machines is treated purely as a by-product, their output being unaffected by any variations in the total electrical demand upon the station.

Provision is made to ensure equal sharing of load between any primary sets which may be on load, and likewise between condensing sets.

This provision is necessary because of the fact that a control impulse of given duration can hardly be expected to give, in practice, a precisely similar movement to the speeder gear of each machine when more than one machine of the same class is being operated on, in parallel. In course of time even minute differences in controlling effect might prove cumulative and be a serious source of unequal loading. To achieve equal load-sharing, each machine is provided with a relay consisting of two balanced wattmeter movements, one of which provides a torque proportional to the load of that particular generator, the other movement acting with opposing torque proportional to the average load on all generators of the same class. Contacts are provided in such a manner as to cut off "raise" impulses to any machine which may be taking more than its fair share of load, and to cut out "lower" impulses to any machine which is relatively underloaded.

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* I.C.I.-Warren Patent No. B.P. 320038.

† Reyrolle-Warren Patent No. B.P. 303779.

During the normal running of the station it frequently happens that the primary turbines are running fully loaded with a certain quantity of steam being bypassed through a reducing valve. To cater for this condition four limit-switches are provided on the speeder-gear mechanisms of the primary turbines; these operate when these machines are fully loaded and serve to change over the pressure control from the turbines to the reducing valves. The passing-on of the control in this manner takes place entirely automatically in either direction.

Long periods frequently arise during which it is possible to generate all the load by means of the primary and feed-heating turbines alone. This possibility was not overlooked in the design of the control scheme. Under these new conditions all fluctuations in electrical load due either to changes in demand or to alterations in load on the feed-heating turbines have to be taken up by the primary turbines, and the surplus high-pressure steam, the existence of which is, of course, now a necessary condition of operation, has to be bypassed by means of the reducing valves.

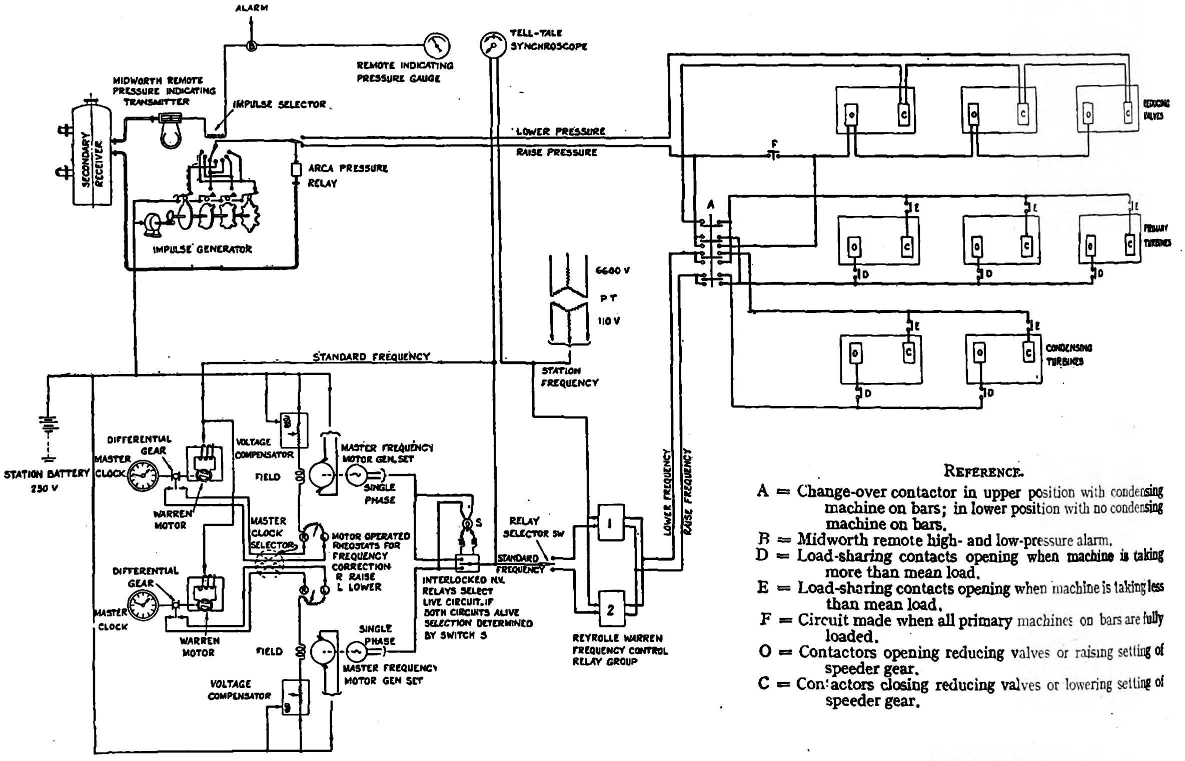
To cater for this, a change-over contactor (see Fig. 23) is provided which comes into operation automatically and serves to bring into operation both the frequency control on the primary turbines and the pressure control on the reducing valves. This particular feature, which is of the greatest importance in achieving the principles of operation already laid down, is effected quite simply by the mere interchanging of certain circuits and forms an apt illustration of the essential flexibility afforded by the system of control adopted, a flexibility, moreover, which it is practically impossible to achieve in any non-electrical system.

(*d*) *Description of Automatic Scheme.*

Space does not permit a detailed description of the control apparatus itself to be given, but a general outline of the essential items will be of interest, not only because it is the first installation applied to power station control but also because of the rapid development and utilization of automatic control features in all branches of engineering which have taken place in recent years.

The pressure-control impulses are obtained by the rotation of a drum which is divided circumferentially into four segments, each of which generates impulses at a constant rate depending upon which of the four segments is in operation (see Fig. 23). The selection of drum segments is effected by means of a device responsive to steam pressure, provided with contact-making segments corresponding to those on the drum. The result of this interaction is that impulses are generated with a frequency which increases, the further the steam pressure deviates from its normal value.

Discrimination between pressures above and pressures



ALARM
TELL-TALE SYNCHROSCOPE
REMOTE INDICATING PRESSURE GAUGE
MIDWORTH REMOTE PRESSURE INDICATING TRANSMITTER
IMPULSE SELECTOR
SECONDARY RECEIVER
LOWER PRESSURE
RAISE PRESSURE
ARCA PRESSURE RELAY
IMPULSE GENERATOR
6600 V
P T
110 V
STANDARD FREQUENCY
STATION FREQUENCY
STATION BATTERY 250 V
DIFFERENTIAL GEAR
MASTER CLOCK
WARREN MOTOR
VOLTAGE COMPENSATOR
FIELD
MASTER FREQUENCY MOTOR GEN. SET
SINGLE PHASE
MASTER CLOCK SELECTOR
MOTOR OPERATED RHEOSTATS FOR FREQUENCY CORRECTION
R RAISE
L LOWER
S
INTERLOCKED N.V. RELAYS SELECT LIVE CIRCUIT. IF BOTH CIRCUITS ALIVE SELECTION DETERMINED BY SWITCH S
RELAY SELECTOR SW
STANDARD FREQUENCY
LOWER FREQUENCY
RAISE FREQUENCY
1
2
REYROLLE WARREN FREQUENCY CONTROL RELAY GROUP
DIFFERENTIAL GEAR
MASTER CLOCK
WARREN MOTOR
FIELD
SINGLE PHASE
MASTER FREQUENCY MOTOR GEN SET
VOLTAGE COMPENSATOR
A
F
O
C
E
D
REDUCING VALVES
PRIMARY TURBINES
CONDENSING TURBINES

REFERENCE.

A = Change-over contactor in upper position with condensing machine on bars; in lower position with no condensing machine on bars.
B = Midworth remote high- and low-pressure alarm.
D = Load-sharing contacts opening when machine is taking more than mean load.
E = Load-sharing contacts opening when machine is taking less than mean load.
F = Circuit made when all primary machines on bars are fully loaded.
O = Contactors opening reducing valves or raising setting of speeder gear.
C = Contactors closing reducing valves or lowering setting of speeder gear.

FIG. 23.—Scheme for the automatic regulation of process steam pressure and station frequency.

below normal is obtained by means of a contact-making pressure-regulator of a standard type. The function of this regulator is duplicated on the pressure-responsive device operating in conjunction with the drum, so that, if either apparatus becomes faulty, control is immediately cut off before mis-operation can result.

The adjustment of the actual length of the impulses themselves is carried out by means of two time-lag relays which are so connected that the failure of one of them can at the worst only effect cessation of control and so enable the operator to put a stand-by set of apparatus into commission.

The automatic frequency-control scheme marks an important stage in the development of this type of control in this country, and the following brief description of it forms an interesting comparison with the recently evolved American schemes, some of which have now been applied to the control of power stations.[*]

In contradistinction to the prevalent American practice of generating the controlling impulse at a steady rate and graduating the control by varying the lengths of the impulse, the method employed at Billingham is to retain a fixed duration of impulse and to vary the frequency with which it occurs. Thus, if the system frequency departs from normal by 1 cycle per second, we get one impulse generated per second; in fact the actual frequency of the impulses is numerically the same as the frequency error.

In actual practice it is found that under normal conditions connection is made, broadly speaking, once every 20 seconds, though it must be remembered that this time-interval would be somewhat longer were it not for the influence of the varying loads on the primary turbines.

The standard frequency is obtained from a standard chronometer which controls the speed of a small motor-generator set by means of two movable contacts which vary the field strength of the d.c. driving motor when its speed varies slightly from the standard set by the clock. In addition, there is a quick-acting voltage-compensating device which renders the speed of the set independent of any fluctuations in the d.c. supply voltage.

The generator is wound to give a single-phase supply at 110 volts, 40 cycles, and this operates a set of relays in conjunction with a similar supply from the potential transformers connected to the running turbo-alternators. The relays act as an electrical differential device in much the same way as an ordinary synchroscope, generating the controlling impulses in the manner already described.

In common with the remainder of the automatic apparatus, the frequency-control relays and the motor-generator, together with its various controlling devices, are in duplicate, an interesting feature in this case being the provision for the automatic changing-over from one motor-generator to another in case of any trouble developing on one machine.

With a view to ensuring that the control-room attendants should have at all times a ready means of observing the behaviour of the controls, indicating lamps are provided which light up when controlling impulses are being given to the turbines or to the reducing valves. In addition, an indication of the process steam-pressure is provided on a pressure gauge mounted in a prominent position on the control pedestals, beside which is also mounted a synchroscope to indicate any deviation of the station frequency from the standard.

To convert any turbine or valve from automatic to manual operation, suitable switches are provided on each generator control panel and reducing-valve pedestal.

To cater for times when it should be necessary to operate the station entirely manually, care was taken to ensure that the task should be rendered as easy as possible for the operator. Thus the regulation of the steam admission to all turbines and reducing valves is carried out on the control pedestals, from which point the operators can observe the steam pressure, the station frequency, the generator loads and the reducing-valve openings.

In addition, indication is provided in the control room of the exhaust pressures of the feed-heating turbines, together with the levels of the water in the process condensate-tanks. These latter indications are sufficient to enable the feed-heating turbines to be regulated in accordance with the steam requirements of the evaporation plants.

The operating experience obtained during the past few months has shown that the behaviour of the plant follows very closely along the lines anticipated and it has shown, in particular, how important is the course regulation of the primary turbine governors in its effect upon the operation of the plant as a whole. The installation of the automatic control scheme, which, as already described, was rendered essential by the unusual conditions of steam and electric load requirements existing at Billingham, has been proved by experience to be fully justified, and the success which has attended its adoption may be considered to mark the beginning of a new era in power-plant control.

Section (5). OTHER SPECIAL FEATURES.

(*a*) *Alternative Auxiliary Supply System.*

The most important consideration from the point of view of continuity of supply of both steam and electricity from the power station is that of reliability of the electrical supply for driving the auxiliaries.

The normal auxiliary supply system has already been described.

Various methods of obtaining a duplicate supply were considered and it was ultimately decided to utilize the existing 11 000-volt supply from the adjacent North Tees power station. The chief difficulty arising in the utilization of this source lay in running the two supply systems in parallel, this being essential in order to avoid even a momentary interruption of supply to the auxiliaries in case of failure of the normal supply. Bearing in mind this consideration and having regard to the fact that nearly all the essential boiler-house auxiliaries require speed variation, the situation has been met by permanently connecting one 2 000-kW motor-convertor to a third or "transfer" busbar on the auxiliary e.h.t. switchgear which is supplied from a 11 000/6 600-volt transformer. The transformer is situated in one of the substations of the existing 11 000-volt network and is connected to the "transfer" busbar by a suitably protected 2 000-kVA interconnector (Fig. 22).

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[*] R. Brandt: "Automatic Frequency Control," *Electrical World*, 23rd February, 1929; J. U. Benziger and J. T. Johnson, "Automatic Frequency Control at Mitchell Dam," *ibid.*, 29th June, 1929, and H. A. McCrea: "Automatic Control of Frequency and Load," *General Electric Review*, 1929, vol. 32, p. 309.

This motor-convertor is paralleled on the d.c. side with the remaining convertor fed from the "normal" auxiliary e.h.t. busbar and remains "floating" on the Newcastle Electric Supply Co.'s mains, i.e. its field is adjusted so that it is running light. In the event of a failure of the power station supply the normally-loaded convertor automatically shuts down and the one running from the public supply immediately takes over the load.

The total emergency load comprises the following essential auxiliaries:—

(1) Forced- and induced-draught fans (d.c.).
(2) Primary air fans, coal feeders and air preheaters (d.c.).
(3) Stand-by condenser extraction pumps (d.c.).
(4) Stand-by feed pumps (a.c.).

The motors for the first three groups are supplied from the auxiliary d.c. busbars and hence their duplicate supply is derived from the motor-convertor running on the "transfer" busbar. On the other hand, all feed pumps are driven by 6 600-volt motors supplied direct from the "normal" auxiliary e.h.t. busbars, with the exception of the two stand-by feed pumps which are supplied from the "transfer" busbar. These two pumps are able to deal with a feed-water supply sufficient to maintain three boilers on normal load, which adequately meets the factory steam demand under emergency conditions.

(b) *Automatic Synchronizing.*

Automatic frequency-control and steam-pressure regulation having been adopted as a necessity it was decided to employ a recently developed, relay-operated scheme * of automatic synchronizing of the alternators, upon the principles of which the former was based.

The method of ensuring the essential reliability of operation is unique in that it is effected by interlocking certain of the relays in such a way that the failure of any one of them renders the apparatus incapable of synchronizing the alternator. The sequence of operation is analogous to that of the combination lock on a safe, in that faulty operation at any point in the sequence prevents its completion and thus also the opening of the safe.

The speed-controlling function embodied in this apparatus is similar to the method of operation of the automatic frequency control described in Section (4), with the exception that the running machines now provide the frequency with which the speed of the incoming machine is matched. In this way quick and accurate operation, with an entire absence of any tendency towards hunting, is obtained.

To obviate any possibility of a set being "motored" when synchronized, the apparatus permits of paralleling only when the alternator is running slightly above the synchronous speed. This feature would occasionally give rise to slow operation when the alternator speed is initially below normal, as in this case exact speed-matching is obtained before synchronizing can take place. In order to prevent this the "raise speed" impulses are designed to persist for a greater length of time than the "lower speed" impulses, so that the period of exact speed-matching is materially reduced under these circumstances.

The average time taken for the apparatus to synchronize an alternator by this method, starting from the moment when the turbine is under the control of its governor, is approximately 30 seconds. This is considerably in advance of manual operation. Although both methods are available in the station, the former is looked upon by the operating staff as being a distinct asset, especially in a station of this character supplying both steam and electricity, where, in the interests of flexibility, a larger number of relatively small sets have been installed than would have been the case in a station built solely for electricity supply.

(c) *Automatic Control of Feed Pumps.*

A method * of maintaining a constant discharge pressure on the intermediate feed pumps by automatic means has been devised in the shape of a contact-making pressure regulator, the contacts of which are connected to the contactors controlling the speeds of the pumps. Direct-current control impulses are then transmitted at intervals which maintain the pump speeds at the value necessary to give the required pressure. Up to the time of writing, this feature has not been in operation, but it is expected to prove as successful as the other automatic features, of the principles of which, in fact, it is merely another application.

(d) *Battery Booster Control Scheme.*

Several of the vitally important d.c. circuits, such as those feeding the emergency lighting, the reducing-valve and governor motors and the oil-switch solenoids are fed directly from a 230-volt, 400 ampere-hour battery which is in turn coupled to the positive and neutral wires of the main d.c. supply through a contactor fitted with reverse-current protection (Fig. 24).

The battery is charged by means of a reversible booster which is also used to maintain the voltage of the battery busbars at the normal value during such times as the battery is disconnected from the main supply, this being done by means of a voltage regulator operating on a separate exciter coupled to the main shaft. Under normal working conditions the battery is left floating, the number of cells being so chosen that when fully charged they take a small "trickle" charge which is just sufficient to maintain the plates in a healthy condition.

The control of the battery and booster represents a divergence from normal practice in certain respects. In the first place it was found to be possible to dispense altogether with the usual buffer resistance by suitably designing the various control circuits. In order to appreciate how this could be done it is sufficient to remember that no danger exists in momentarily short-circuiting the booster during the running-up period before the field circuit is energized. On the other hand, there is no disadvantage in open-circuiting the battery circuit altogether while the booster bars are in parallel with the main d.c. supply or, in other words, when the line contactor is closed. By adopting such a procedure the heavy current which would otherwise circulate through the booster armature when short-circuited, with a residual field current still flowing, would cause damage and necessitate the provision of the buffer resistance, the use of which this scheme avoids.

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* Reyrolle-Warren Patent Nos. B.P. 294970 and 294971.

* I.C.I.-Warren Patent No. B.P. 324156.

A further interesting feature relates to the automatic change-over from the hand control of the booster excitation to the automatic control if trouble develops on the main d.c. system while the battery is being charged. In the ordinary way it is necessary for the attendant to stand by during charging periods ready to change the action of the booster from negative to positive in case the services of the battery are suddenly required. Complete automatic operation, however, in conjunction with an alarm device is certainly preferable and in this case has never failed to give every satisfaction since it was installed.

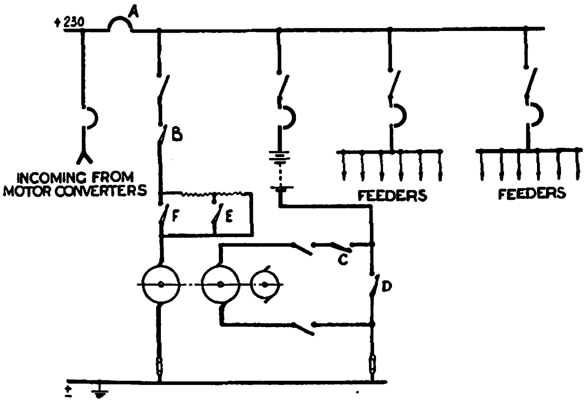

FIG. 24.—Battery booster control scheme.

A = reverse-current circuit-breaker.
B = booster motor contactor.
C = booster contactor.
D = booster short-circuiting contactor.
E = first motor-starting contactor.
F = second motor-starting contactor.

(e) *Neutral Earthing Scheme.*

The neutral points of the 8 alternators are connected to a common earth-bar via single-pole, oil-immersed, compound-filled, metal-clad switches incorporating the neutral bar. The latter is connected to the earth plates through a grid resistance of 2·78 ohms. In the event of a fault in the resistance it can be short-circuited, thus connecting the system directly to earth.

The "neutral earth" comprises two banks of earth tubes, each consisting of six 2-in. bore cast-iron pipes, 6 ft. long, buried in the ground on the south side of the station. An instrument panel is provided for periodical measurement of the resistance between the two banks. In addition, all electrical apparatus in the station itself is connected to copper earth-bars running systematically around the station on lightly insulated supports, these bars being connected direct to two further "station earth" banks which are separate from the "neutral earth" banks.

The oil switches and the resistance are situated on the ground floor of the switch house, adjacent to the station reactors, and are remote-controlled from their respective generator panels in the control room on the top floor. Hand operation of any generator control switch trips the main oil switch and the neutral switch, whilst operation of the Merz-Price relay on the occurrence of a fault trips the main oil switch, the main field circuit-breaker and the neutral switch.

The neutral earthing scheme is automatic in operation and provides the following features:—

(1) One only of the five 12 500-kW alternators can be earthed at a time.

(2) Selection of the machine to be earthed follows a definite order, depending upon the number and type of machines on load, the arrangement ensuring that a condensing set will always be earthed in preference to a primary set, and also that a primary set will only be earthed when no condensing set is running.

(3) When the main switch and consequently also the neutral switch of the earthed machine trips, the neutral switch of another running machine is automatically closed.

(4) If for any reason the system is left unearthed, a combined audible and visual alarm is operated.

The second feature was specially devised because of the different characteristics of the various generating sets.

(f) *Special Instruments.*

Wherever possible, special instruments developed by Synthetic Ammonia and Nitrates, Ltd., for use in factory processes, have also been adopted in the boiler and power plants, especially steam and water flowmeters. Standard practice throughout the factory with regard to temperature measurements has also been followed, viz. resistance thermometers up to 600° F., iron-constantan thermo-couples up to 1 500° F., and chromel-alumel thermo-couples above 1 500° F.

The following cases, however, were outside the scope of the company's standard apparatus and practice:—

Boiler Plant.—The boiler control panels are equipped with well-known combined steam-flow, air-flow recorders, 9-point draught gauges, and motor-driven electrical CO_2 recorders.

Power Plant.—Electrically-operated process steam-flow recorders are installed in the control room, together with pressure gauges actuated on the repeater system and also feed-tank level gauges.

CONCLUSION.

It is impossible to describe in detail every feature of the Billingham plant, and consequently in the preceding pages the authors have in a general manner dealt only with the most outstanding features. The information given, however, will reveal that the Billingham steam and electric power plant constitutes an important advance in the design of high-pressure, high-temperature power plants. Credit is due to the various contractors for the readiness and courage with which they met the multitude of new problems involved, especially in view of the short time available, and also to the research department of Synthetic Ammonia and Nitrates, Ltd., for the work carried out there, especially that in connection with pipework.

The authors desire to record their appreciation of the assistance rendered in the compilation of this paper by the following members of the staff of Synthetic Ammonia and Nitrates, Ltd.: Messrs. S. Boyle (photographs, etc.), G. H. Corner, H. J. Churchman, B.Sc., D.I.C., J. Johnston, H. Rissik, B.Sc., and T. R. Warren, B.A., B.Sc. (automatic control features).

APPENDIX 1.

Efficiency Calculations.

(1) *Boiler Efficiency.*

Heat power supplied by the combustion of 1 280 tons per day of coal having a calorific value of 11 700 B.Th.U. per lb.

$$= \frac{1\,280 \times 2\,240 \times 11\,700}{24}$$

= 1 396 000 000 B.Th.U. per hour

= 409 500 kW

Total heat of steam at 645 lb. per sq. in. abs. and 833° F. = 1 425 B.Th.U. per lb.

Total heat of feed water at 401° F. = 375 B.Th.U. per lb.

Therefore heat power supplied to 1 075 000 lb. per hour of steam

= 1 075 000 × (1 425 − 375) B.Th.U. per hour

= 1 128 000 000 B.Th.U. per hour

= 331 000 kW

$$\text{Boiler efficiency} = \frac{\text{Heat power supplied to steam}}{\text{Heat power supplied by coal}}$$

$$= \frac{331\,000}{409\,500} = \underline{81 \text{ per cent}}$$

(2) *Overall Thermal Efficiency.*

Power in steam to turbo-alternators (Appendix 3) = 59 150 kW

Power in steam to process plants = 82 550 kW

Total available steam power, less power to feed heaters and pumps (Appendix 2) = 141 700 kW

Therefore proportion of total steam power

$$\text{taken by turbo-alternators} = \frac{59\,150}{141\,700} = 0{\cdot}4175$$

Proportion of heat power in coal converted to electrical power = 409 500 × 0·4175 = 170 900 kW

Electrical power generated (Appendix 3) = 43 500 kW

Proportion of electrical power taken by auxiliaries = 2 200 kW

Therefore electrical power available at busbars = 41 300 kW

$$\textit{Overall Thermal Efficiency} = \frac{\text{Electrical power available}}{\text{Heat power required}}$$

$$= \frac{41\,300}{170\,900} = \underline{24{\cdot}22 \text{ per cent}}$$

$$\text{Alternatively, efficiency} = \frac{\text{Electrical power generated}}{\text{Heat power required}}$$

$$= \frac{43\,500}{170\,900} = 25{\cdot}45 \text{ per cent}$$

APPENDIX 2.

Increase in Thermal Efficiency due to Feed-Heating and to Increased Temperature and Pressure.

If it is assumed that to generate steam under different conditions of temperature and pressure, and from different feed temperatures, 1 280 tons per day of coal having a calorific value of 11 700 B.Th.U. per lb. are burned when the boiler efficiency is 81 per cent, then the following comparison of thermal efficiencies can be made:—

Case (1). *Steam Generated at* 290 *lb. per sq. in. abs. and* 653° *F. without Feed-heating.*

Heat supplied to steam .. .. = (Total heat − Heat in feed water at 84° F.)
= (1 340 − 52) = 1 288 B.Th.U. per lb.

Heat power given to steam (see Appendix 1) = 1 128 000 000 B.Th.U. per hour

$$\therefore \text{ Steam generated} \quad = \frac{1\,128\,000\,000}{1\,288} = 874\,000 \text{ lb. per hour}$$

Energy in the steam * .. .. = 448 B.Th.U. per lb.

∴ Theoretical power available .. .. .. = 874 000 × 448
= 391 000 000 B.Th.U. per hour
= 114 500 kW

Allowing for the power taken by the feed pumps, the total steam power available .. .. = 113 600 kW

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* The energy in the steam is here defined as the energy which is theoretically available from it when it expands adiabatically from its initial temperature and pressure to the final condensation temperature of 84° F.

Case (2). *Steam Generated at* 290 *lb. per sq. in. abs. and* 653° *F. with Single-stage Feed-heating to* 176° *F.*

Heat supplied to steam .. .. = (1 340 − 144) = 1 196 B.Th.U. per lb.

Steam generated .. .. = $\frac{1\,128\,000\,000}{1\,196}$ = 942 000 lb. per hour

The energy in the steam is 448 B.Th.U. per lb. as in Case (1); if we assume that 10 per cent of the total steam is withdrawn from the turbine at 185° F. for feed-heating purposes, then

Theoretical power available .. .. .. = (942 000 × 448) − (94 200 × 157)
= 407 000 000 B.Th.U. per hour
= 119 400 kW

Allowing for the power taken by the feed pumps,
the total steam power available .. .. = 118 400 kW

Case (3). *Steam Generated at* 645 *lb. per sq. in. abs. and* 833° *F. without Feed-heating.*

Heat supplied to steam .. .. = (1 432 − 52) = 1 380 B.Th.U. per lb.

Steam generated .. .. = $\frac{1\,128\,000\,000}{1\,380}$ = 822 000 lb. per hour

Energy in the steam .. .. = 538 B.Th.U. per lb.
Therefore theoretical power available .. .. = 822 000 × 538
= 444 000 000 B.Th.U. per hour
= 130 000 kW

Allowing for the power taken by the feed pumps,
the total steam power available .. .. = 128 100 kW

Case (4). *Steam Generated at* 645 *lb. per sq. in. abs. and* 833° *F., with* 7-*Stage Feed-heating to* 401° *F., i.e. Power-Plant Conditions.*

Heat supplied to steam .. .. = (1 432 − 409) = 1 023 B.Th.U. per lb.

Steam generated .. .. = $\frac{1\,128\,000\,000}{1\,023}$ = 1 075 000 lb. per hour

The energy in the steam is 538 B.Th.U. per lb. as in Case (3); here, again, allowance must be made for the steam supplied to the feed-heaters before the theoretical power available can be arrived at. The steam power taken by the various stages of the feed-heating system is detailed in Table 10, from which it is seen that the total steam power supplied for regenerative feed-heating purposes is 86 500 000 B.Th.U. per hour, or 25 350 kW.

Therefore theoretical power available .. .. = (1 075 000 × 538) − 86 500 000 B.Th.U. per hour
= 169 250 − 25 350 kW
= 143 900 kW

Allowing for the power taken by the feed and extraction pumps, the total steam power available .. .. = 141 700 kW

TABLE 10.

Stage	Steam supplied to	Steam conditions		Energy in steam	Steam quantity	Theoretical steam power	
		Temperature	Pressure				
		° F.	lb./sq. in. abs.	B.Th.U./lb.	lb./hr.	B.Th.U./hr.	kW
7	No. 7 heaters	653	290	448	73 500	33 000 000	9 660
6	No. 6 heaters	534	124·5	375	49 400	18 500 000	5 430
5	No. 5 heaters	414	62·1	308	43 400	13 400 000	3 930
4	No. 4 heaters	301	29·3	248	40 800	10 100 000	2 960
3	No. 3 heaters	205	12·73	189	31 800	6 000 000	1 760
2	No. 2 heaters	167	5·59	131	29 900	3 960 000	1 156
1	De-aerators	131	2·28	77	20 000	1 540 000	454
	Total					86 500 000	25 350

APPENDIX 3.

TECHNICAL DATA.[*]

(*a*) COAL PREPARATION PLANT.

Coal-conveying capacity	4 800 tons/day (4 880 tonnes[†]/day)
Coal-pulverizing capacity	3 240 tons/day (3 290 tonnes/day)
Pulverized-coal consumption (normal)	1 280 tons/day (1 300 tonnes/day)

Raw-coal feed hopper.

The hopper accommodates three 100-tons/hour skip hoists and has a 1¼-in. gap between screening bars.

Skip hoists.

Number installed	3
Number working	2
Capacity	100 tons/hour (101·6 tonnes/hour)

Belt conveyors.

Number installed	2
Number working	2
Capacity	160 tons/hour (163 tonnes/hour)
Belt speed	300 ft./min. (1·52 m/sec.)
Belt width	30 in. (71 cm)

Raw-coal bunker.

Total capacity	1 068 tons (1 084 tonnes)
Number of discharge openings	12

Pulverizers.

6 roller mills installed; capacity	13½[‡] tons/hour (13·7 tonnes/hour)
3 roller mills working; normal output	10·8 tons/hour (11·0 tonnes/hour)
4 ball mills installed; capacity	13½[‡] tons/hour (13·7 tonnes/hour)
2 ball mills working; normal output	10·5 tons/hour (10·7 tonnes/hour)
10 mills installed; total capacity	3 240 tons/day (3 290 tonnes/day)
5 mills working; total normal output	1 280 tons/day (1 300 tonnes/day)

Pulverized-coal bunkers.

Number installed	8
Capacity	60 tons (61 tonnes)

(*b*) BOILER PLANT.

Coal burned	1 280 tons/day (1 300 tonnes/day)
Calorific value of coal	11 700 B.Th.U./lb. (6 500 tonne-cals./tonne)
Feed-water supplied	1 093 400 lb./hour (11 900 tonnes/day)
Steam generated	1 075 000 lb./hour (11 700 tonnes/day)
Blow-down loss	18 400 lb./hour (200 tonnes/day)

Boilers.

Number of boilers installed	8
Number of boilers working	5 (1 standing by; 1 cleaning; 1 spare)
Type	4-drum, with water screens and Murray water-cooled walls
Water capacity	98 000 lb. (44·5 tonnes)
Normal working pressure	715 lb./sq. in. abs. (50·3 kg/cm^2)
Maximum working pressure	815 lb./sq. in abs. (57·3 kg/cm^2)
Boiler heating surface	7 640 sq. ft. (710 m^2)
Heating surface of screens and walls	2 380 sq. ft. (221 m^2)
Total heating surface	10 020 sq. ft. (950 m^2)
Actual evaporation	215 000 lb./hour (normal) to 270 000 lb./hour (max.) (97·5 tonnes/hour to 122 tonnes/hour)
Actual evaporation, in lb./sq. ft. per hour	21·2 (normal) to 26·8 (max.)
(Actual evaporation, in kg/m^2 per hour)	(503 to 621)
Factor of evaporation	1·1

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[*] British Standard Units are employed throughout. The corresponding metric units are given in brackets.

[†] One tonne = 2 204 lb.

[‡] 15 American tons = 13½ English tons.

Combustion chambers (arch-less type).

Volume above water screen	12 800 cub. ft. (362 m^3)

	Normal load	Maximum load
Dry coal fired	119 500 lb./hour (54·3 tonnes/hour)	150 000 lb./hour (68 tonnes/hour)
Dry coal fired per cub. ft. of combustion chamber	9·35 lb./hour	11·7 lb./hour
(Dry coal fired per m^3 of combustion chamber)	(150 kg/hour)	(188 kg/hour)

Economizers (steaming type).

Heating surface	23 030 sq. ft. (2 140 m^2)

	Normal load	Maximum load
Water inlet temperature	401° F. (205° C.)	401° F. (205° C.)
Water outlet temperature	523·4° F. (273° C.)	523·4° F. (273° C.)
Gas inlet temperature	1 150° F. (621° C.)	1 150° F. (621° C.)
Gas outlet temperature	600° F. (315·5° C.)	640° F. (338° C.)
Draught loss	0·885 in. H_2O (0·00225 atmo.)	1·375 in. H_2O (0·0035 atmo.)
Coefficient of heat transfer	1 250 B.Th.U./sq. ft./hour (3 380 kg-cals/m^2/hour)	1 550 B.Th.U./sq. ft./hour (4 210 kg-cals/m^2/hour)

Superheaters (combined radiant-heat and convection type).

Heating surface	5 000 sq. ft. (465 m^2)

	Normal load	Maximum load
Initial steam temperature	523·4° F. (273° C.)	523·4° F. (273° C.)
Final steam temperature	850° F. (455° C.)	856° F. (458° C.)
Coefficient of heat transfer	893 B.Th.U./sq. ft./hour (2 420 kg-cals/m^2/hour)	1 110 B.Th.U./sq. ft./hour (3 010 kg-cals/m^2/hour)

Air preheaters (rotary type).

Heating surface	37 000 sq. ft. (3 440 m^2)

	Normal load	Maximum load
Gas quantity at inlet	7 300 000 cub. ft./hour (206 600 m^3/hour)	9 700 000 cub. ft./hour (276 000 m^3/hour)
Gas quantity at outlet	5 130 000 cub. ft./hour (145 300 m^3/hour)	6 850 000 cub. ft./hour (194 000 m^3/hour)
Gas temperature at inlet	600° F. (315·5° C.)	640° F. (338° C.)
Gas temperature at outlet	230° F. (110° C.)	255° F. (124° C.)
Air quantity at inlet	3 650 000 cub. ft./hour (103 400 m^3/hour)	4 680 000 cub. ft./hour (132 800 m^3/hour)
Air quantity at outlet	5 820 000 cub. ft./hour (165 000 m^3/hour)	7 650 000 cub. ft./hour (216 900 m^3/hour)
Air temperature at inlet	60° F. (15·5° C.)	60° F. (15·5° C.)
Air temperature at outlet	500° F. (260° C.)	520° F. (271° C.)
Coefficient of heat transfer	715 B.Th.U./sq. ft./hour (1 935 kg-cals/m^2/hour)	922 B.Th.U./sq. ft./hour (2 635 kg-cals/m^2/hour)

De-dusters.

	Normal load	Maximum load
Gas quantity	5 130 000 cub. ft./hour (145 300 m^3/hour)	6 850 000 cub. ft./hour (194 000 m^3/hour)
Gas velocity	10 ft./sec. (3·05 m/sec.)	13·5 ft./sec. (4·12 m/sec.)

Stacks.

Effective diameter	8 ft. (2·44 m)
Effective area	50 sq. ft. (4·65 m^2)
Stack height	132 ft. (40·3 m)
Gas velocity (normal load)	28 ft./sec. (8·5 m/sec.)

(c) ASH REMOVAL PLANT.

Main ash sluice.

Ash quantity (dry)	160 tons/day (162·5 tonnes/day)
Water quantity	161 500 galls./hour (734 m^3/hour)

Slurry whirl pit.

Pump capacity (normal)	220 500 galls./hour (1 000 m^3/hour)
Head (normal)	32·5 ft. (10 m)

Ash settling pit.

Capacity	12 500 cub. ft. (345 m^3)
Water velocity	3·28 ft./min. (1 m/min.)
Overhead grab crane capacity	45 tons/hour (45·7 tonnes/hour)

Ash ropeway system.

Ropeway capacity	45 tons/hour (45·7 tonnes/hour)

(*d*) HIGH-PRESSURE (PRIMARY) TURBO-ALTERNATORS.

Number installed	3
Number working	2
Maximum continuous rating	12 500 kW
Steam conditions at inlet	645 lb./sq. in. abs. and 833° F. (45·3 kg/cm^2 and 446° C.)
Steam conditions at exhaust	290 lb./sq. in. abs. and 653° F. (20·4 kg/cm^2 and 345° C.)
Total steam flow	1 075 000 lb./hour (11 700 tonnes/day)
Total theoretical steam power available	32 100 kW
Total electrical output	23 800 kW
Percentage of maximum continuous rating	95·2
Turbine efficiency	76·5 per cent
Alternator efficiency	96·9 per cent
Overall efficiency	74·2 per cent

(*e*) CONDENSING TURBO-ALTERNATORS.

Number installed	2
Number working	1
Maximum continuous rating	12 500 kW
Inlet steam conditions	290 lb./sq. in. abs. and 653° F. (20·4 kg/cm^2 and 345° C.)
Exhaust steam conditions	0·58 lb./sq. in. abs. and 84° F. (0·04 kg/cm^2 and 29° C.)
Condenser vacuum	28·82 in. Hg (730 mm Hg)
Dryness fraction at exhaust	0·89
Total steam flow	104 000 lb./hour (1 130 tonnes/day)
Total theoretical steam power available	13 450 kW
Total electrical output	10 200 kW
Percentage of maximum continuous rating	81·6
Turbine efficiency	78·5 per cent
Alternator efficiency	96·7 per cent
Overall efficiency	75·9 per cent
Cooling water temperature (inlet)	59° F. (15° C.)
Cooling water temperature (outlet)	79° F. (26° C.)
Cooling water, quantity	75 750 cub. ft./hour at 59° F. (2 115 m^3/hour at 15° C.)

(*f*) FEED-HEATING TURBO-ALTERNATORS.

Number installed	3
Number working	2
Maximum continuous rating	6 000 kW
Inlet steam conditions	290 lb./sq. in. abs. and 653° F. (20·4 kg/cm^2 and 345° C.)
Exhaust steam conditions	12·73 lb./sq. in. abs. and 205° F. (0·9 kg/cm^2 and 96° C.)
Dryness fraction at exhaust	0·992
Total steam flow (inlet)	241 000 lb./hour (2 620 tonnes/day)
Total steam flow (exhaust)	107 000 lb./hour (1 166 tonnes/day)
Total theoretical steam power available	13 600 kW
Total electrical output	9 500 kW
Percentage of maximum continuous rating	79·2
Turbine efficiency	73·5 per cent
Alternator efficiency	95·5 per cent
Overall efficiency	70·2 per cent

(*g*) FEED-HEATING SYSTEM AND DISTILLATION PLANT.

Number of sets installed	3
Number of sets working	2
Total feed water output	1 093 000 lb./hour (11 900 tonnes/day)
Feed water conditions (normal)	820 lb./sq. in. abs. and 401° F. (57·7 kg/cm^2 and 205° C.)
Total raw water supplied	230 000 lb./hour (2 512 tonnes/day)
Total distillate gained	209 000 lb./hour (2 276 tonnes/day)

Feed pump	Water quantity	lb. per sq. in.		Temperature ° C.		Power	Speed
		In	Out	In	Out		
	tonnes/day					h.p.	r.p.m.
Main boiler (" A ") feed pump ..	11 900	346	870	213	205	900	1 180
Intermediate (" B ") feed pump ..	10 562	107	370	141·5	(141·5)	450	1 180 to 400
Intermediate (" C ") feed pump ..	9 646	30	130	91·8	(91·8)		

The steam and water balance is given in Table 11.

(*h*) Extra Distillation Plant.

Number of sets installed	3
Number of sets working	2
Number of evaporation stages	6
Maximum total quantity of gained distillate (per set)	60 000 lb./hour (650 tonnes/day)
Total steam from l.p. steam mains	14 700 lb./hour (160 tonnes/day)
Total raw water supplied	86 400 lb./hour (940 tonnes/day)
Total distillate gained	79 000 lb./hour (860 tonnes/day)

(*j*) Switchgear.

Power delivered to auxiliaries at 6 600 volts (a.c.) ..	2 200 kW
Power delivered to auxiliaries at 400 volts (a.c.) ..	2 400 kW
Power delivered to auxiliaries at 460 volts (d.c.) ..	1 400 kW
Power available at outgoing feeders	37 500 kW
Power delivered by turbo-alternators	43 500 kW
Rupturing capacity, main e.h.t. switchgear (6 600 V)	500 000 kVA
Rupturing capacity, aux. e.h.t. switchgear (6 600 V)	100 000 kVA
Rupturing capacity, aux. l.t. switchgear (400 V) ..	50 000 kVA

Table 11.

Feed-heaters			De-aerators	2nd stage	3rd stage	4th stage	5th stage	6th stage	7th stage
Steam	Quantity (tonnes/day)	Entering	218	326	346	444	472	538	800
		Leaving *	218	326	346	444	472	538	800
	Temperature (° C.)	Entering	55	75	96	149	212	184	345
		Leaving *	55	75	96	120	146	173	213
	Pressure (lb./sq. in. abs.)	Entering	2·28	5·59	12·73	29·3	62·1	124	290
		Leaving *	2·28	5·59	12·73	29·3	62·1	124	290
Total heat of steam (tonne-cals./tonne)			580·5	606·5	633·0	661·5	691·0	721·3	749·5
Energy in steam (tonne-cals./tonne) ..			43	73	105	137·5	171	208·3	249
Feed-water	Quantity (tonnes/day)	Entering	6 164	7 286	9 300	9 646	10 090	10 562	11 100
		Leaving	7 286	9 300	9 646	10 090	10 562	11 100	11 900
	Temperature (° C.)	Entering	29	47·7	72	(91·8)	116·5	(141·5)	168·6
		Leaving	(47·7)	72	91·8	116·5	141·5	168·6	213
	Pressure (lb./sq. in. abs.)	Entering	(14·7)	(14·7)	(14·7)	130	118	370	358
		Leaving	(14·7)	(14·7)	30	118	107	358	346
Theoretical power in steam (kW) ..			454	1 156	1 760	2 960	3 930	5 430	9 660

* Steam leaves heaters as condensate.

Discussion before The Institution, 13th March, 1930.

Mr. C. H. Merz: The designers of this plant have had a great deal of experience beyond that involved in the lay-out of power stations, as is shown by the varied and original way in which they have approached the problems before them. Some of the points specially referred to as novel are, perhaps, not quite so novel as would appear. For instance, the cable tunnels are in accord with recent practice in power stations in various parts of the world. The designers of plant of this kind have first to decide whether they are going to plan it as a self-contained plant, relying on its own resources for almost all purposes, or whether they propose to adapt it for work in conjunction with any outside system. In this particular case, due, I believe, largely to the fact that the question of periodicity was uncertain in the locality concerned, the designers decided to lay out the whole plant as a separate entity—a fact which must be borne in mind when it is subjected to technical criticism. They have adopted what may be described, in comparison with ordinary power-station practice, as a horizontal lay-out. An unusual feature of the plant is that it is spread over a large area; it is open to question as to whether this is good practice, and whether, if there were room, the average power station would be improved by the adoption of this kind of design. There are obvious reasons, in addition perhaps to those of finance, why the designers adopted it in this case. The plant had to be constructed in the minimum of time, and the adoption of this lay-out, of standard buildings, etc., clearly facilitated rapid erection. When time, however, is not of such importance, or when the designer has a free hand, the questions of cost and of the operating results of the plant must be considered. It is clear to me that the capital cost involved by this method of lay-out of power plant is considerably higher than that of established practice, and a greater weight of steel is involved. What is equally important, from actual experience of plant in which the component parts of the equipment are spread about, I can say that the operating costs will be materially higher, so that I do not feel inclined to support this departure from a conventional lay-out. Regarding the general question of the steam cycle, the steam pressure is greater than that hitherto employed in this country for plant at all approaching this size. The first high-pressure plant using feed heating and the other general characteristics of the steam cycle now adopted as standard in power stations, was installed some 10 years ago at the North Tees station, adjacent to this plant. It was based upon suggestions of the late Dr. Ferranti, who had thought out the matter in considerable detail many years previously. I do not think that this side of his work has been recognized as freely as some of the others, although it had its recognition in the United States, I am glad to say, in a very substantial way. The steam pressure adopted in this plant is 30 per cent higher than that of the original North Tees plant, and is an advance upon other designs. Why has there not been a greater advance in this country in the direction of higher pressures? So far as my own experience over several years is concerned, it cannot be in any way due to troubles with the high pressure, nor with any of what were in the past the unusual elements of the steam cycle, including reheating. As is pointed out in the paper, if a higher pressure had been attempted it would have involved reheating, and I think that if I were associated with the work of designing a plant of this description, which is required to run independently, I should probably agree with the authors in avoiding reheating. Whilst at first sight it would seem that the complication and the capital cost of the turbines adopted are greater than for high-pressure turbines bled in the usual way, it must be recognized that in this case the average efficiency of the plant under somewhat changing conditions had to be considered. Doubtless, the adoption of the separate feed-heating turbines has simplified the matter from that point of view: over the average life of the plant, which is of primary importance, it will probably prove to be an economical arrangement. The authors claim that this plant is estimated to produce electricity at lower cost than any other coal-fired station in the world. That claim cannot be substantiated, as there are several coal-fired stations in different parts of the world which are to-day producing energy far more cheaply than this plant ever can produce it, as the cost is largely settled by the price of fuel. The plant is several times described in various parts of the paper as unusual. It has been designed, as I have said, to meet unusual conditions, but I suggest that the design itself will also prove to be unusual. I do not think that, as a general rule, such a plant would again be designed to run almost entirely as a separate entity. It is clear that much of the complication and consequent large capital cost of the plant arises from the fact that the designers have had two conditions continually before them: the first is the correct regulation of the supply of process steam so as to provide for the right quantity of this, and the second is the necessity of maintaining a proper supply of electrical energy. I suggest that if the designers had not been limited or controlled by the conditions to which I have referred, and if the grid had been in existence, a far more efficient method of dealing with the problem could have been adopted. This method would, I feel sure, be applied in the future, if such a case should ever again arise. In the proposed method the process steam is considered as the main and only problem of the special plant, and its amount is regulated to suit the needs of the process without regard to the quantity, large or small, of the electricity generated. The process steam which is not required by the process itself is used to generate electricity for the grid, and any deficiency in the electricity generated by the process steam at any time is taken from the grid. This, I feel sure, is the correct general solution and it is unfortunate that such an important plant as that described in the paper had to be built at a time when these principles could not even be considered. This general principle has governed the design of the waste-heat plants which have been running for many years on the North-East Coast, where in essence the problem is the same as that at Billingham. It was adopted for the Mersey Power Company's plant some 18 years ago; this installation supplies process steam in a very similar way to that adopted in the Billingham plant and is to-day producing energy at a cost which is one of the lowest in the country.

Mr. W. M. Selvey : I agree with Mr. Merz that the idea of cable tunnels and tunnel floors is not new. I am pleased to see that absolute pressures are used in the paper, but I am relieved to find that absolute temperatures are not employed. With regard to the provocative statement that this station can produce current more cheaply than one of standard design, I think the authors have not made their meaning clear. Apparently, the idea which is intended is that by the combination of process steam and electricity a better overall figure is obtained than would have been the case if the grid had been available and the balance of the current had been purchased from the grid supply. On the question of the design, I agree with Mr. Merz in the opinion that the horizontal lay-out will not necessarily be the standard practice of the future. I appreciate the fact, however, that the Billingham plant is endowed with two very marked features. The first is the enormous array of change-over pipes on the steam side—a feature which was necessary because the designers were not only committed to this kind of steam plant, but they had also to make full use of the boiler equipment already in existence. Secondly, there is the fact that the high-pressure boilers have to be supplied with a large amount of "make-up" distilled feed-water. It would appear, from the fact that the ideas of the authors have actually come into effect, that pulverized fuel is now firmly established, despite the critical attitude of the public. From what the authors have said, it seems that when striking advances were made in other directions the pulverized-fuel scheme was almost automatically adopted as part of the equipment. It is disappointing to find that interesting details as to pulverization are dismissed in so few words at the beginning of Section (3); information, particularly as to the heating mills and the type of mills used in the pulverization system, has been omitted. Any further facts that the authors could supply in this connection, would be welcome. The design of the superheaters is interesting, and in this connection it is well known that an experimental superheater which is running at a pressure of about 1 000° F. has been made at Detroit. All kinds of special devices are being tested in order to find out whether the advantages of economy can be obtained by higher superheating temperatures without increase of pressure. The authors have decided to go half-way, and great ingenuity has been shown in the construction of the type of superheater in use at Billingham. There is another advance in the simplicity shown by the apparatus; by means of the steaming economizer it has been possible to eliminate the baffles in the pulverized-fuel boiler. The authors have referred to the design of the turbine shown in Fig. 20 to the effect that it had great merits, but that it was not the object of the paper to enter into the question of turbine design. I am interested in that turbine—a machine which, I think, should provide some unusual results. On page 1264 the great advance which has been made in turbine governors is mentioned. It is well known that in cases where the power passing through the turbine is large compared with the inertia of the rotor, the question of governors has given rise to considerable apprehension among turbine designers. The system of governors in use at Billingham represents an important advance in this direction. It is a big achievement that a plant of this kind should have been erected in Great Britain, where we have the habit of depreciating ourselves. The success is a result, I suppose, of the rationalization which Lord Melchett has been so successful in bringing about; and it shows what can be done when adequate resources are available. Even although its output capacity of 37 500 kW or 50 000 kW is not that of a super-station, the Billingham installation is very impressive as a private plant.

Mr. T. R. Warren : I think that a limit will eventually be reached beyond which it will not be possible further to improve thermal efficiency, at least while steam is used as the working fluid. A great deal still remains to be done, however, to reduce working costs, and I can foresee further developments in the design and utilization of automatic features to this end. Many other considerations render it essential to develop improved methods of operation, if we are to keep pace with the rapid advances now being made in all fields of power generation and transmission. The paper shows the important part played by governing characteristics in the operation of a compounded station, and throws new light on many problems concerning the stability and operation not only of power stations but also of power systems. With regard to Mr. Merz's observations in connection with the grid, if the Billingham station had been linked with an outside supply the steam pressure would have been affected by changes in the system frequency and this would have led to difficulties. Automatic frequency control, as described in the paper, offers decided advantages in the control of power systems. The number of stations capable of being conveniently interconnected is at present limited owing to serious difficulties in regard to control. I think, however, that as improved methods become available this number will be increased without the formation of systems too unwieldy to be handled. Only in this way, in my opinion, can the full benefits resulting from interconnection be realized.

Mr. H. W. Clothier : I suggest that the authors show on Fig. 15 how any turbine can be supplied from any boiler by the addition of the boiler connections to the diagram. The paper describes a station designed with a typically British regard for safety. The use of secondary steam for process work introduces new features, but, apart from these, there are other noticeable items associated with the special precautions, attributable to the designers' purpose in providing a system in which the provision of an unfailing supply was to be of supreme importance. Having regard to the three main requirements, safety, reliability and extra service in providing process steam, it is significant that the designers have employed complete automatic control. The form of control adopted has been built up round two fundamental devices in the development of which Mr. Warren has taken a prominent part. The first is the sequential automatic synchronizer; unlike the Continental synchroscope, it operates by means of definite relays, as illustrated in Fig. 23, and it has been explained that the rate of control is proportional to the frequency error. The use of sequential relays is an advance, I think, upon the method of permissive control; here the contact works between the two fingers and there may be a lag in the movement which establishes hunting—an effect which is absent from the sequential relay mode of synchronizing. The second is the master frequency control incorporating a separate motor-generator, which is kept in step by means of a master clock and also functions through sequentially operated relays of an identical pattern to those used for the automatic synchronizer. The essential feature of these automatic systems is the use of simple reliable relays with unfailing contacts for making connections and correctly reproducing the corresponding manual operations. At every stage it should be possible to convert the automatic action to manual operation by a switch. The paper and the slides suggest the possibilities of applying these developments to ordinary power-station circuits. I should like to ask the authors whether their experience in the operation of this apparatus is sufficient to warrant their recommending its application to ordinary power-station service. Frequency control would appear to have a particular field of service in the interconnection of large generating stations, and more so in dealing with the difficult problem of load-sharing, and control by frequency regulation of generating stations in parallel. It seems to me that the present hand control must involve a great amount of human responsibility and worry, particularly at times of emergency, whereas when responsibility is taken by automatic means the burden on many men's minds is at once relieved. The automatic work is performed in a predetermined way and in a fraction of the time taken by manual operation. The predetermined way arising out of such pioneer work as described by the authors is, as it were, a storage of brain capacity in mechanical equipment, the store being made available for constant and instant emergency service. Whether the emergency takes the form of sudden changes in load location, results of abnormal condition, or faults on the steam and electrical side, the automatic control should be equally effective. The schemes tried by the authors, with the addition of the necessary pilot wires, contain all the elements for "Centrovisory," load-sharing and automatic frequency control, for example, in a distribution system such as the British grid where all the generating plant would be kept in step within narrow limits. This condition would be particularly helpful in synchronizing any two sections of the network; even automatic synchronizing of sections would be possible, and, incidentally, when delays due to faults can be reduced to a negligible amount an efficient public time service may be provided as well.

Mr. H. Rissik: With regard to the removal of the ash dust from the boiler flue gases, of the three methods available for dealing with this problem that of dry separation by centrifugal means is the most common in this country. It has the disadvantage that it deals effectively with only the larger particles of grit and requires a relatively large consumption of power, i.e. about 25 to 30 kW per ton of coal burnt per hour. In view of present high boiler ratings this fact must not be lost sight of, especially as a de-dusting efficiency greater than 90 per cent is seldom obtained. By far the simplest and most satisfactory method is that of electrostatic precipitation of the ash particles. Chiefly on account of its higher initial cost this method has as yet found little favour in this country, although it is used extensively abroad and particularly in Germany, where the cost of an installation having a guaranteed efficiency of 90 per cent varies from 15 to 20 shillings per sq. ft. of boiler heating surface. In contradistinction to centrifugal systems, the de-dusting efficiency decreases with rising boiler load. At Trenton Channel, for example, an efficiency of 90 per cent is readily obtained at normal load, but this falls to 75 per cent at 30 per cent overload. The latest installation at Klingenberg has a de-dusting efficiency of 96 per cent and deals with more than 12½ million cubic feet of flue gas per hour. The two foregoing methods have the common disadvantage that they do not in any way alleviate the damage to vegetable life from sulphurous fumes emanating from boiler stacks. The method of dust removal by contact with either a spray or a falling film of water undoubtedly gets rid of sulphur dioxide from the flue gases at the same time. Wet de-dusters of the water-spray type are the more common, the water quantity required being about 10 per cent of the boiler load. The system employing a falling water-film, of which that at Billingham is the first to be installed in this country, is certainly the most promising, as a de-dusting efficiency of 90 per cent is obtained together with a sulphur dioxide removal of 30 per cent. On the other hand, the quantity of water required (25 lb. per 1 000 cub. ft. of flue gas) to give satisfactory results is in most cases prohibitive, being comparable in amount to the boiler feed-water supply. To power station engineers the most interesting features of the Billingham plant are, I think, the simultaneous automatic control of station frequency and process steam pressure, and the unorthodox arrangement of the high-pressure and intermediate-pressure pipework systems. With regard to the former, the method adopted is novel and, being inherently more flexible, is undoubtedly of wider application than the system of automatic control recently developed in the U.S.A., for the distribution of steam from industrial power plants which are tied into an electrical network. The American system is, nevertheless, ingenious in that it maintains constant the pressure at the exhaust and extraction outlets of turbo-generator sets in which the output depends entirely upon the demand for extracted or exhaust steam. At the same time, it allows of instantaneous transfer from steam-pressure control to speed control independent of steam pressure, without causing a rise in speed of the turbines. In connection with the authors' remarks on pipework lay-out, it should be noted that the Detroit Edison Company have also had recourse to building a scale model of their new 100 000-kW plant, and with precisely the same object in view, namely, to facilitate the design of the pipework system. It would be interesting to know how far this procedure has become common practice in the design of modern power plant in this country.

Mr. T. S. Blenkinsop (*communicated*): The results achieved by the Billingham plant are well in advance of any others obtained in this country. A great amount of skill was involved in the design and lay-out of the pipework, not only in the power station itself but also in the works, although the latter, which is of more conventional construction as regards pressure and temperature, did not involve factors so unknown as entered into the design of the power station. I should be glad to know why the high-pressure steam ranges were pulled up on erection to an amount equal to the full expansion of the pipe between anchors, whereas the high-pressure feed and intermediate-pressure steam ranges were only pulled up to half this amount. I should also like to know why, in the case of the flanges, a 10-in. steam flange was made 6 in. thick, whereas a 10-in. feed flange for the same pressure was only made 3 in. thick. The type of high-pressure joint adopted is of special interest, and the results confirm my own experience of the efficiency of a similar construction when other more elaborate and costly types of joints have failed. The unusual care taken in the tightening-up of the flange bolts is no doubt partly responsible for the success attained. I notice on page 1256 a statement that a number of drain pipes were led to a single steam-trap to reduce the cost of traps installed, and, while I favour this arrangement, my object would not have been solely the reduction of cost but rather an endeavour to overcome, as far as possible, a necessary evil. Reference is made to the urgent need of appropriate British Standard Specifications for the higher temperatures and pressures, and it is regrettable that it has been left to private enterprise to develop requirements suited to present conditions.

Mr. A. D. Maclean (*communicated*): The paper is of great value to all engineers on account of the numerous problems which have had to be solved, due partly to the unusual magnitude of the plant involved and partly to the fact that the plant is required for an industrial works where the load conditions are different from those obtaining in central power stations, and where extreme reliability is essential. Not only is the boiler plant as a whole the largest in Great Britain, but the individual boiler units are also the largest, and the remarkable results secured will no doubt encourage the more general adoption of larger units, as is the tendency in other parts of the world. On page 1234 dates indicating the speed with which the various problems were solved and the plant erected, are given. Such rapid progress is evidence of extremely efficient organization, but apart from this such speed could only be made possible by close co-operation between the technical staff of Imperial Chemical Industries and the staffs of the selected contractors. The heaviest burden of the preliminary work must necessarily have fallen upon the shoulders of the authors and their technical assistants, and the energy and ability with which they tackled the problems as they arose call for admiration. The problems governing the lay-out and selection of plant are necessarily different from those in connection with central stations, chiefly owing to the excess of steam requirements over the steam necessary for electric generation only. This factor brings into prominence the question of feed heating, and the authors' solution of the problem is interesting. Central station engineers would not as a rule be in favour of 7-stage feed heating, but from the point of view of an ordinary power station the arrangement is equivalent to 4-stage heating, and the figures given in the paper clearly justify the arrangement adopted. No doubt numerous arrangements were investigated before the selected scheme was finally adopted, but it would be of interest to know whether consideration was given to steam drives for the feed pumps, the exhaust steam being utilized as part of the feed-heating cycle. On the face of it this would appear to enable a somewhat simpler arrangement to be made. With regard to the various automatic controls which have been developed to meet the unusual conditions of operation, the solutions to these difficult problems will be of particular interest to engineers, in connection with other industrial plants where similar problems frequently arise. Mr. Merz has referred to the arrangements made for the accommodation of cables. Whilst I agree with him that in the majority of modern power stations this question has received adequate consideration, I cannot agree that this is always the case. It is certainly not so in the case of most industrial plants, where the cable-runs are usually settled more or less as an afterthought. The importance of this question has become increasingly apparent in recent years on account of the greater concentration of plant in individual power stations and the higher pressures involved; modern practice demands that in laying out a power station as much consideration shall be given to the requirements of cable-runs and outlets from the site for main feeder lines, as to such matters as coal supply and circulating water. In a station with which I was at one time associated the special consideration given to cable-runs resulted in a total absence of cross-overs within the power-station site, and complete phase separation of 33-kV cables within the power house and switch house. The trouble taken to secure this result was thoroughly justified on the scores of cost, freedom from trouble and isolation of faults. The arrangements made by the authors in the way of special cable galleries result in an excellent mechanical lay-out of cables, but there is some doubt as to whether they have not introduced the risk of an extensive shut-down in the event of a serious fault causing a fire in the vertical gallery. It would be interesting to know what provision the authors have made in connection with this hazard. A further paper in 12 months' time, describing the actual operating experience gained on the plant, would be welcome. It is inevitable that a complicated and extensive installation such as this should give rise to some troubles, and a description of these, together with the means adopted to overcome them, would be of great value.

Mr. A. C. Sparks (*communicated*): It is unfortunate that all questions of cost are purposely excluded from the paper, as the general impression given by drawings of the lay-out and certain other features is that the cost per kilowatt and possibly the operating charges would be high. In view of this, I doubt whether the authors' claim that the estimated cost of electrical energy at the busbars is well below the unit cost of any coal-burning station in the world, will be generally accepted without some figures and information as to the basis of the estimate. It would be of interest to know the minimum degree of de-aeration that is considered necessary in the design. Information as to the operation and effectiveness of the de-dusting equipment, the effectiveness and control of the de-superheater to obtain dry saturated steam, the basis of the figures as to the calorific value of the coal (given in Appendix 1) and the analysis of this coal, would also be welcome.

[The authors' reply to this discussion will be published later.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 24TH MARCH, 1930.

Mr. F. C. Winfield: Apart from the automatic control features, which are largely novel and, I think, mainly peculiar to the special requirements of the Billingham station, there do not appear to be many points to criticize in regard to the electrical arrangements of the station. The lay-out of the switch house appears to have been largely governed by the decision to make the switch bay of the same general dimensions as other bays in the station. This was no doubt done to facilitate quick construction, and the resultant lay-out appears to be quite straightforward. I agree with Mr. Clothier that the main switch chamber should be divided into four physical sections, but keeping the lay-out shown in the paper it would appear that the authors have attempted to divide the main switchgear physically into two sections. The division, however, appears to me to be very incomplete since the longitudinal dividing wall (which, incidentally, is rather weak—being only 4½ in. thick) does not reach to the full height of the chamber. Further, the middle busbar section switch, which constitutes the electrical dividing point between the two halves formed by the wall, is not itself enclosed in a separate chamber. Fire, therefore, in one half-section may affect the isolating devices and busbars connected to this section switch and involve the switchgear in both chambers. I notice that considerable use is made of uncovered steelwork in the main switch chambers. We have had some experience in the past year or two, in a station not very far from Billingham, of the danger of using uncovered steelwork in the event of fire. The position at Billingham seems to be even worse, since, as far as I can judge, the roof of the main switch chamber is made up of steel plates which form the floor of the control cable chamber. A fire in these circumstances might be attended with disastrous results, and I would certainly suggest that some fire protection should be given to this steelwork. The 6 600-volt auxiliary switchgear is also mounted in a single chamber and is relatively closely packed. It is sectioned electrically but not physically and, since this gear is the heart of the station, fire or other serious accident in this chamber would result in complete shut-down. The alternative supply from the Newcastle-upon-Tyne Electric Supply Co. is also brought into the same board, so that this constitutes no safeguard. This is relatively small gear and the fire risk should not be great, but it must always be borne in mind that the human element is indeterminable and that, even with the best switchgear, bad maintenance or breakage of a mechanical part or other accident may result in failure of a circuit breaker with explosion and fire. The authors remark that the cable bridge which carries the outgoing feeders was made necessary by the site conditions. It is my view that in any station in which a very large number of feeders are brought out from the power-station busbars, special provision either in the nature of a cable bridge or a cable tunnel should be provided, as the difficulty of accommodation and maintenance of large numbers of underground cables going in various directions is very great. I should like to know what considerations led to the use of 6·6 kV as the second voltage for auxiliary supplies. Two voltages are clearly necessary for the size of motors with which the authors have to deal, but I should have thought that 3 000 volts would have been more suitable than 6 600 as giving considerably more reliable motors and extending the range of use of this second voltage to motors of much smaller size. I do not think that this would involve any material increase in the cable cost. It is interesting to know that special water-cooling has been applied to many of the motors, and I should be glad if the authors could give some particulars of the arrangement, particularly as regards the supply of water. By the arrangement adopted for running the convertors the Billingham power station is tied to the Newcastle Electric Supply Co.'s system, and later thereby to the "grid," by a link consisting of two 2 000-kW convertors in series. I think that this arrangement will prove troublesome in practice, since any shock on either system will be felt at the link. I agree that so long as protective gear operates satisfactorily there should be no interruption to supplies, but no protective gear is infallible, and, should the reverse-power protection fail, complete shut-down of both convertors appears inevitable. The stand-by protection seems to employ inverse time-limit fuses, which are indiscriminative in the condition being considered, so that this would afford no relief. The special arrangements made in connection with the battery booster are interesting, but in the ordinary type of station operated by supply companies batteries are required for emergency lighting and other purposes besides switch operation, and this generally makes duplicate batteries desirable in any case. The usual practice is to charge one battery whilst using the other, and with such an arrangement these special features are not necessary. I congratulate the authors upon their courage in making such an extended application of automatic control gear. Such gear is practically essential for the load-sharing control, but they have not hesitated to go further than this and employ it almost everywhere.

Mr. A. Howell: The Billingham plant, although an electric power station, has for its primary object the generation of steam for the efficient carrying out of process work, the secondary object being the amount of electrical power which can be generated by that steam in its passage to the process work. The practice of passing steam at high pressure through turbines and exhausting this steam at the correct pressure for use in process or other work is, of course, not new and the main item of interest in the plant in question is the adoption of the high initial pressure and temperature. In a normal power-supply station the amount of boiler plant and generating plant installed are both governed by the electrical load, as the production of electrical power is the initial object. Due, however, to the fact that in the Billingham station the electrical power output is not the primary object, coupled with the necessity for the provision of a plant to supply such a large quantity of boiler-feed make-up water, any direct comparison with a normally designed steam-driven electrical generating station is impossible, and thus there is little in the paper that is controversial. Such controversial points as there are have cautiously been evaded. I refer to the capital cost of the plant and the authors' claim (page 1234) that the estimated cost of electrical energy at the busbars of the station is well below the unit cost of any coal-fired electrical generating station in the world. This claim is not qualified in the printed paper, but I note that when reading the abstract Mr. Humphrey judiciously added a rider to the effect "of any published figures." From an examination of Figs. 1 and 2 it would appear that ample ground space was available. Consequently there was no necessity to economize in the space to be occupied by the plant, and—with the exception of the switch house—the various auxiliaries, etc., in the power plant have been spread out so as to be kept below the first-floor level, rather than built upwards as is the alternative usually forced upon the power station designer when the cost of land is of material consideration. The designers, therefore, appear to have decided upon a standard type of building and have generally spread out the plant details at one level; this has undoubtedly saved a considerable time in planning the station lay-out. It also appears that the cubic capacity of the buildings has not been an important feature in the design, as the retention of the same height of building for each bay of the power plant has been governed by the height demanded by the switch house, this height apparently being adopted in order to keep the roof line at one level. If space had been of importance the feed-heating bay, the pipe bay and the turbine bay could, no doubt, have been reduced, as the cranes appear to be situated well above the height required to handle the largest pieces of apparatus in their respective bays. In the case of the power stations of public supply undertakings matters of this description naturally turn upon the limitation in capital cost commensurate with output, and, although the Billingham plant cannot by reason of its special duties be compared with such stations, it is somewhat disappointing that the authors have been prohibited from disclosing the capital cost. This would have been interesting, as far, at least, as the boiler plant is concerned, for, apart from the high pressure and superheat, which do not materially affect the disposition of plant, there are no extraordinary features in the lay-out. Some of the previous speakers have commented upon the rapidity of erection, and those responsible are to be congratulated upon the short space of time occupied in bringing the plant into being. At the same time, it should be appreciated that a performance of this nature is only a matter of man-hours up to economic saturation point, and of the limit imposed by the cost of construction. These points are unfortunately not referred to, nor is any statement made as to the output capacity of the plant available for giving an external supply to the factory at the end of the 15 months, and therefore no basis of comparison is given upon which to be guided as to the merit of the stated performance. Did the period of 15 months include the preparation of the whole of the working drawings for the fabrication of the steelwork and the civil engineering drawings for the construction of the foundations? Regarding the lay-out of the coal-pulverizing plant, it would be interesting to know why it was decided to install such a large number of mills. Although only 1 280 tons of coal per day are normally burnt in the boilers, the 10 pulverizers are capable of milling 3 240 tons of coal per day. Since the pulverized-fuel bunkers are only large enough to accommodate 6 hours' coal supply to the boilers and the pulverized-coal storage is limited to this period it is not possible to run the whole of the mills together at one time, and thus enable the daily coal requirements to be milled in either one or two shifts. Assuming, therefore, that five mills are running more or less continuously there appears to be 100 per cent of spare milling plant for use in case of breakdowns. It would be interesting if this point were made clear. Has any conclusion yet been come to, on the plant in question, regarding the amount of maintenance and the fineness of the grinding of the roller mills as compared with the ball mills, with the same coal? In present-day designs there is a great demand for maximum natural lighting in buildings, but I imagine that there is an absence of natural light in the pulverizer house due to the provision of a floor at the top of the raw-coal bunkers. This floor precludes the use of roof lighting as regards its utility below the raw-coal bunkers, and the division walls between the pulverizer house and the boiler houses make the building dependent for its direct natural light upon windows in the gable ends. This is not, I imagine, very efficient for a building some 200 ft. long containing a considerable amount of plant, with the result that artificial light probably has to be provided continuously. Again, the provision of a solid floor over the raw-coal bunkers would appear to prevent ventilation of the building via the roof ventilators. The ventilators shown in Fig. 2 seem to be large enough to deal with the cubic capacity of the whole building, and their only use would appear to be to take away the dust as it rises from the raw-coal bunkers during filling operations. At the present time, due to the publicity given to the power generating industry, much attention is being paid to the emission of smoke and grit from power-station chimneys. The paper contains very meagre information upon the important subject of dust removal, but from Mr. Bansall's remarks I gather that the gas velocity through the de-duster of 10 ft. per sec. (mentioned in the paper) has now been reduced to 8 ft. per sec., the efficiency of separation at this speed being 80 to 90 per cent. It would be of interest to know what is the increase in efficiency due to the decrease in gas speed. An efficiency of dust separation of 90 per cent must certainly be a great benefit to the amenities of the neighbourhood, as must also the removal of one-third of the sulphur from the outlet gases. I note that the slurry discharged from the de-dusting plant is fed into a slurry pit along with the boiler ash and thence passed to settling tanks. The easy and cheap handling of slurry from wet washers or de-dusters has presented some difficulty in the past as the dust is so fine that it remains in suspension in the settling tanks for a considerable period, and trouble has been experienced due to fine dust passing away in suspension in the overflow water. It would be interesting to know whether this has been experienced when combining the boiler ash with the slurry from the washer, and whether any special provision was made in the ash-settling pit (such as baffle weirs) so as to ensure the waste water from this pit passing away to the drainage system in a clean condition, thus leaving behind the whole of the dust from the de-duster to be handled by the grab. Regarding the pipework lay-out, the provision of a special building with its attendant crane is a departure from ordinary practice and the size of this building has, no doubt, given the designers ample space for large bends to permit of pipe expansion. The special nature of the plant calls for a considerable amount of piping over and above that of a normal generating station, but economy in space could possibly have been effected by the use of corrugated expansion bends, as these can be manufactured from solid-drawn tubes thick enough for pressures up to 800 lb. per sq. in. Mr. Humphrey's statement that the boiler plant was the world's largest pulverized-fuel-fired plant is apt to be misleading without the qualification of temperature. The maximum output of the 8 boilers of this plant is 2 160 000 lb. of steam per hour. At the State Line generating station at Chicago, U.S.A., which is a separately owned station not possessing its own distribution system but giving only bulk supply, the boiler house contains 6 pulverized-fuel-fired units, each built for an output of 450 000 lb. of steam per hour at 800 lb. pressure. The total output from this plant is therefore 2 700 000 lb. of steam per hour, which is greater than that of the boiler plant described. The temperature at the State Line station is only 756° F., which is 100 deg. F. lower than that of plant under discussion. The question of temperature should therefore be used as a qualification when speaking of this boiler plant as the world's largest pulverized-fuel-fired installation.

Mr. H. W. Clothier also took part in the discussion. The substance of his remarks is included in the discussion before the Institution (see page 1277).

[The authors' reply to this discussion will be published later.]

North Midland Centre, at Leeds, 25th March, 1930.

Mr. G. P. Henzell: The paper is of special interest in that it describes a considerable departure from the usual central station plant. I am interested to know that the designers decided to use mild steel for the superheater after alloy steels had been carefully considered and had been turned down on the grounds of cost and unreliability. I agree that their cost is a disadvantage, but I should like to have some further information regarding their reliability. The superheater itself, as shown on the boiler lay-out, is interleaved between the front bank of boiler tubes, and it seems to me that it would be somewhat difficult to renew a tube without partially dismantling the boiler. I do not altogether approve of the very sharp return bend in the superheater tubes, as this might possibly give trouble due to choking. With regard to the high-pressure steam piping, I think that the designers have acted wisely in adopting very stiff flanges, although I do not agree with them as to the advisability of using screwed-on flanges for such a high temperature. Was consideration given to the loose flange over a stepped-up end? It seems to me also that the jointing material used would eventually soften and possibly blow out as, owing to its thickness, a considerable area is exposed to the high-pressure steam. The steaming economizer is new in practice and I should like to ask whether any trouble due to "water hammer" has been experienced. Is the feed-water regulator placed on the inlet side of the economizer? At Billingham great care has been exercised over the purity of the feed water, and, in this connection, the oxygen content is the only factor that may cause anxiety. It would be interesting to know what the average oxygen-content is, and whether there is any automatic device to take care of it. In describing the high-pressure turbine the authors said that the alternator fan is the only separate auxiliary. This could, of course, have been avoided by driving the fan from the turbine shaft. I do not fully understand the complicated system of automatic control, but I notice that it has been so designed that it automatically goes out of action in the event of failure and leaves the system free for manual operation. I should like to know whether in the working of the impulse system of control any mechanical troubles have been experienced owing to the possible slipping of cogs or ratchets.

Mr. W. Dundas: Among the many interesting features of the plant at Billingham is the adoption of higher initial steam temperatures, without recourse to the use of special materials in the construction of the superheater. It appears that the success obtained is due to the high velocity of the steam through the superheater, as indicated by the unusual pressure-drop of 40 lb. per sq. in., and further comments by the authors on this subject would be of much assistance. The quantity of boiler blow-down (approximately $1\frac{3}{4}$ per cent of the evaporation) is somewhat high. Has a system of continuous blow-down been adopted, or any provision been made for reclaiming the heat lost thereby? The gain in efficiency obtained with the seventh heater appears to be small; have any other factors required in operation determined its adoption? The series arrangement of feed pumps provides a very flexible combination, and particulars of the authors' patented control ensuring stability in operation without the use of surge tanks would be of interest. The type of pipe joint adopted as a result of their experimental investigation is somewhat unexpected and it is a departure from the generally accepted essentials of the metal-to-metal face and welded joint, which has given good results under relatively severe conditions. The adoption of such an elaborate and extensive system of automatic control is a bold step, and one can imagine the effect of a failure on the operation of the plant and the possible consequences and delay in rectifying matters. I should be glad if the authors could give some indication as to the effect of automatic control on the personnel required for operating the plant, expressed in terms of water evaporated.

Mr. T. R. Warren: I think there is little doubt that the Billingham station will influence the design and control not only of future power stations, but also of future power systems, and the paper is particularly opportune coming as it does at a time when the "grid" will shortly be put to the test. The problems arising in connection with the operation of a compounded station such as that at Billingham are hardly less intricate than those encountered in the operation of interconnected systems, but in both cases the governing of the turbines is one of the most important factors to be considered. In America, where interconnection has been carried out perhaps to a greater extent than elsewhere, misapprehension as to certain aspects involved still appears to exist. For example, it is sometimes stated that sensitive governing, by preventing any tendency of the systems to alter in frequency, diminishes load-swinging and so improves stability. At Billingham the opposite view was taken, and it is therefore important to examine more closely the arguments for and against these opposing doctrines. The advocates of sensitive governing lose sight of the fact that the relation between the load on a turbine and its speed is actually the characteristic of the governor itself, and that relatively large changes of load occur in this case with a correspondingly small change in frequency. With coarse governing, however, such changes in load must result from much larger changes in frequency and these latter are, of course, prevented by the inertia of the system itself. In support of this argument it has been found that the addition of oil dashpots to the governor mechanism eliminates load-surging on large systems, and such a measure necessarily produces the same effect as coarsening the action of the governor, when considered over small periods of time, but it is inferior in principle in that it is an unnecessary complication. Intimately bound up with the question of governing is the development of automatic frequency control, an example of which is described in the paper. In America it is now recognized that this form of control, when applied to large systems, possesses merits which cannot be ignored, and several tests have been recently carried out with varying degrees of success. The results obtained over a period of 6 months on the interconnected systems in the Chicago area, which have a normal load of 900 000 kW, are encouraging, but recent attempts to control the frequency of another system on which the load was 200 000 kW were unsuccessful owing, as far as I can see, to incorrect design of the control scheme. As explained on page 1265, when controlling more than one machine automatically it is essential to provide load-sharing means, as this enables sufficient plant to take its share in the duty of frequency control to prevent undue load-changes on any one machine. One of the main advantages of the frequency control applied to the Billingham station is that it enables the governors to be coarsened, and this advantage—as I have attempted to explain—applies to interconnected systems as well. Among the other interesting and novel features described, the automatic electrical operation of the reducing valves at the station is, I think, worthy of note. Valves for this special duty had to comply with three main requirements: (1) They had to be of the non-seated type owing to the difficulty in adjusting the limit switches with great accuracy. (2) Wear of the valve under the combined action of temperature and constant operation had to be avoided. This ruled out the parallel-slide type. (3) The amounts of valve-travel for opening and closing impulses of equal duration had to be identical. The valves consequently had to be of the balanced non-seated type. The usual method of guarding against the sudden failure of a primary machine is to interlock its governor with the corresponding reducing valve, so as to cause the latter to open immediately upon a shut-down of the turbine. Such a drastic procedure as this was unnecessary at Billingham owing to the effect of the large capacity of the process-steam mains in stabilizing the process-steam pressure. With this in mind, it was considered more prudent to allow the automatic steam-pressure control to take care of any emergency which might arise—particularly as this permits of operation upon all three valves simultaneously and so divides the extra duty between them. To cope with wide fluctuations in steam pressure it was arranged that the impulses should occur at a maximum rate of one every 2 seconds, and from calculations this was found to be sufficient to meet all cases.

Mr. R. M. Longman: The electrical switchgear appears to be much the simplest part of the plant. I congratulate the authors on the excellent lay-out which they have achieved under conditions which differ from those generally existing in a power station, namely that the cables are not taken underground. Ample room is provided both for the low-tension and the high-tension cables. Although the space occupied is rather greater than usual it must have paid for itself in the accessibility of all the incoming and outgoing cables. I presume that the cables are lead-covered, armoured and without an external wrapping, so as to reduce any possible risk of fire; perhaps the authors will confirm this. Why was a process voltage of 6 600 adopted, particularly when the existing supply from the Newcastle-upon-Tyne Electric Supply Co. was at 11 000 volts? I think the answer to my question is that the authors wanted as many motors as possible to be run direct at the high voltage without transformation, and they were dubious of using 400-h.p. and 600-h.p. motors at 11 000 volts. As far as the question of motor convertors is concerned, I do not think that there is any need to consider the necessity of using 6 600 instead of 11 000 volts. There are, and have been for many years, a large number of 11 000-volt motor convertors in use in this country under very arduous conditions. The use of armour-clad switchgear is undoubtedly another great asset in this lay-out. With the cubicle or any other type except the armour-clad, the space required for such switchgear would be almost prohibitive. The control apparatus is unusual and represents a great step forward, but I should like to know what sort of frequency graph it gives. Can a fairly steady frequency be maintained? What is the maximum variation, and is the plant run in synchronism with that of the Newcastle Electric Supply Co.? The large amount of power required leads one to consider whether other arrangements of the generating plant which would have give equally satisfactory results in practice could not have been devised. In the lay-out of the electrical equipment (Fig. 22) I noticed the use of reactors, especially tie-bar reactors, with the idea of diminishing the disturbance to the system and of reducing the size of the switchgear required. It would be interesting to know whether they have any real effect and how the interconnection has operated. The generators have 12 per cent reactance so as to bring the total short-circuit current on the busbars to the 500 000 kVA mentioned. The question of the operating staff was mentioned by Mr. Dundas, and I should like to know how many operators are actually required for a plant of this size. Such a large number of valves—I suppose they run into hundreds—must necessitate operators well trained with the plant, if they are to know what to do and where to go. Possibly the apparatus works so smoothly that the valves rarely have to be operated. The large amount of steam required for the process work and the very small amount of condensate water which is returned from it is an unusual feature. Is there no way of reducing this waste of water, because of the water which is required a very large proportion is taken direct and has to be evaporated? I was interested in a description of the de-duster plant by one of the authors, and I feel that they would be right in eliminating the electrical precipitation method although this has many good features, but on the score of cost, space required and reliability they were probably correct in their decision.

Mr. E. A. Logan: In motoring circles the value of racing to the industry in general is sometimes questioned, and the answer is given that the standard models are improved as a result. The Billingham plant might be described as the " sports " model, and there is much in the present paper which will give a lead for future standard models and help to improve power stations in general. I have asked myself the question: Is the Billingham plant a heat-generating station exporting electricity as a by-product, or is it an electrical generating station exporting heat as a by-product? I now realize that neither view is correct, and that in point of fact the title of the paper is the most accurate description which could have been applied. Neither function is subordinate to the other and the plant must properly be regarded as a co-ordinated whole, supplying heat and electricity. Mr. Warren's description of the automatic control gear has made this point clearer. Even realizing that electricity is not a by-product of this plant full credit must be given for the efforts made to secure such a high overall thermal efficiency, the figure of 25·45 per cent quoted on page 1270 being one that even purely electrical stations not concerned with process work can regard as enviable. The question of main cables on a chemically contaminated site has been dealt with in a neat, effective and cheap way. There is another example in this country of a station of much the same rating with contaminated site conditions, but here the problem has been solved by placing the cables in underground tunnels. Except from the point of view of cost, the over-ground method being probably the cheaper, both methods have the great advantage of ease of maintenance. The tunnel method suffers somewhat from the difficulty of dissipating the heat losses, and forced ventilation is necessary at times of heavy load, but on the other hand the cables are screened from the direct rays of the sun. Was any allowance made in the cable rating for the effect of a high temperature due to heat from the sun? I should be pleased to have particulars of the treatment of the cables outside the buildings where, presumably, they are subject to the rather violent corrosive action of the chemically charged atmosphere. Cables supported on bridges, as described by the authors, call for racking, and a controversy is at present raging as to the correct centres of the supporting cleats on which cables are erected. Perhaps the authors may be able to add some information regarding the distance apart of the supporting cleats. I note that certain "draw-out" busbar section-switches are provided in the switchgear lay-out. It appears that some special type of plug-in contact will be required to carry the very large busbar current. I should be glad of information on this point.

Mr. W. L. M. French: I am interested in high-pressure pulverized-fuel installations and regret that the authors do not give more details with regard to their actual operating experiences with this method of firing. Little information is given concerning the class and type of fuel generally being consumed at the station, other than its calorific value of 11 700 B.Th.U. per lb., which suggests that the fuel used is of reasonably good quality. One amongst many of the assets of a pulverized-fuel plant is its claimed ability to utilize low-grade and even waste fuels without seriously reducing commercial steaming efficiency. I should therefore like to have the authors' opinion with regard to the use of low-grade fuels, from a commercial point of view. No information is given in connection with the drying of the fuel. However, an examination of Figs. 2 and 3 reveals the fact that this process is carried out by admitting pre-heated air into the pulverizing mill circuit. This results in very rapid drying of the fuel, but has the great disadvantage that the air must be extracted at a later stage from the mill circuit. What happens to this moisture-laden air? If it is discharged to the atmosphere heat losses and dust-emission will result, yet if it is returned to the furnaces of the boilers the moisture will increase the stack heat-losses and reduce the furnace temperature. When burning small or slack fuel in a stoker-fired plant moistening of the fuel prior to burning becomes an advantage, since it binds the fuel together on the grates and so reduces excess air-losses. It also prevents the smaller particles from being drawn off the grates into the flues in a semi-consumed condition. These advantages are entirely absent from a pulverized-fuel plant. With a fuel containing a given amount of free moisture, theoretically the quantity of heat required to evaporate this moisture should be the same whether it be done by means of some external drying plant or in the furnace itself. From an overall heat-efficiency point of view the latter method would be the better, since serious heat losses occur with most drying apparatus. With pulverized fuel, the extent to which the coal should be dried appears to be determined more by the greater ease with which dry coal can be pulverized. Also, if moisture be present in the pulverized fuel, trouble may be experienced due to clogging of the screw conveyors, arching of the fuel in storage bins, bridging-over in feeder openings, and, above all, intermittent feeding to the burners causing pulsations in the flame. I should like to know what troubles the authors have had in this direction, and what they have found to be the limiting percentage of moisture.

Mr. A. F. Carter: In view of the great complications in a system like the Billingham station, I should be glad if the authors would describe the procedure adopted when starting up the plant. Will they also explain what is likely to happen in the event of a shut-down through the falling out of step of the various machines, and the probable time required in getting back to normal conditions?

Mr. T. Roles: I congratulate the authors, the manufacturers and all who have had anything to do with this plant on the boldness of the design. I am interested to note the extent to which automatic control is used in connection with the plant, as an engineer who has had a good deal to do with the design of the high-pressure plant which is being installed at Bradford has expressed the opinion that too many automatic devices are incorporated in it. I should like to know whether at Billingham the feed pumps are hydraulically balanced, or whether a Michell thrust is used in connection with them in order to take the heavy thrusts which they may have to sustain under working conditions. When high-pressure working was first mooted, a great deal was said as to the difficulty likely to be experienced in connection with valves. It was stated with regard to some early plants that a safety valve had only to blow off once for the seat to be cut up and require replacing. I should be glad to know whether the high-pressure safety valves have blown off on a number of occasions, and, if so, the effect on their seats. I assume that the automatic valves are all electrically, and not hydraulically, operated. Has electric operation been found satisfactory under all circumstances? With regard to the ordinary valves, I notice that parallel-slide valves are used, and as a few years ago it was thought that such valves would not be suitable for high pressure the authors' experience in this connection would be interesting. There has been some controversy as to whether to use the ordinary type of water gauge, fitted with a tube made of some special glass (" Pyrex " glass was at one time said to be very suitable), or whether a gauge made up of flat glass bolted into a frame was better. Perhaps some information regarding the water gauges in use, their length of life and whether much trouble has been experienced in connection with them, could be given. Have the boilers been worked up to full load and overload for a considerable time, and have any ill-effects been observed in any of their parts, such as the superheater and furnace tubes?

[The authors' reply to this discussion will be published later.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 1ST APRIL, 1930.

Mr. W. S. Burge: The magnitude of the demand for process steam and electric power at these works is such that the usually accepted practice of the automatic pass-out turbine has been departed from, and I consider that the consulting engineer has been well advised to divide between different classes of prime movers the duties of base load supply, peak load supply and feed heating, because by so doing he has eliminated as far as is humanly possible all chance of failure of supply and furthermore he has done this with little sacrifice of efficiency. I gather from the paper that pressure control on the process mains and also trimming of the steam supply are in this installation taken care of by the automatic reducing valves, whilst the duty of trimming the electric power demand is taken up by the normal-pressure condensing turbines. The ambitious and necessarily complicated scheme of regenerative feed-heating is isolated from the primary high-pressure units by the provision of separate feed-heating turbines, and thus the primary high-pressure back-pressure turbines are reduced to the simplest possible proportions. One of the greatest difficulties in high-pressure turbine work is to secure a unit of sufficient output to afford a satisfactory blade height through the first few stages of the turbine, and if the output and steam quantity through the high-pressure cylinder happen to prove sufficient for good design these very conditions that make it comparatively easy to deal with the high-pressure section of the machine are a serious embarrassment in the low-pressure section. The primary turbines at Billingham are only rated at 11 900 kW each, but they take some 537 000 lb. of steam on full load. If expanded down to normal vacuum, this amount would yield about 60 000 kW, so that, while these machines work under almost ideal conditions in regard to quantity of steam, the steam is disposed of well before its large volume is able to introduce the usual mechanical difficulties connected with low-pressure expansion. I consider that these primary machines thus have an almost ideal duty. Although the use of automatic reducing valves on a power-station scheme is sometimes considered to be fundamentally wrong from the point of view of efficiency, I do not subscribe to this opinion in circumstances such as those of the plant under discussion. I have little doubt that the loss in thermodynamic heat-drop due to these valves is in normal operation amply balanced by the additional security which they give for continuity of supply in emergency. I should be glad to know whether the reducing valves have yet been called upon to pass the full steam quantity, and if so whether any provision is made for taking the thrust due to energy dissipation. What is their maximum speed of opening? In view of the existence of these valves it has been necessary to install steam de-superheaters; these have a function which is fundamentally wrong—one does not like to burn coal for superheating steam and then to de-superheat it without any thermodynamic gain—but taking all the circumstances into account I fail to see how this could have been avoided without departing from the general engineering policy of the whole scheme. It would be interesting to know whether the de-superheaters are used for the purpose of heating the feed water, because, if so, criticism cannot be levelled at them from the thermal point of view. The use of steam at a total temperature of 856° F. is one of the most outstanding features of the plant, and I hope that this advance will be rewarded with good results. I believe that for many years we have been making bigger advances in high-temperature steam development than any other country, and the credit for this should be given to our long-suffering steel industry. I find that the U.S.A. have lagged behind our own country in regard to the use of high-temperature steam, partly because their boiler plants are forced more than ours and also because their skill as steel makers is inferior to our own. The superheaters are the part of the plant most affected by the combination of high temperature and high pressure, and I presume that the unusually large pressure-drop across the boilers has been deliberately provided with a view to maintaining a high steam speed through the superheater coils for the purpose of cooling the latter. I have found that in the U.S.A. it is becoming standard practice to run radiant and convection superheaters in combination, and also on light loads to limit the steam speed through the superheaters to not less than 2 000 to 1 500 feet per minute. There is also a good deal of controversy as to the best type of steel to use for superheater work, and I believe that experience over there tends to confirm the authors' choice of best quality mild steel. By heating the feed water passed into the economizers up to 401° F. the authors have advanced considerably beyond standard practice, and I am particularly interested in this because I feel that one of the most difficult problems with which power-station engineers are faced at the present time is that of heating their feed water by extraction to the maximum temperature, while still maintaining a minimum terminal temperature at the base of the stack. This problem involves questions of boiler, economizer and air-heater design, and particularly that of furnace design. From data given in the Appendix to the paper it would appear that this plant had realized a feed temperature of 401° F. into the economizer, and a final stack temperature of only 230° F. after the air heater. These two figures are coincident with an air temperature of 500° F. into the furnace, and they give definite proof of very high reception efficiency at the back end of the boiler plant. With pulverized fuel and air heating to 500° F. I should also expect remarkably high combustion efficiency, and I am therefore surprised to find that with definite proof of exceptionally high reception efficiency and strong indications of very high combustion efficiency the overall efficiency of the boiler plant is only given as 81 per cent. I suppose that this figure of 81 per cent is a net value and that it includes the whole of the auxiliary power taken in pulverizing and conveying; this, in my experience, generally accounts for some 3 to 4 per cent of the total amount of coal burned. Have the authors any figures on this subject? In the U.S.A. the heat release per cubic foot of combustion space per hour on most pulverized-fuel systems is now about 18 000 to 20 000 B.Th.U. What is the corresponding rate at Billingham? Information as to the average furnace temperature at economic load and the average ash-fusing temperature would be welcome. I notice that the average evaporation per square foot of heating surface per hour (including the economizer surface) is as high as 17 lb., and this is particularly interesting in view of the fact that only a few years ago 7 to 10 lb. was considered to be a good figure. I consider that this great increase in the evaporation per unit of surface constitutes the chief advance in boiler design, and that the advance is mainly due to pulverized fuel. My experience shows that the chief value of pulverized fuel lies in rating rather than in efficiency.

Mr. K. Baumann: The plant is described as having been laid out on horizontal lines, and this applies not only to the installation as a whole, but also to the individual units. Thus the boilers are not arranged with the economizers and air heaters above the boiler proper, in a way which, I believe, originated in the United States, where in some localities ground space is expensive and economy in this respect is of importance. When using pulverized-fuel boilers, for which a high combustion chamber is necessary in addition, these designs require very high buildings. It would be interesting to know whether the authors have investigated the relative costs of what may be called a "vertical" boiler and the type of boiler which they have adopted. I am interested in the mode of calculating the efficiency of the plant. It judges the commercial value of steam at different pressures not by its heat content, but by the amount of work which it is capable of performing, on the basis of the regenerative or feed-heating cycle. I think that the authors are to be congratulated on having made what may be called a large-scale application of the second law of thermodynamics to power-plant accountancy. A few weeks ago I had an opportunity of advocating the same principle for the purpose of comparing power-station performances on the basis of the regenerative cycle and not—as has been done in the past—on that of the Rankine cycle. I have an impression that some engineers regarded this comparison on the basis of the regenerative principle as rather unjust to some of the existing power stations, and I am therefore glad to find support for my view in the methods adopted by the authors. I note, however, that their calculation of the theoretical power available is based on the adiabatic heat-drop and that it makes an allowance for the steam required for feed heating during actual operation, rather than for the steam which would be required in an ideal regenerative cycle with 100 per cent efficiency. Whilst the difference involved is small, the result is not strictly correct. A chart of the Mollier type is required, although it should not give the heat-drop but what one might term the "Kelvin heat-drop," i.e. the theoretical power available in an ideal regenerative steam cycle. A few weeks ago we were proud to announce that in this neighbourhood a boiler efficiency of 80 per cent and a net engine-room efficiency of over 30 per cent had been obtained. The figures given in Table 3 for the boiler-plant efficiency and for the engine-room efficiency are 34·6 and 70 per cent respectively. This may be the result of the method of accountancy adopted by the authors, but I should prefer to consider the boiler plant purely as a heat-transmitting apparatus. The authors have assigned the cycle value to the steam at the boilers. I suggest that it would be better to give the boiler-plant efficiency in the usual way, and to debit the engine-room efficiency with the shortcomings of the second law of thermodynamics. The lay-out of the steam pipes may appear complicated at first sight, but one must remember that such pipes should be laid out with due regard for flexibility. I think that this has been fully realized by the authors, and their object is certainly attained in the lay-out shown in Fig. 17. The pipe flange which has been adopted is of interest. A similar type, i.e. the screwed flange, has been used in the high-pressure installation at Mannheim, where the steam pressure is 100 atmospheres (1 420 lb. per sq. in.) and the temperature is of the same order as at Billingham. The Mannheim flange was attached by welding on the steam pipe at the back of the flange—a design which I do not consider to be so good as that adopted at Billingham. It has been reported that difficulties due to steam leakage have been experienced at Mannheim, and it would be interesting to hear whether the authors have had similar trouble. The bolt stresses at Mannheim are considerably higher than those at Billingham. The creep strength of steel is not as high as, a few years ago, we thought it to be, and I therefore consider the adoption of low bolt stresses at Billingham to be good practice. With regard to the estimated or anticipated steam consumptions (Table 8), the primary turbines have been tested at the makers' works with reduced loads but under the full heat-drop conditions, and, although the results are not yet available for publication, I may say that this turbine is considerably more efficient than is stated in the paper. I hope in the near future to have an opportunity of giving further information with regard to the design and performance of this primary turbine.

[The authors' reply to this discussion will be published later.]

TEES-SIDE SUB-CENTRE, AT MIDDLESBROUGH, 2ND APRIL, 1930.

Mr. R. J. Huntley: The plant must appear to many to be complex, but we found to our relief that as it settled down to steady running it became relatively simple to handle. A first impression was that the machines were spread over an unusually large area, but later experience made one realize that the plant could not have been more compactly placed without being made unmanageable. A more compact arrangement could have been obtained by coupling mechanically on one shaft a primary turbine, a feed-heating turbine and a condensing turbine, but this would have sacrificed a flexibility in the plant which is invaluable for efficient running. It must be remembered that, in addition to 80 000 kW of generating plant, the building contains feed pumps and feed heaters capable of handling a water quantity equivalent to an electrical capacity of about 200 000 kW, and a distillation plant that would be sufficient to meet the normal make-up requirements of a power station of about $1\frac{1}{2}$ million kW capacity. Therefore this feed-water plant could not have been hidden away under the turbine floor, or squeezed between the turbines and the boiler-house wall, as in stations of more normal design. We who operate the plant are specially glad that economic considerations permitted the designers to lay out a steam-control floor in the pipe bay, for in times of trouble it has meant that one man has been able to control the whole of the turbine floor from this point, and to have operated half-a-dozen main steam valves at the same time, rapidly and without fear of mistakes. The provision of four steam lines supplying a primary turbine, and four exhaust 275 lb. per sq. in. lines, has proved an advantage; full load can be maintained on only three lines and 10 000 kW on two, thus making it possible to carry out maintenance work on steam ranges without undue difficulty. The primary turbines are running absolutely reliably, and are the simplest turbines in the station to put on load. About 4 hours are usually taken to bring the steam lines up to pressure, about 2 hours to warm up the turbine, and in the neighbourhood of $\frac{1}{4}$ hour to run the turbine up to speed from standing. Recently one of them was warmed up and put on load in $\frac{3}{4}$ hour. The turbine is warmed up on a bypass exhaust valve from the 275 lb. per sq. in. mains; when up to pressure the exhaust valves are opened, and the turbine is run up on two $2\frac{1}{2}$-in. bypass valves to about 1 800 r.p.m., when it is necessary to crack a main stop-valve to reach full speed. The main reducing valves used for bypassing the primary turbines showed no signs of wear or scoring on the valve faces when opened up for inspection 2 or 3 months ago, although they had been in continuous service for from 6 to 9 months. Certain fundamental points about the plant have always to be remembered. The exhaust pressure of the primary turbines must always be held at 275 lb. per sq. in.; the maximum load that can be put on a primary turbine at any time depends on the steam flow through the station; and the maximum load that the feed-heating turbines can carry is governed by the feed-water flow, that is to say, by the steam flow. It is seen, therefore, that a complete cessation in steam demand by the process plants reduces the total generating capacity of the station to about 28 000 kW, the load being carried on the two condensing turbo-alternators and one feed-heating turbine. It is interesting to know that the automatic pressure and frequency controls on the turbines work satisfactorily. I must admit that I have been converted from complete scepticism to a belief that this apparatus is worth while. It is yet too soon to say that it is completely satisfactory. Time alone will prove its reliability, and experience only will show how it handles sudden changes of steam and electric load of large magnitude. Sudden reduction in the boiler-house steaming rate, occasioned, say, by the loss of a boiler, may necessitate going over to hand control and allowing the constant 275 lb. per sq. in. steam pressure to fall and so ease the steam demand on the high-pressure boilers and throw an overload on the 275 lb. per sq. in. boiler house. The automatic pressure-control definitely keeps a steadier 275 lb. per sq. in. pressure than does manual control. The speed regulation of the feed-heating turbines, which are loaded and controlled manually to keep a constant back-pressure, will probably have to be coarsened, for at present it is too sensitive, and changes of electrical load on the station, which should be taken up immediately by the machine on automatic frequency control, affect these machines. It is also of interest to know that it is perfectly practicable to control the steam pressure, station frequency and load distribution on turbines by hand; in fact, the station was run in this manner until quite recently. Therefore the justification of the automatic control in this station is that it is more efficient than manual control and saves operating labour. One feed-heating turbine with its feed heaters and the " B " and " C " feed pumps associated with them form an entity, and the getting-away of one group and transferring to it, step by step, electrical and feed-water load from another group is one of the neatest operations in the station, and one which can be performed without varying the final feed-water temperature by more than two or three degrees. The most vital machines in the plant are the two 6-stage sealing water pumps, delivering cold water under pressure to feed-pump glands, keeping them cool and preventing the hot feed-water reaching the gland packing. A 3-minute shut-down of these pumps is sufficient to cause the feed-pump glands to seize. The incorporation of the No. 2 feed heaters in the distillation plant is ingenious. Actually, the 6 evaporators forming one distillation set are grouped to give two sets, one a quadruple effect—consisting of 4 evaporators—drawing its steam from the turbine and exhausting the vapour from the last effect into the de-aerator which acts as the first stage feed-heater, and one a double effect—consisting of two evaporators—ing its steam from the same source and exhausting the vapour to the second stage—or No. 2—heater. I would ask the authors why they provided each feed heater with an extraction pump to extract the condensed steam and add it to the feed-water range immediately after its heater, instead of allowing the condensate to drain to the previous stage heater and flash off a certain amount of steam before draining to the next lower stage, the condensate from all the heaters finally entering the de-aerator heater at a low temperature. For a given size of heater, their method is more efficient in that they use smaller quantities of higher-grade steam and larger quantities of lower-grade steam than would be the case in the cascade drain arrangement, but it seems to me that the same efficiency could be obtained by increasing the heater heating surface, even though this increase would have to be very considerable at the lower stages. Cascade draining would, of course, entail an increase of the capacity of the " B " and " C " feed pumps to that of the " A " pumps. The economic balance thus weighs the increase of size of heaters and feed pumps, coupled with decreased operating, labour and maintenance costs, against the employment of 19 separate heater extraction pumps.

[The authors' reply to this discussion will be published later.]

SCOTTISH CENTRE, AT GLASGOW, 8TH APRIL, 1930.

Mr. N. C. Bridge: The authors remark that the conditions governing the design of the plant described differ essentially from those relating to a public supply station. In my view there are two, and really only two, fundamental differences, and these are so exceptional that they might well be further emphasized in their bearing on the general conception of the plant. I refer to the 100 per cent load factor and the 40 per cent make-up feed. The process steam requirement has scarcely the same bearing as the foregoing factors, since what is done to meet this is analogous, apart from the relative capacity of the condensing turbines, to what has to be done in pressure-compounding an existing station. The same considerations arise in regard to the initial steam conditions, and the same inherent complications as regards emergency provisions for pressure reduction and de-superheating. There is undoubtedly, however, a good deal more justification for the compounding arrangement in the case of Billingham than in the case of any public supply station. The authors mention continuity of supply as being a primary condition, but this is equally the aim in public supply stations, upon which not one, but usually a number, of important industries depend for continuity of operation. The load factor on the Billingham plant must be the envy of public supply undertakings, and it is only this factor, I think, that saves the whole design from condemnation as decidedly extravagant in its conception and in the elaboration of auxiliary equipment and automatic controls. The authors claim that the estimated unit cost of power is lower than that of any other coal station in the world, but this statement is not very helpful, since no indication is given as to how the charges are assessed as between power generation and process steam, and it is not even made clear as to whether capital charges as well as operating costs are included. As regards the proportion of make-up feed water required, the position is entirely different. The separate feed-heating turbine exhausting to an evaporating and de-aerating plant is undoubtedly the proper means of dealing with this particular need, though this again introduces complications which would be quite inexcusable in a normal plant with 4 per cent or so of make-up. The question of maintaining the output from an evaporator, where river water is used for the raw feed, is one that must claim increasing attention in view of the total ban on undistilled make-up necessitated with high-pressure boiler plant. Some form of chemical treatment to reduce the rate of scale formation on the evaporator tubes would appear to be essential if " outage " and cleaning costs are to be kept within reasonable limits, and it is quite understandable that this question, in the case of the Billingham plant, would assume a perplexing importance. There is, however, only a very brief reference to the matter in the paper, in the last paragraph under the heading "Distillation" on page 1261. The introduction of phosphate appears to be of some value in throwing down the hard salts as sludge instead of allowing them to adhere as scale, but, as often happens, the remedy gives rise to a fresh problem. Priming takes place and a proportion of the salts are carried over with the vapour in suspension. This, at any rate, is what is happening in a case that has just come to my notice, and we are now trying to find a remedy for the priming. Perhaps the authors from their extensive experience will deal a little more fully in their reply with this question of the pre-treatment of raw water. As regards the steam-water cycle adopted at Billingham, one rather hesitates to criticize a scheme which is so obviously the outcome of the most careful thought and expert advice, but some explanation seems desirable as to the justification for the seventh stage feed-heater. This heater is shown to require live steam of a potential value of nearly 10 000 kW, and the only reason given for its adoption is to permit of the accurate adjustment of the final feed temperature. What is there about the boiler plant that needs this extraordinary sacrifice of energy to obtain such precision with the feed temperature? The increased gain in thermal efficiency due to the last heater does not appear to be more than about 0·25 per cent and it would, I think, have been much simpler to have increased the capacity of the economizer. The final boiler feed-pumps would certainly have been less troublesome to design in this case. In endeavouring to adjust the authors' thermal efficiency calculations to a further case with only six heaters, I have noticed a discrepancy, as between Appendix 1 and Appendix 2 (Case 4), in the figures for the steam and water heat values for the adopted conditions. The figures in Appendix 2 seem to be incorrect in this respect, though the resultant figure given for steam generated appears to be correct.

[The authors' reply to this discussion will be published later.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 14TH APRIL, 1930.

Dr. C. C. Garrard: It is particularly appropriate that this valuable paper should be sponsored by Imperial Chemical Industries, Ltd., as it is to the chemical industry, I believe, that we must look for any real advance in the methods of generating power. Watt invented practically everything in connection with the steam engine 150 years ago. I do not know the thermal efficiency of Watt's engine, but the authors obtain a thermal efficiency of 24·22 per cent (see page 1270). At this rate of progress it would require, say, 450 years yet before we approach, in steam power generation, the efficiencies to which electrical engineers are accustomed with their machines. But this, of course, is only a fantastic suggestion because with steam power generation, as at present understood, we approach asymptotically to a theoretical upper limit of thermal efficiency, which in any case is nowhere near the efficiencies obtained, as I have said, with electrical machines. I feel convinced, however, that before long the chemical engineer will revolutionize the generation of power and thereby eliminate what are, after all, the present wasteful methods. The authors claim a cost of generation of electric power well below the unit cost of any electric generating station in the world depending on coal as a fuel. The thermal efficiency of 24·22 per cent is, however, exceeded by several modern power stations. In addition, it must be remembered that the load factor of any public supply generating station is lower than that of Billingham. For example, the Philadelphia Power Co. reported several years ago that the overall thermal efficiency of their Richmond station was 24·7 per cent at a load factor of 54 per cent. I believe I am correct in saying that at the present moment there is in course of construction an electric supply station which will have an overall efficiency of 27 to 28 per cent, and that with less extreme steam conditions than those mentioned in this paper. It follows, I take it, that the low cost of production obtained by the authors is due in great part to the high load factor (close on 100 per cent) and the low price of fuel. It would be interesting if the prohibition of publication of cost figures could be relaxed to let us know this latter figure. The design of the whole plant seems to me to constitute a great triumph for the principle of automatic control. There is no doubt that for routine duties a machine is more reliable than a man. I am not quite clear about the impulse generator (Fig. 23). On the shaft of this there appear to be 4 discs. I take it that 1, 2, 4 or 8 impulses are generated per revolution of the shaft. If so, this would seem not quite to agree with the description given at the foot of column 2 of page 1266. Why was this method of impulsing for pressure control adopted? I can understand such a scheme for frequency control as it is the natural thing to do, viz. to operate by impulses depending upon the difference between the actual frequency and the standard clock frequency. Was the arrangement used for pressure control simply to make it similar to the frequency-control method? It seems to me that it would be simpler to regulate the whole operation by the pressure relay itself, one contact being made when the pressure is too high and the other when it is too low. My difficulty in understanding why this impulse method for pressure control is necessary would doubtless be obviated if it were explained how the contactors or relays which receive the impulses respond to such impulses. I assume that with a high speed of impulses the valves are opened and closed more quickly than with a low speed of impulses. If this be so are hunting troubles thereby entirely prevented? Possibly the impulse method for pressure control is more free from such troubles than the simpler method.

Mr. W. A. Barnett (*communicated*): I should like to ask why the boiler blow-down loss appears to be so high, viz. 18 400 lb. per hour, approximately 1·7 per cent of total evaporation and 5·8 per cent of total raw water supplied, considering the fact that the water goes through a good distillation process. Does this figure include blow-down from all parts of the plant, evaporators, etc.? Are any chemicals used to preserve slight alkalinity in the system, thereby causing concentration in the boilers? Although the oxygen content of the actual boiler feed is low, has any internal corrosion of the steel economizer or boiler tubes been experienced? There is no mention of automatic combustion control. Would not this have somewhat improved the boiler efficiency and operation? As simplicity is a factor which needs consideration from the points of view of operation, safety, and continuity of service, the complications of the system caused by live and bled steam feed-heating seem to be great when the slight increase in efficiency is considered. I should be glad if the authors would say why a frequency of 40 cycles was adopted, in view of the fact that 50 cycles is the standard throughout the country.

Mr. R. H. Rawll (*communicated*): It seems that three motor-convertor sets are utilized to provide the d.c. supply for the more important auxiliary drives. One of these sets runs "floating" on the supply company's mains on account of it being considered essential that an alternative supply for the d.c. auxiliary drives should always be available. Great care seems to have been exercised in the design of the whole steam and electric plant to provide duplicate units, and yet this stand-by motor-convertor is not duplicated. I can understand that if this particular set remained stationary until it was required for use in an emergency, its duplication would not be justified on economical grounds, but since it is always running, whether required or not, a fault developing on it might put it out of commission just at the time when it was required for stand-by purposes. I assume from the paper that one of these motor-convertor sets is always run from the supply company's mains. If, of course, each of the three convertor sets can be run either off the station busbars or the supply company's mains, the above criticism does not apply. I should therefore be glad to be enlightened on this point. It is also stated in the paper that the auxiliary d.c. supply is at 460/230 volts, 3-wire, the neutral being earthed. This supply at 230 volts, of course, provides the energy for switch operation, etc. I presume that all control switches are of the double-pole type, because otherwise an earth on a control circuit might inadvertently operate the switch, etc., to which it is connected.

[The authors' reply to this discussion will be published later.]

THE SERRA HYDRO-ELECTRIC DEVELOPMENT, SÃO PAULO, BRAZIL (WITH SPECIAL REFERENCE TO THE ELECTRICAL LAY-OUT).

By R. W. H. COUZENS, M.A., Associate Member.

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SUMMARY.

The paper is a general description of the hydro-electric development at the Serra de Cubatão, in the State of São Paulo, Brazil. The general load and climatic conditions which led to the development are outlined, together with the advantages of the site chosen for the power house and reservoirs. The method of the provision of power for constructional purposes is next described.

There follow details of the permanent lay-out and the construction of the power house and its equipment. The switch-house lay-out and equipment, and the control and relay systems are described. Details of the earthing system, the 88 000-volt outdoor equipment, the transmission line and the São Caetano terminal station for the city of São Paulo are set forth.

Finally, the capacity and cost of the development and the São Paulo system are dealt with.

GENERAL.

In 1924 it was estimated that about 1 per cent of the potential water power in South America was developed. Brazil is one of its richest countries as regards water power, largely owing to the fact that over a considerable proportion of the coast-line the land is a well-watered plateau dropping steeply near to the coast. As elsewhere, however, the largest waterfalls are at a great distance from industrial activity.

The city of São Paulo has grown exceedingly rapidly as regards population and electrical load; so that, while in 1900 only 1 000 h.p. was installed and there was no storage reservoir, by 1910 a total of 27 000 h.p. was installed and 7½ million kWh of storage capacity was available. In 1916 the peak load was 25 000 kW and the storage capacity had increased to 110 million kWh; and 10 years later, in 1926, the peak load was 59 000 kW, with 148 000 h.p. installed and a storage capacity of 120 million kWh. In June 1929 the peak load was 88 600 kW and the storage capacity 238 million kWh.

In the middle of 1925 the following plants were supplying power: Parnahyba, with a capacity of 18 000 kVA, at a distance of 14 miles from the terminal station; Sorocaba, with a capacity of 58 000 kVA, at a distance of 48 miles from the terminal station; and a reserve steam plant in the city, with a capacity of 10 000 kVA.

It will thus be seen that the capacity of the plant installed is in all cases greatly in excess of the peak load to be carried, since certain plants are dependent on river flow and are used in flood season to full capacity, while others, with ample storage, store the flood-water and operate at full capacity during the dry season. The cycle of weather appears to cover a period of 10 or 11 years, which include two dry years with an intervening season of scanty rain which is insufficient to refill the reservoirs. Such a season occurred in 1924–5, and rendered necessary the erection of a power plant of two 14 000-h.p. units at Rasgão, on the River Tieté, below Parnahyba; this plant was in operation within 12 months of the decision to erect it. It was also decided to construct with all possible speed a plant at the Serra de Cubatão—a project which had previously been studied and decided on, delays, however, occurring in the acquisition of land and rights.

The construction of this plant was begun in March, 1925; the first unit was in operation in October, 1926, and the second in April, 1927.

POWER-HOUSE SITE.

The site of the Serra penstocks and power house is a spur on the edge of the rolling plateau which follows the coast but slopes gently inland. The site is distant only 22 miles from São Paulo and 10 miles from the port of Santos, whence railway transport is available direct to the power house itself.

The prevailing winds are south-east from the Atlantic Ocean, and these precipitate their moisture on reaching the plateau, causing on its edge a very high average rainfall, which decreases rapidly further inland. The rainfall at the Alto da Serra—the top of the pipe-line—is probably 173 to 264 in. (4·4 to 6·7 m) per annum, averaging about 197 in. (5 m). No accurate data at this particular place were available before construction began, but since then the fall has been greater than at the Alto da Serra on the São Paulo Railway, some 10 miles distant to the north, where it averages about 150 in. (3·8 m).

On the plateau rise a number of small tributaries of the Tieté River, whose normal course to the Atlantic Ocean is over 2 000 miles; and the small difference in elevation in the valleys enables large reservoirs to be formed by relatively low dykes and so provides storage for the flood-waters of these streams.

RESERVOIRS.

An effective storage capacity of 37 771 million cub. ft. (1 070 million m^3) is obtainable; the reservoirs proposed are shown in Fig. 1. The Rio das Pedras reservoir nearest to the power house has a maximum water-level of 2 384 ft. (727 m) and a surface area of 2·7 sq. miles (7 km^2). It is formed by a concrete dam of arch and gravity section, about 99 ft. (30 m) high, which closes the gorge at the point where the Rio das

Pedras had cut its way through the crest of the plateau. This affords a spill-way for flood-waters; and further to the east, by a dredged connection and control works, the valley of the Perequê serves as an additional spill-way.

The Rio das Pedras reservoir is connected to the Rio Grande reservoir to the north-west by the Summit Canal which, including the portion within the two reservoirs, is 10 miles (16 km) in length. The Rio Grande reservoir has an ultimate water-level of 2 442 ft. (745 m) and a surface area of 53 sq. miles (137 km^2). There will thus be a difference in level between the Rio Grande and the Rio das Pedras reservoirs of from 10 to 60 ft. (3 to 18 m) available for power production in a power station of 18 900 h.p. capacity at the Summit Control. The Rio Grande dam forms the main storage reservoir to the north-west, and north-westwards from this point the river is being dredged and straightened to form a canal to connect with the Tieté River, on which the Parnahyba and Rasgão power stations of the company are situated. These power plants on the lower Tieté were originally served by the storage reservoir at Santo Amaro, with a surface area of 13 sq. miles (34 km^2) and containing 6 869 million cub. ft. (194 600 000 m^3) at an elevation of 2 416 ft. (736·6 m). The City of São Paulo is at present drawing 35·3 cub. ft. (1 m^3) of water per sec. and later will draw 141·2 cub. ft. (4 m^3) per sec. from this last reservoir to supplement the city water supply.

By installing pumps of a capacity of 5 295 cub. ft. (150 m^3) per sec. at the Marumby and Rio Grande dams it will be possible to divert surplus and flood-water from the Tieté and its tributaries to the Rio Grande and then through the Summit Control to the Rio das Pedras reservoir, and thus, by the expenditure of the energy necessary to pump the water up 115 ft. (35 m), to obtain the advantage of a total head of some 2 400 ft. (732 m), at the same time relieving the low-lying portions of the city, which are badly flooded after long rains. The pumping operations can usually be performed at night and on holidays and generally at times of low load, but in the flood season, when much surplus power is available from other plants, they will operate continuously.

The total flow, regulated by the storage of the above-mentioned reservoirs and the others shown in Fig. 1, is sufficient for a total capacity of over 400 000 kW. The existing two units have a capacity of 33 000 kVA each, and it is planned that further units each of 48 000 kW capacity shall be installed as and when required by the growth of load. The third unit has already been purchased and will be in operation during 1931.

The formation of these reservoirs necessitated five road alterations on the main São Paulo–Santos highway, the largest of which is by the village of Rio Grande, where the road has to be raised 49 ft. (15 m), for which purpose a reinforced-concrete bridge 263 ft. (80 m) long and an embankment 1 094 yds. (1 km) long, requiring 654 000 cub. yds. (500 000 m^3) of material, are being constructed.

The chain of reservoirs and canals will connect the edge of the Serra with the City of São Paulo. The company has legislative authority to connect the city with the port of Santos by lighters and an aerial rope-way from Santos to the top of the Serra, or by means of a boat incline up the slope of the Serra and suitable boat-lifts and locks at the Summit Control and the Rio Grande and Marumby dams, thus relieving the congestion at the port. Detailed studies are still in progress and no final decision as to this part of the project has yet been reached.

General Construction and Lay-Out.

For constructional purposes a camp was established at the power-house site for the erection of the power house and penstocks, since all the material arrived by rail from Santos. A second camp was established at the Alto da Serra for the construction of the dam, the tunnel, the siphon and the surge tank. A third camp, detached from the remainder by about 9 miles (14 km), was established to cut the Summit Canal with a 12-in. and a 10-in. suction dredge to join the Pedras basin with the basin of the Rio Pequeno. In order to provide power for constructional purposes in a time of great shortage, it was proposed to build three temporary plants, each of 900 kVA capacity, with about 656 ft. (200 m) head, down the original falls of the Rio das Pedras. However, owing to the lack of labour and the cessation of the power shortage one only was built and was operated in parallel with a line from the City of Santos Improvements Co.'s supply. Later, after the permanent transmission line had been completed, the load was carried on a 40 000-volt circuit from São Paulo. The power house was a temporary wood-and-masonry structure with a galvanized-iron roof. The unit was a 1 200-h.p. impulse turbine manufactured by the Hilpert Co., of Rio de Janeiro, coupled to a 900-kVA generator formerly in use at Rio de Janeiro; a turbine-driven and a motor-driven exciter were also provided. This plant generated and transmitted at 3 800 volts. A construction substation was located in the main power-house camp about a mile from the temporary power house, and here a 3 000-kVA transformer bank with a ratio of 13 000/3 800 volts and a tertiary winding for 6 600 volts was provided. The 13 000-volt winding provided the parallel connection with the Santos supply and also fed the two suction dredges working on the canal connecting the reservoirs some 9 miles (14 km) from the power house; while the 6 600-volt service supplied power for the hoists, compressors, rock-crushing plants and derricks at the upper camp, the 3 800-volt supply being used around the power house for supplying compressed air for the pipe line, crushing plants, derricks, ice plant and other necessary equipment.

Hydraulic Works.

From the Rio das Pedras reservoir the water is conducted through a short cut 984 ft. (300 m) in length into the Cascatinha ravine, closed by two earth-filled dams with concrete-core walls, and, from this branch of the reservoir, through a tunnel 1 608 ft. (490 m) long and 10·6 ft. (3·25 m) in diameter lined with concrete and capable of supplying water for four units. A second tunnel was driven for a distance of about 164 ft. (50 m) from the intake in order to avoid risk of damage to the intake works which might be caused by blasting in construction at a later date. Four tunnels ultimately are planned. There is a sand trap in front of the tunnel

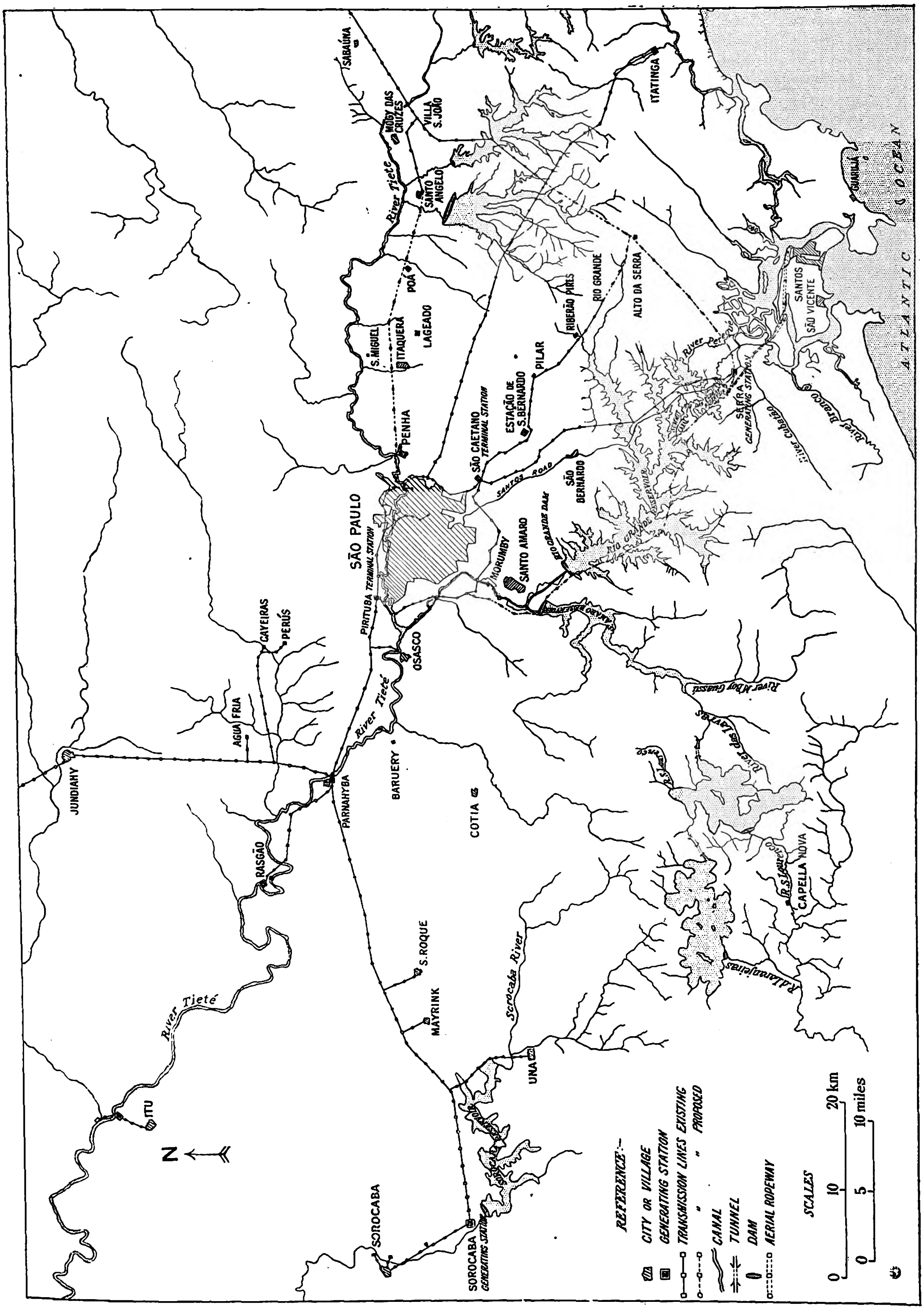
SÃO PAULO
PIRITUBA TERMINAL STATION
SÃO CAETANO TERMINAL STATION
ESTAÇÃO DE S. BERNARDO
PILAR
SÃO BERNARDO
SANTOS ROAD
SANTO AMARO
MORUMBY
RIO GRANDE DAM
RIO GRANDE RESERVOIR
RIO GRANDE
RIBERÃO PIRES
ALTO DA SERRA
CUBATÃO GENERATING STATION
SERRA GENERATING STATION
River Perequê
SANTOS
SÃO VICENTE
GUARUJÁ
ATLANTIC OCEAN
River Cubatão
River Branco
ITATINGA
SABAÚNA
MOGY DAS CRUZES
VILLA S. JOÃO
SANTO ANGELO
POÁ
LAGEADO
S. MIGUEL
ITAQUERA
PENHA
River Tieté
OSASCO
CAYEIRAS
PERÚS
AGUA FRIA
JUNDIAHY
PARNAHYBA
BARUERY
COTIA
RASGÃO
River M'Boy Guassú
River das Lavras
R. S. Lourenço
CAPELLA NOVA
R. Juquiá
R. Itapanhaú
S. ROQUE
MAYRINK
Sorocaba River
UNA
ITU
SOROCABA
SOROCABA GENERATING STATION
N
REFERENCE:-
CITY OR VILLAGE
GENERATING STATION
TRANSMISSION LINES EXISTING
" " PROPOSED
CANAL
TUNNEL
DAM
AERIAL ROPEWAY
SCALES
0 10 20 km
0 5 10 miles

FIG. 1.—São Paulo and District transmission system and reservoirs (existing and proposed).

intake, and trash racks to be provided with stop logs with hoisting gear and, later, with electrically-driven automatically-operated rack-cleaners.

An inverted siphon of steel, 427 ft. (131 m) long and 8·21 ft. (2·5 m) in diameter, crosses a ravine 98·5 ft. (30 m) in depth from the tunnel to the surge tank hill and enters the surge tank. The siphon is to be enlarged at a later date and constructed of reinforced concrete. There is an anchor-block at the bottom of the siphon, with a sand trap and large blow-off valve.

The surge tank is of reinforced concrete and its top is 2 426 ft. (739·5 m) above sea-level. The top of the superstructure is 2 510 ft. (765·2 m) above sea-level, the nozzle of the turbines below being 30·4 ft. (9·26 m) and the tail-race, in the old bed of the Rio das Pedras, 13 to 20 ft. (4 to 6 m) above sea-level. Arrangements have been made for four pipe lines in the present surge tank, only two having been installed at present. Stop logs with hoisting gear are provided at the outlet.

PENSTOCKS.

The high-pressure pipe lines were manufactured by the Ferrum Co., of Poland. The internal diameter of the pipes is 5 ft. (1·55 m) at the top, reducing in three stages to 3·6 ft. (1·1 m) at the bottom. The two penstocks are secured by 15 concrete anchors weighing from 1 200 to 5 000 tons each, the soil being decomposed rock. An expansion joint is provided between each pair of anchor-piers, and saddles are placed under the pipes at approximately 33 ft. (10 m) spacing, and at an elevation of 2 083 ft. (635 m) the penstocks are carried through two concrete-lined tunnels under the main São Paulo–Santos highway.

The minimum thickness of the pipe is 0·394 in. (10 mm) and the maximum thickness of plain pipe at the ninth anchor-pier is 1·261 in. (32 m); below this, 24 heavy bands of seamless high-carbon steel are shrunk on to each section of the pipe, the thickness of the pipe being 0·946 in. (24 mm) and the bands averaging 4 in. (100 mm) long and 1·892 (48 mm) thick. The total weight of each pipe line is approximately 1 600 tons; the maximum gradient on the line is 86 in 100 and the maximum velocity of water in the pipe is 264·75 cub. ft. per sec. (7·5 m^3 per sec.). A spare pipe of each size is provided, and the spare pipes are located on the top of the anchor-piers.

The company is conducting an extensive series of tests on test pipes, which are designed on the assumption of safety even under the worst possible condition, namely the fracture of the needle spindle of the nozzle of one wheel determining the stresses which may be set up in the various sections of the pipe.

At the top of each penstock are the usual screens and gate, and in the valve house, 49·25 ft. (15 m) from the surge tank, an air vent-pipe is carried up to the height of the surge tank. Above this is a butterfly valve 5 ft. (1·55 m) in diameter with an automatic paddle trip and a solenoid trip. The latter is in two halves, which are operated by two distinct circuits from the 250-volt control battery in the power house, the one running in rubber-insulated lead-covered cable in conduit between the penstocks from the power house to the valve house, the other running in rubber-insulated lead-covered and armoured cable laid in the soil by a circuitous route keeping on the far side of a fold in the hill so as to be out of danger in the event of a slide or an accident to the penstocks. These circuits are operated by two push-buttons connected in parallel, each push-button operating both circuits and a lamp to indicate flow of current. One set of push-buttons is on the main control desk in the power house and the other beside the corresponding unit in each case.

A recording and indicating Venturi meter is installed just below the first anchor-pier; and in the fifteenth anchor-pier at the entrance to the power house a Y-piece divides the water for use in the two wheels which form one unit. At the bottom of each penstock are the hydraulically-operated electrically-controlled gate-valves of the turbines.

POWER HOUSE.

General constructional features.—The entire framework of the power house is composed of reinforced, graded concrete which, by suitably proportioning rock of different sizes, reduces voids to a practical minimum, and so obtains a greater strength, corresponding to the higher cement/water ratio, with the use of less cement, care being taken that there is sufficient of the intermediate and finer sizes to permit of its being placed without excessive labour or bad work.

The main columns are 3·28 × 3·94 ft. (1 × 1·2 m) in section, spaced at 14·76 ft. (4·5 m), 44·28 ft. (13·5 m) being required for each unit, the breadth of the power house between inside faces of columns being 51·66 ft. (15·75 m).

Two travelling cranes each of 90 tons capacity are installed, the height of the crane beam being determined by the clearance of 39 ft. (12 m) required for lowering the generator rotor sections on to the shaft. Roof trusses of steel support a reinforced-concrete roof which is covered with asphalt.

On the main generator floor, at an elevation of 32·8 ft. (10 m), are located the main units, governors, governor oil pumps, pressure receivers, air compressors, film oil pumps, exciters and generator field control panels.

Below this, at an elevation of 20 ft. (6 m), are the flood lubricating-oil system pumps, filters, sump pumps (a.c. and d.c.) and pumps for emergency water supply for cooling bearings and transformers, pumping water from the tail-race to a tank on anchor-pier No. 14 and controlled by float-switches in the tank. There is also a high-pressure bus pipe for the operation of the exciter turbines from any penstock.

The present lay-out in the power house, consisting of two units, two exciters and a spare exciter with auxiliaries, may be briefly described as follows:—

Turbines.—The main turbine units were manufactured by the Pelton Co., of San Francisco. Each has two runners overhung from two horizontal bearings, and is of the impulse type with a guaranteed full-load horse-power of 40 000 at a net head of 2 230 ft. (680 m), a static head of 2 345 ft. (716 m), and a speed of 360 r.p.m.; the runaway speed is approximately 85 per cent in excess of normal, and the flywheel effect of the generator is 3 million lb.-ft.². The bearings are 24 inches in diameter and 72 in. long; 8 oil rings are provided for automatic lubrication, and an indicating thermometer indicates the temperature at either end of each bearing barrel. Copper tubes provide a circulation of water for oil cooling in the bearing pedestals. A high-pressure pump introduces oil at 250 lb. per sq. in. under the shaft in the bearing so as to float it on a film before starting up the unit. Flood lubrication is provided, and protection against interruption is secured by oil tanks on the roof to be used in emergency.

The buckets, of cast steel, are of the modern Pelton type, fastened by pressed-on bolts to the rims of disc wheels which in turn are pressed on to the ends of the shaft. The main needle and a relief needle immediately beneath it are mechanically linked through a dashpot mechanism which determines the closing time of the relief nozzle after it opens on closure of the main nozzle. A stream baffle-plate of cast iron fitted with a renewable splitter of cast steel receives the discharge of both nozzles, and is supported on **I**-beams and rigidly embedded in concrete. A braking nozzle is provided on each wheel, directing a jet on to the backs of the buckets to stop the unit. The nickel-steel hollow shaft carrying the generator and turbine rotors is 30 ft. in length and has a maximum diameter of 30 in.

Generators.—The generators were supplied by the International General Electric Co., and each has a maximum continuous capacity of 33 000 kVA at 0·85 power factor with a normal voltage of 11 000 and a possible over-voltage of 5 per cent at full load. The excitation is 250 volts maximum, using 105 kW at maximum load. The rotor spider is composed of four main sections of rolled steel punchings approximately ¼ in. thick, these sections being shrunk on to the shaft in the field. The field poles are each secured to the rim by two T-shaped dove-tails, four taper keys being used for each T to lock the poles in place. The stator frame is in two pieces, the necessary coils for joining the split in the field being shipped separately. Six embedded temperature coils of the resistance type register slot temperatures on an indicator dial in the control room.

The ventilation of the generators is effected by fans on the rotors. These suck air from the power house and discharge it through air ducts to the back of the switch house. In order to prevent the entry of insects, the rolling doors to the transformer platforms are supplemented by galvanized mesh-screen doors. A small flow of the hot air from the air ducts is used for drying lockers in the operators' changing room, and doors are provided for diverting the hot air into the remainder of the power-house basement, thereby keeping dry the motors of the oil and sump pumps and any generators which are shut down.

Fire protection is provided for by means of perforated piping inside the end-shields of the stators, controlled by valves in a metal case on the stator frame. This is intended to be used in emergency to spray water on to the windings.

In accordance with the specifications, and in addition to a test at runaway speed, a dead short-circuit was applied to the generator for 10 seconds with full-load excitation (corresponding to about 12 500 volts at no load) without damage to generator or switchgear.

Exciters.—One exciter is provided for each machine, and consists of a 200-h.p. overhung impulse turbine, supplied by the Pelton Co., of San Francisco, coupled to an induction motor, and a 125-kW 250-volt d.c. generator supplied by the Westinghouse Electric and Manufacturing Co.

There is also a spare exciter, of similar manufacture, consisting of a 400-h.p. overhung impulse turbine coupled to a synchronous motor, a 250-kW d.c. generator and a pedestal-type exciter. This machine serves to supply a.c. power for local service in the event of failure of back power when the main units are not running. All three exciters have provision for connection to a d.c. busbar and also to the control-battery charging panels in the control room.

Transformers.—The main transformers were built by the International General Electric Co. and are set on a platform above the tail-race between the power house and the switch house. Three single-phase oil-insulated water-cooled core-type transformers are provided for each unit. Each has a capacity of 11 000 kVA and a ratio of 11 000/50 800 volts, the low-voltage windings being connected in mesh and the high-voltage in star for a line voltage of 88 000 volts. These transformers are of the conservator type with calcium chloride breathers, and have an impedance of 8·71 per cent.

Four tappings are provided on the high-voltage windings, in steps of 2½ per cent above normal voltage. Alternating-current temperature coils are provided to indicate the temperature reached in the hottest part of the windings, and capillary-tube thermometers in the oil indicate its temperature on the outside of the tanks and are fitted with alarm contacts. Oil gauges are fixed on the conservators, and oil sampling cocks and filter connections are provided at the tops and bottoms of the tanks and on the conservators.

Considerable difficulty was experienced in drying the first bank by operation on short-circuit, some 60 days being expended for this purpose. The cores of the second bank were therefore removed from their tanks and placed in a shed through which hot air was passed.

THE SWITCH HOUSE.

The main generator leads consist of two 1·18-sq. in. (1 500 000 circular mils) cables, each of 1 360 amperes capacity, insulated for 13 000 volts and supported on 25 000-volt insulators. They are carried along the ceiling of the air duct and up to an auxiliary busbar in the roof of the switch house, whence connections are taken to potential transformers and switches.

The general lay-out, to conform with the wiring diagram (Fig. 2), includes two main 11 000-volt busbars of 4 in. × ¼ in. copper supported from the ceiling at a height of 48 ft. (14·7 m), only one being installed for the present two units. Above this is a cable room 6·5 ft. (2 m) in height devoted exclusively to the installation of control cables and conduits. Above this at a height of 55·7 ft. (17 m) are the main breakers and instrument transformers, while in the centre section at this elevation is the control room, completely shut off from the generator by a plate-glass bay window for its entire length. On the floor above the control room is the battery room, while in the wings, supported from the

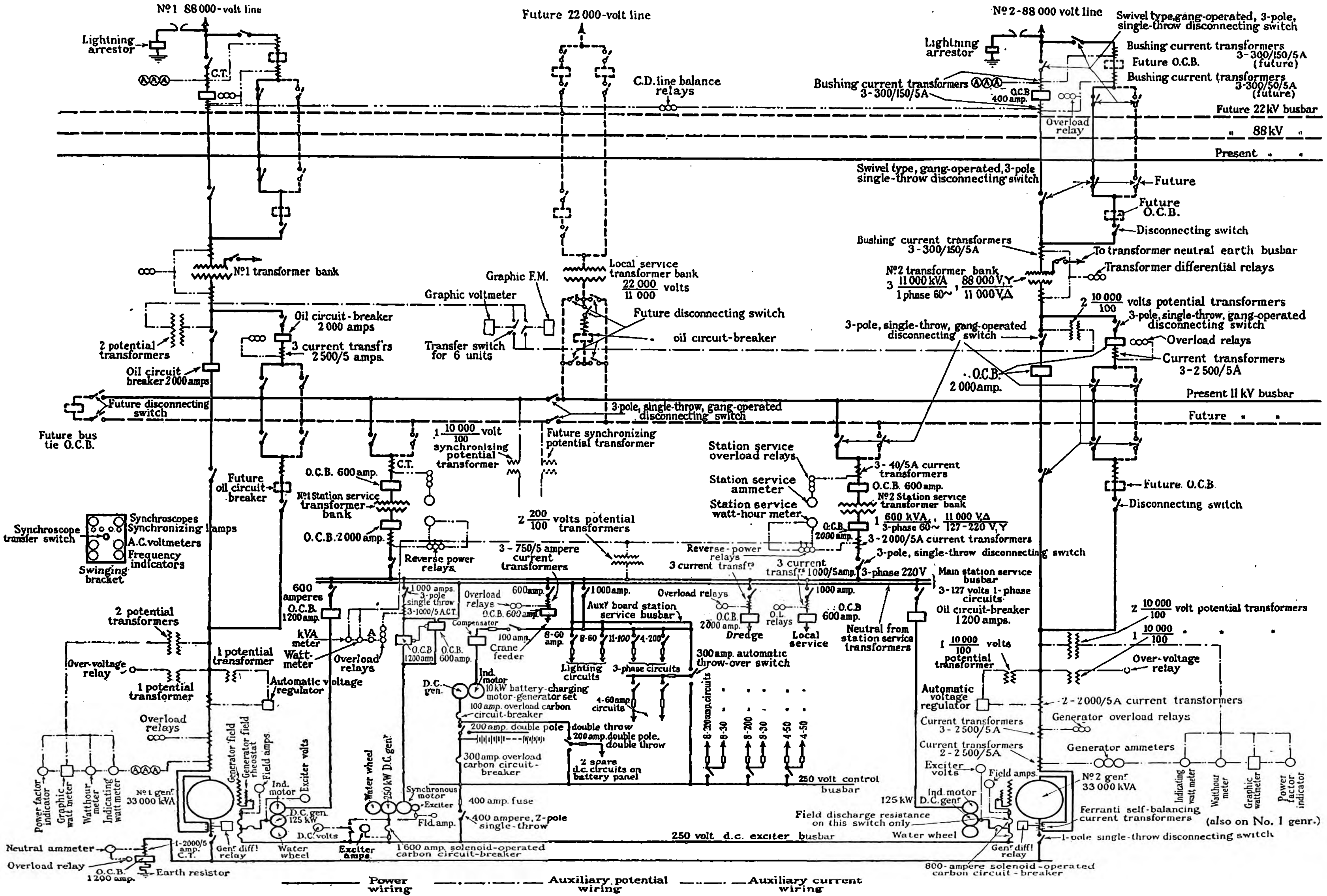
Nº1 88 000-volt line
Lightning arrestor
C.T.
Future 22 000-volt line
C.D. line balance relays
Nº2-88 000 volt line
Lightning arrestor
Swivel type, gang-operated, 3-pole, single-throw disconnecting switch
Bushing current transformers 3-300/150/5A (future)
Future O.C.B.
Bushing current transformers 3-300/50/5A (future)
Bushing current transformers 3-300/150/5A
O.C.B. 400 amp.
Overload relay
Future 22 kV busbar
" 88 kV "
Present " "
Swivel type, gang-operated, 3-pole single-throw disconnecting switch
Future
Future O.C.B.
Disconnecting switch
Bushing current transformers 3-300/150/5A
To transformer neutral earth busbar
Transformer differential relays
Nº2 transformer bank 3 11 000 kVA / 1 phase 60~, 88 000 V.Y / 11 000 V.Δ
Nº1 transformer bank
Local service transformer bank 22 000 / 11 000 volts
Graphic F.M.
Graphic voltmeter
Future disconnecting switch
oil circuit-breaker
Transfer switch for 6 units
Oil circuit-breaker 2 000 amps
3 current transf'rs 2 500/5 amps.
2 potential transformers
Oil circuit breaker 2000 amps
2 10 000/100 volts potential transformers
3-pole, single-throw, gang-operated disconnecting switch
3-pole, single-throw, gang-operated disconnecting switch
Overload relays
Current transformers 3-2 500/5A
O.C.B. 2 000 amp.
Present 11 kV busbar
Future " "
Future disconnecting switch
Future bus tie O.C.B.
3-pole, single-throw, gang-operated disconnecting switch
1 10 000/100 volt synchronizing potential transformer
Future synchronizing potential transformer
C.T.
O.C.B. 600 amp.
Future oil circuit-breaker
Nº1 Station service transformer bank
O.C.B. 2 000 amp.
Station service overload relays
Station service ammeter
Station service watt-hour meter
3-40/5A current transformers
O.C.B. 600 amp.
Nº2 Station service transformer bank
1 600 kVA, 3-phase 60~ 11 000 VΔ / 127-220 V.Y
O.C.B. 2000 amp.
3-2 000/5A current transformers
3-pole, single-throw disconnecting switch
Future O.C.B.
Disconnecting switch
Synchroscopes
Synchronizing lamps
A.C. voltmeters
Frequency indicators
Synchroscope transfer switch
Swinging bracket
2 200/100 volts potential transformers
3-750/5 ampere current transformers
Reverse power relays
Reverse-power relays
3 current transf'rs
3 current transf'rs 1000/5 amp.
3-phase 220V
Main station service busbar
3-127 volts 1-phase circuits
Oil circuit-breaker 1200 amps.
600 amperes O.C.B. 1200 amp.
1000 amps. 3-pole single throw 3-1000/5 A.C.T.
Overload relays
600 amp.
O.C.B. 600 amp.
Compensator
O.C.B. 1200 amp.
O.C.B. 600 amp.
100 amp.
Crane feeder
8-60 amp.
1000 amp.
Aux'y board station service busbar
8-60
11-100
4-200
Overload relays
O.C.B. 2000 amp.
Dredge
O.L. relays
Local service
1000 amp.
O.C.B. 600 amp.
Neutral from station service transformers
kVA meter
Watt-meter
Overload relays
Automatic voltage regulator
2 potential transformers
Over-voltage relay
1 potential transformer
1 potential transformer
Overload relays
Lighting circuits
3-phase circuits
300 amp. automatic throw-over switch
4-60 amp. circuits
8-200 amp. circuits
8-30
8-200
8-30
4-50
4-50
D.C. gen.
Ind. motor
10 kW battery-charging motor-generator set
100 amp. overload carbon circuit-breaker
200 amp. double pole
double throw 200 amp. double pole, double throw
2 spare d.c. circuits on battery panel
300 amp. overload carbon circuit-breaker
400 amp. fuse
400 ampere, 2-pole single-throw
250 volt control busbar
Synchronous motor
Exciter
Fld. amp.
250 kW D.C. gen'
Water wheel
1600 amp. solenoid-operated carbon circuit-breaker
Exciter amps.
D.C. volts
Water wheel
D.C. gen. 125 kW
Ind. motor
Exciter volts
Field amps
Generator field rheostat
Generator field
Gen' diff' relay
Nº1 gen' 33 000 kVA
1-2000/5 amp. C.T.
Earth resistor
O.C.B. 1200 amp.
Neutral ammeter
Overload relay
Power factor indicator
Graphic watt meter
Watthour meter
Indicating watt meter
2 10 000/100 volt potential transformers
1 10 000/100
1 10 000/100 volts potential transformer
Over-voltage relay
Automatic voltage regulator
2-2000/5A current transformers
Generator overload relays
Current transformers 3-2 500/5A
Current transformers 2-2 500/5A
Generator ammeters
Exciter volts
Field amps.
Nº2 gen' 33 000 kVA
125 kW
Ind. motor D.C. gen'
Field discharge resistance on this switch only
Ferranti self-balancing current transformers (also on No. 1 genr.)
Indicating watt meter
Watthour meter
Graphic wattmeter
Power factor indicator
250 volt d.c. exciter busbar
Water wheel
Gen' diff' relay
1-pole single-throw disconnecting switch
800-ampere solenoid-operated carbon circuit-breaker
Power wiring
Auxiliary potential wiring
Auxiliary current wiring

FIG. 2.—Wiring diagram of electrical equipment in Serra power house.

roof beams, are auxiliary busbars for generators and transformers.

The battery has a capacity of 280 ampere-hours on the 8-hour rate at 250 volts, and is used for control circuits and emergency lighting. It is charged by the trickle-charge method.

The oil circuit-breakers and switchboards were supplied by the Westinghouse Electric and Manufacturing Co., and the 11 000-volt isolating switches and busbar supports by the Delta Star Electric Co., of Chicago. All the 11 000-volt equipment is insulated for 25 000 volts in order to give an increased factor of safety. All phases are separated by barriers consisting of concrete 3 in. thick in vertical runs and two thicknesses of $\frac{3}{4}$-in. transite asbestos in horizontal runs, the minimum clearance to earth being 10 in.

The 11 000-volt oil cell-type circuit-breakers, which are solenoid-operated, have a guaranteed rupturing capacity of 896 000 kVA at 11 000 volts. The isolating switches are lever-operated with a system of sequence locks for the protection of operators, and indicating lamps on the main control desk show the position of the switches at any time.

Many of the bolts for holding busbar supports and isolating switches were set in the forms before the concrete was poured, nuts being placed on either side of the wood to hold the bolts firmly in position; some of the bolts were split at the end and bent into "ram's horn" shape, and others had the ends bent over at right angles for a length of about 4 diameters. In order to determine whether the strength of the bolts as set in a 4-in. slab was equal to the strength of the busbar supports and would withstand an ultimate stress on short-circuit of 1 million kVA, it was decided to test four sets of bolts to destruction by a cantilever arrangement. The average failure was at 5 500 lb. on a $\frac{1}{2}$-in. bolt of the "ram's horn" shape in a 4-in. slab, and it was found that the failure occurred in the split of the bolt rather than in the concrete, but that, in any case, the pull was greatly in excess of that required for the calculated maximum short-circuit stress.

The local-service and station-service equipment is situated in the north bay of the switch house at the same elevation as the generator floor. It consists of two 600-kVA transformers stepping down from the east and west sections of the main busbar from 11 000 volts to 220 volts (star-connected). The low-voltage busbar feeds the exciter motors, the cranes, and the local and construction, light and power circuits, and a circuit stepping up to 3 800 volts for local services. It may be of interest to note that the synchronous motor of the 250-kW spare exciter is started by throwing in an oil circuit-breaker connecting its three phase leads to two phases and the neutral of the busbar, and then throwing over to the three normal phases by means of a second circuit breaker electrically interlocked with the first.

All the control cables are lead-covered and laid in galvanized corrugated cable-pans supported on pipe structures, cables carrying alternating current being kept separate from those carrying direct current. Although these cables are somewhat difficult to bring up to a control board of the bench or desk type, yet they should be vastly superior to rubber-covered wire in conduit owing to the extreme dampness to which they are subjected, and to the ease of inspection and maintenance which they render possible. The colour scheme in multiconductor cable also makes for rapidity in installation.

The switchboards are located in the control room overlooking the generator floor from an elevation of 23 ft. (7 m) above it. The glass window permits the operator at the main control board to see all units and the gate-opening indicators on the turbines, and cuts off the majority of the sound. Signals to the turbine floor are conveyed by mechanical signal devices of the ship's telegraph type with telephone attachment.

The main control board is of the desk or bench type with a mimic busbar indicating the position of all switches, while red and green lamps show whether the latter are closed or open at any time. One section of the board serves for one unit and one for the exciters and station-service equipment. Governor control and emergency shut-down switches are also installed on this board, while on the vertical section are the generator ammeters, wattmeters, power-factor meters and line ammeters. Voltmeters, frequency meters and synchroscopes are provided on a swinging panel. The relay board is situated behind the bench board and carries, in addition to relays, kWh meters and recording voltmeters and frequency meters. Behind the relay panel are the d.c. and a.c. feeder panels and the lighting panel, together with a panel for control of the local circuits, the breakers of which are connected to the station-service busbar 32·8 ft. (10 m) below.

On the east side of the control room is an annunciator panel and a transformer temperature-indicating panel with provision for future banks of transformers. The annunciator panel is of a special design with enamelled-wire coils for tropical power-house service, and has 48 drops connected to either a red, a green, or a white light at the top of the panel and a corresponding bell indicating the degree of urgency of the alarm. A special feature is that it is possible to disconnect the light and the bell at once, but the drop cannot be reset until the alarm contacts at the apparatus are open, indicating that the abnormal condition has been removed. A special 24-volt battery is provided for the operation of this equipment, and is charged by a Tungar rectifier.

A voltage-regulator panel of the Westinghouse vibrating type, with a section for each exciter, is located on the west side of the control room.

RELAY SYSTEM.

The relay system is designed to give a maximum degree of protection to the equipment. Differential protection for each generator is provided by Ferranti self-balancing current transformers and relays which operate multi-contact relays to trip off the generator field, the exciter motor and the generator-to-transformer and generator-to-busbar circuit breakers. The transformer differential protection consists of bushing-type current transformers on the high-voltage bushings of the transformers, and series-connected current transformers outside the delta on the low-voltage side: these actuate induction-type relays which in turn operate multi-contact relays to trip the breakers on the high- and low-voltage sides of the transformers.

Overload protection is also provided on the generators, the busbar-to-transformer connections and the high-voltage lines in a similar manner. Over-voltage protection on the generators is also provided, and the generator field circuit-breakers will not open until the generator oil-switches are open. The station-service transformers also have overload protection which trips their high- and low-voltage circuit breakers and both No. 1 and No. 2 exciter motors; and reverse-energy relays are provided to prevent feeding-back from the station-service busbar to the main busbar. Each of the multi-contact relays of each of the above systems gives an indication of operation on the annunciator panel.

The outgoing lines are provided with overload relays and selective differential current relays for balanced current between the two circuits (or more in the future).

INDICATORS AND ALARMS.

Owing to the small staff required for normal operation of the plant, numerous indicators and alarms are fitted, amongst which may be mentioned the following:—

(*a*) Temperature indicators and alarms on the generator main bearings and on the main transformers.

(*b*) Smoke indicators in the air ducts, giving an immediate indication of any smoke coming from the generator.

(*c*) A needle recorder on each turbine recording positively and mechanically the travel of the four needles of the two power and two relief nozzles, thus showing the full history of the machine and governor operation in dealing with the load variations. This apparatus records the penstock pressure in addition to the position of the main and relief needles.

(*d*) Rack-loss indicators on the trash racks at the surge tank.

A high- and low-water indicator in the tail-race is contemplated, but has not yet been fitted.

THE EARTHING SYSTEM.

Special attention was paid to the earthing system owing to the high resistance of the soil, which has caused trouble in other plants, owing partly to the lack of dissolved salts in the water and partly to the impermeable nature of the soil and underlying rock. It was thought that with a high-voltage neutral solidly earthed and connected solidly to the penstocks any unbalanced current would tend to follow the line of these to the reservoir which runs parallel to the trunk telephone lines from São Paulo to Santos, thus causing trouble on the commercial telephone circuits, the transmission-line earth wire being of $\frac{3}{8}$-in. Siemens-Martin steel and of comparatively high resistance. It was therefore decided to earth all the equipment inside the power house solidly to the penstocks and also to a copper plate in the tail-race, while a number of pipes were driven in the outdoor station to well below the water-level. To these pipes the high-voltage earths, including the transmission-line earth wire, were connected. These two systems were at first connected by bolted terminals. A series of tests was carried out during one night, and it appeared that half the current would be more or less evenly divided between the penstocks and the transmission-line earth wire and the remainder would pass through the pipe connection to earth; while with a total of 30 amperes in the earth the noise on the trunk telephone lines rendered conversation impossible. The normal earth current is, however, not measurable.

THE OUTDOOR STATION.

All the 88 000-volt equipment is located out-of-doors on the south side of the power house. The complete equipment will consist of a double busbar with a bypass from each transformer bank to the corresponding line: only a single busbar is installed for the first two units. The busbar and connections are of 4/0 B. and S. gauge (0·166 sq. in.) copper cable suspended from lattice galvanized-steel towers. The oil circuit-breakers were supplied by the Westinghouse Electric and Manufacturing Co.: they are solenoid-operated and frame-mounted and are rated at 600 amperes at 88 000 volts with a rupturing capacity of 915 000 kVA at that voltage. They have bushing-type current transformers for use with indicating ammeters and overload protection. The isolating switches were supplied by the Railway and Industrial Engineering Co., of Greensburg, Pennsylvania, and are lever-operated, 3-pole, double-break switches, horizontally mounted, those directly connected to the lines being so arranged that, by the removal of pins, two poles or one may be closed separately for testing purposes. A lightning arrestor of the International General Electric Co.'s oxide-film type is provided on each line. The lead-covered control cables for operation and control of the circuit breakers, and for connecting auxiliary switches on the isolators to indicating lamps on the main control board, are run in concrete trenches filled with sand and covered with removable concrete slabs.

THE TRANSMISSION LINE.

The transmission line consists of lattice galvanized-steel towers with suspension-type insulators and 4/0 B. and S. gauge (0·166 sq. in.) copper cable with $\frac{3}{8}$-in. Siemens-Martin steel earth-wire above. Each tower carries two circuits, 8-ft. vertical and 16-ft. horizontal clearances being provided. The conductors are vertically above one another, this type of construction being cheaper and not objectionable in the absence of sleet. The length of the line is 22 miles to the São Caetano terminal station on the east side of the city, or 41 miles to the Pirituba terminal station on the north-west side of the city.

The tower foundations are ground anchors consisting of a grid of steel channels and **I**-beams set in earth. The towers are built to a specification wherein the maximum loading likely to occur and the permissible stress in the material are given; and it is the practice of the company to test towers by direct loading, so as to ensure that adequate but not unduly heavy structures are provided.

The conductors are strung to a maximum tension of 3 300 lb., assuming 15 lb. per sq. ft. wind-pressure on the projected area of the conductor at 0° C. without ice. Joints are made with McIntyre copper sleeves when required.

The towers were built to a particularly exacting specification as regards galvanizing, as it has been proved in the Brazilian and other associated companies that a properly galvanized tower will show no signs of corrosion even after 30 years, and may therefore be assumed to be practically permanent. The average span in this lay-out was 787 ft. (240 m) and the maximum span 1 700 ft. (510 m). All the towers were located first on a profile made from a careful survey, on a scale of 1 : 5 000 horizontal and 1 : 1 000 vertical, using a celluloid templet showing maximum sag for a temperature of 55° C. (131° F.) and 15 lb. per sq. ft. wind-pressure. Although this work was done in the office no tower locations had to be changed in the field. A clearance of 26 ft. (8 m) above ground was maintained. The electrical design of the line shows a 6·5 per cent voltage-drop and a 3·2 per cent power loss with 33 000 kVA (the output of one generator) between the power house and São Caetano. In emergency nearly double this amount of power could be carried.

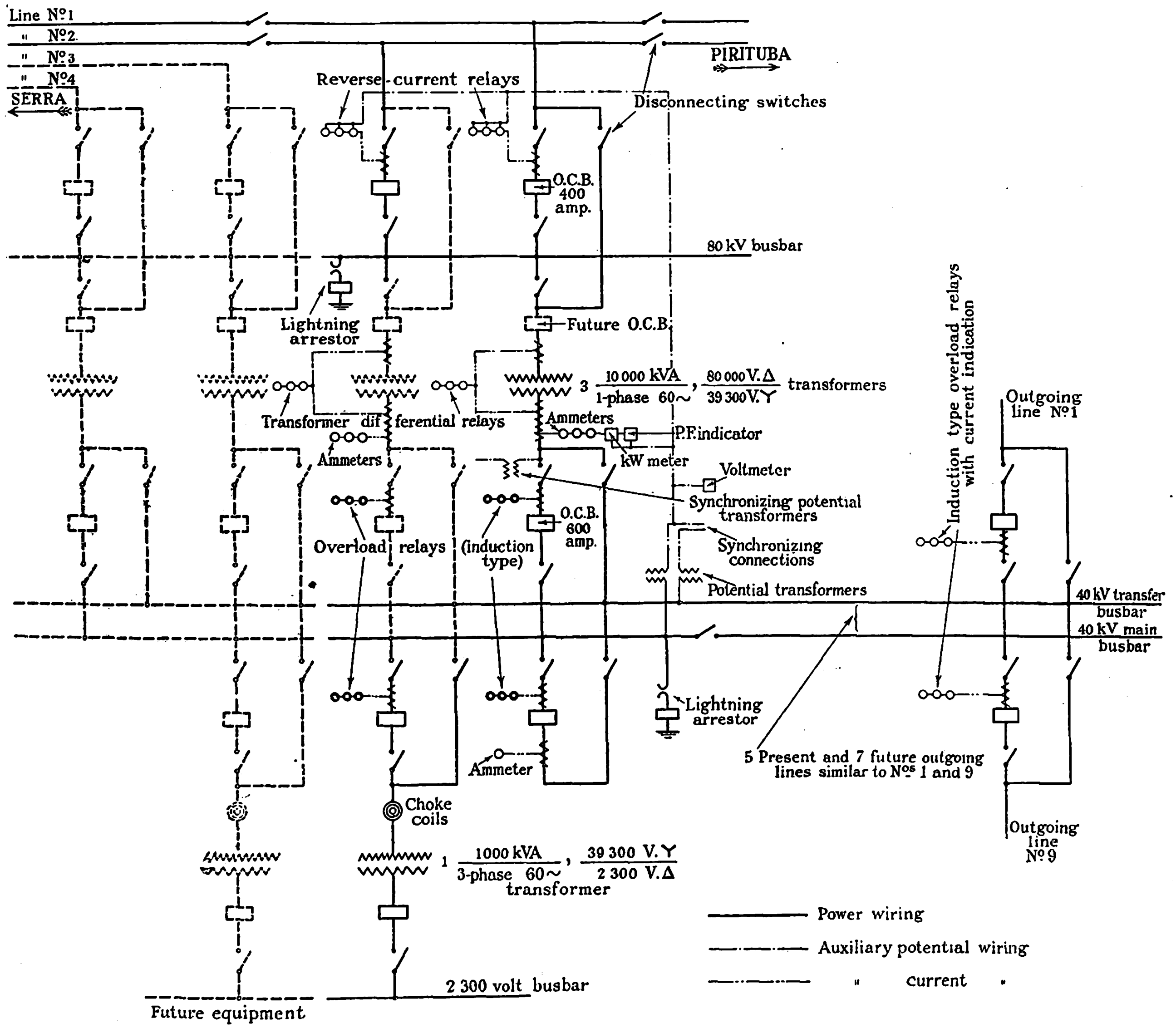
Line No. 1
" No. 2
" No. 3
" No. 4
SERRA
PIRITUBA
Reverse-current relays
Disconnecting switches
O.C.B. 400 amp.
80 kV busbar
Lightning arrestor
Future O.C.B.
3 10 000 kVA 1-phase 60~ , 80 000 V.Δ 39 300 V.Y transformers
Transformer differential relays
Ammeters
P.F. indicator
kW meter
Ammeters
Voltmeter
Synchronizing potential transformers
O.C.B. 600 amp.
Overload relays (induction type)
Synchronizing connections
Potential transformers
Induction type overload relays with current indication
Outgoing line No. 1
40 kV transfer busbar
40 kV main busbar
Lightning arrestor
Ammeter
5 Present and 7 future outgoing lines similar to Nos. 1 and 9
Choke coils
Outgoing line No. 9
1 1000 kVA 3-phase 60~ , 39 300 V.Y 2 300 V.Δ transformer
Power wiring
Auxiliary potential wiring
" current "
2 300 volt busbar
Future equipment

Fig. 3.—Wiring diagram of São Caetano terminal station.

Transpositions are arranged on the "intermittent system of barrelling," using three complete "barrels" between the power house and São Caetano; the communication circuits are co-ordinated with this arrangement and a total of six transposition towers are used.

Communication between the power house and the city is by means of two telephone circuits of No. 10 B. and S. gauge (0·008-sq. in.) copper wire run on hardwood poles along the transmission-line right-of-way and transposed in accordance with the Bell Telephone Co.'s standard practice for badly exposed lines. The instruments are protected by vacuum gaps, insulating transformers, fuses and drainage coils at both ends and at intermediate guard-houses.

It is probable that some of the future transmission lines will be carried up to the Serra on the west side of the penstocks and will follow the west side of the reservoir to the western industrial area of the city, thus avoiding the necessity of having more than 200 000 kVA on any one busbar.

The São Caetano Terminal Station.

A new terminal station for the Serra lines was built at São Caetano (see Fig. 3) on the east side of São Paulo in this centre of industrial development. Here there is a tap from each existing 88 000-volt circuit, both of which continue to the original Pirituba terminal station, with isolating switches on each side of the taps. The São Caetano station consists essentially of outdoor switchgear, step-down transformers, a pump house and a control building. The high-voltage switchgear is exactly similar to that in the outdoor station at the Serra power house, and the busbars are similarly constructed. The transformers, supplied by the Westinghouse Electric and Manufacturing Co., step down from 80 000 volts (mesh-connected) to 40 000 volts (star-connected) and have an impedance of 8·10 per cent. They are water-cooled, and for this reason an intake was constructed to take water from the Rio das Meninos, a small stream running through the station. This intake is divided into two sections and either can be shut off, by stop logs and a gate, from the river and from its 15-in. pipe line, which leads to a round well similarly divided and located just outside the pump house. At the far end of the pump house is a transformer repair house with an electric hoist, above which is a reinforced-concrete water tank with a sufficient supply and head of water to carry three transformer banks on full load for half an hour in the event of failure of all pumps. Valves are provided so that the pumps may work either on the tank or on the transformers direct, and a float-switch is mounted on the tank to control either pump, two 3-in. centrifugal pumps being the initial installation. The warm water from the transformers runs either to the river or to a hot-well, whence it may be pumped through nozzles in the spray basin and from here to the storage tank or transformers, thus forming a closed system, as the river water is often scanty in the dry season though adequate in the rainy months. There are also, in the pump house, two tanks for transformer oil and two for switch oil. These are of a capacity sufficient for the contents of one transformer or one switch, one tank of each pair being used for dirty and one for clean oil. These tanks are connected by piping to a clean and dirty bus-pipe and thence to a pump and filter press. Oil lines also run out in a pipe trench to the transformers, and oil in these and in the breakers can be filtered by means of a flexible hose connection.

The control building contains panels controlling incoming lines and outgoing feeders and local circuits, a battery and motor-generator set being provided for 125-volt control circuits and emergency lighting.

Capacity and Cost.

The present capacity of the Serra power station is 66 000 kVA, and the cost of the initial stage of development, including considerable provision for the future steps, is of the order of £2 000 000, and it is possible, by raising the reservoir-level to the maximum and by bringing in other water supplies, to provide sufficient storage and water for eight or more similar units, the cost of the power from the subsequent units being relatively low.

The São Paulo System.

The operation of the system is controlled from a load-despatching station in the city of São Paulo, and intercommunication between power stations and the city is by telephone, the lines being run along the transmission-line right-of-way.

The system load-factor is at present 56·5 per cent, and it is the general practice to run machines connected to the system at about 80 per cent gate opening, which gives in general their maximum efficiency, thus providing sufficient margin of capacity in the system so that if any machine is disconnected automatically the remainder can take up the load.

Voltage regulators with line-drop compensators are provided at all stations, and voltage is also regulated by hand at two synchronous-condenser stations each of 5 000 kVA capacity in the city.

Lightning storms are severe in this region and cause the majority of the faults on the overhead lines through flash-overs to earth on the insulators. To deal with these, rapid action of sensitive overload and directional and balanced-current relays is essential, and extensive tests are being conducted to determine the reactance and resistance of the ground, which are unusually high.

All substations are provided with batteries for use with the control circuits, and these serve also for emergency lighting in the event of a failure of supply.

Main-line electrification was begun some years ago and will presumably continue; also transmission lines will be extended further out than at present and provide for interconnections with smaller systems in the interior. At present the power supplied by this system is transmitted some 170 miles from the Sorocaba power house (or 190 miles from the Serra power house) to the most distant substation at Rincão on the Paulista Railway, the transmission voltage being 88 000 volts and the steadily growing peak load on the line being at present 17 000 kW. This railway operates at 3 000 volts (direct current), and the latest locomotives on order are rated at 2 400 h.p. (continuous rating).

The São Paulo Tramway, Light and Power Co., Ltd., is a subsidiary of the Brazilian Traction, Light and Power Co., Ltd., a Canadian company which owns the light, power, tramway, gas and telephone interests in Rio de Janeiro and São Paulo and the adjacent districts. The lay-out, design and construction of the Serra development scheme was carried out by the construction staff in São Paulo under Mr. A. W. K. Billings, a vice-president of the said company. The detail electrical design was done in the head office of the Canadian and General Finance Co., Toronto, Canada, as a subsidiary of the Brazilian Traction, Light and Power Co.

The author desires to express his thanks to the Brazilian Traction, Light and Power Co. for permission to present this paper, and to Mr. A. W K. Billings for assistance in its preparation.

A GEOMETRICAL ANALYSIS OF OPEN CARBON ARC PHENOMENA.*

By Professor W. Cramp, D.Sc., Member, and A. P. Jarvis, M.Sc., Student.

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Summary.

The behaviour of a carbon arc with a resistance in parallel is first developed geometrically and proved experimentally. From this the conditions governing the musical arc are deduced and the growth of arc oscillations is traced. Geometrical methods are employed because no direct integration of the differential equations is possible.

The analysis shows that a musical arc, in which the current oscillates about a point on the volt-ampere characteristic, is possible but that it is unstable. An experimental example is given in Table 1. Stability is improved by the presence of the "hysteresis loop."

The tendency for the arc oscillations to grow until extinction ensues is next traced, and this leads to a discussion of discontinuous oscillations.

The necessity for the introduction of a thermal term in the equations, and its effect in permitting these discontinuous oscillations to persist, are explained, and an experimental example is given.

Observation of the discontinuous oscillations leads to the conclusion that no high-frequency inductance is essential, and experiments proving the correctness of this prediction are given, together with oscillograms of the current and voltage under these conditions. It is suggested that this phenomenon has important consequences for power station engineers, and that it forms the best starting-point for the examination of arc oscillations.

The dynamic characteristics for the examples quoted are deduced from the oscillograms, and their main features are analysed.

Introduction.

Much work has been done upon the singing arc since its discovery by Duddell in 1901. On the whole, though these researches have elucidated to some extent the causes underlying the Duddell oscillations, no complete theory covering all the observed facts has been satisfactorily established. The main reason for this is the lack of any mathematical method which is capable of deducing from the complicated conditions existing in the arc the resultant variations in pressure and in current.

In the present paper an attempt is made to show how this may be carried out geometrically, but it is necessary first to summarize briefly the present position of our knowledge regarding the arc characteristic, i.e. the relationship between current and voltage at the terminals of the electrodes. Mrs. Ayrton examined most thoroughly the so-called static characteristic, i.e. the relationship which exists between the above quantities when steady conditions have been established, and she deduced, for an arc of constant length, the relationship $V_a = A + B/i_a$, where A and B are constants, V_a is the arc voltage and i_a the arc current. Subsequently, Steinmetz showed that a similar expression, in which $\sqrt{i_a}$ was substituted for i_a, gave satisfactory agreement for the carbon arc and covered also instances of arcs between metals. The theory underlying the work of Steinmetz assumes that the vapour column of an arc tends always to work at a constant current density σ, so that its area a is directly proportional to the current carried; but this is to assume also that a thermal balance must have been reached, in the sense that the heat generated in the arc column must exactly balance that lost by radiation, convection and conduction. It is also evident that, since the vapour is always in contact with unvaporized electrodes, the average temperature of the arc column must remain almost constant. These assumptions do not hold if a sudden change takes place in i_a, for then heat must be supplied to produce a column of appropriate volume, so that a corresponding quantity of heat has to be supplied or is given up as the current increases or decreases.

Now at constant temperature the heat H in the vapour column is proportional to its volume, i.e. to $l \times a$. But $a = i_a/\sigma$, so that $H = k_1 l i_a/\sigma$. The power involved in a thermal change with constant length is $dH/dt = k_1 l/\sigma \times di_a/dt$. When the arc current is changing, therefore, there appears in the value of V_a an additional term, and the relationship between V_a and i_a for an arc of constant length whose current is rapidly changing becomes

$$V_a = V_a \text{ (taken from the static characteristic)} + k/i_a \times di_a/dt$$

where l is assumed constant and k is written for $k_1 l/\sigma$.

When these changes are taken into consideration, the relationship between i_a and V_a is no longer a curved line, but an area with a curved outline, and this is known as the dynamic characteristic. With a growing current the curve is to the right of the static curve, and for a falling current to the left. This leads to the so-called hysteresis loop of the arc, for which an equation of the form $a + b/i_a + k/i_a \times di_a/dt$ is appropriate. It will be seen that the new term is like a reactance wherein k/i_a simulates L.

A somewhat similar relationship occurs in the instance of a choking coil having an iron core, the coil being fed with a sinusoidal wave impressed upon a direct current of such a value that the iron is worked round the knee of its B–H curve. The effect of the new term is to delay the change of current through the arc, or rather to raise the arc p.d. for rising currents (di_a/dt positive) and to lower it for falling currents, so that there is now, between arc current and arc voltage, a phase displacement which increases with the size of the loop.

The existence of this loop complicates the calculations and its importance as affecting stability is referred to later in this paper. The form of the loop, however, depending, as it does, on the rate of change of current, is different for different conditions. Two main cases may be distinguished. The first is that in which a complete oscillation, entailing reversal, is forced upon the arc, as when the electrodes are fed by alternating current. In this instance the dynamic characteristic takes one of the forms shown by Simon,[*] and Norberg [†] has explained how the third term in the expression for arc voltage accounts to some extent for the peculiar shape. These alternating arcs, however, are not dealt with in this paper, so that their characteristics will not be considered.

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* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

The second variety is that which occurs when the arc undergoes a series of oscillations without reversal, and this covers most of the instances in connection with musical arcs. The characteristic is then of the form shown in Fig. 1, the width of the loop depending upon the amplitude of the current change and upon its rate, and the general shape upon the arc length. The particular illustration is drawn from an oscillogram taken by the authors when a carbon arc 1 mm long was fed simultaneously with alternating and direct currents so as to impress upon the arc a forced oscillation. To this end an a.c. supply of 30 periods per sec. was connected to the arc through a resistance and condenser in parallel with the d.c. supply, and the alternating and direct currents were so adjusted that the arc was not extinguished. The conditions were:—

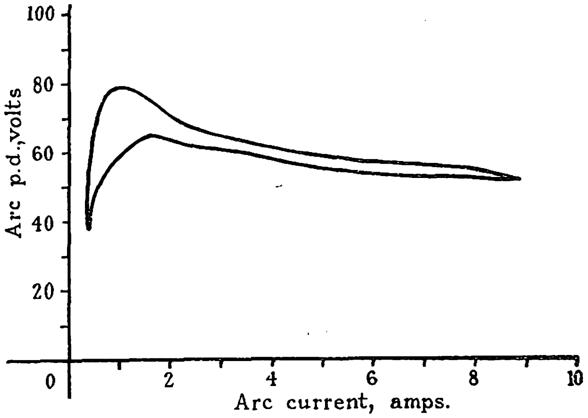

Fig. 1.

Carbons (solid) 18 mm and 11 mm respectively
Arc voltage (R.M.S.) 47·5 volts
Arc current (R.M.S.) 5·25 amps.
Alternating current (R.M.S.) 3·2 amps.
Direct current (R.M.S.) 4·3 amps.

If the ratio of alternating to direct current is reduced, the characteristic still forms a small loop, but in this instance narrower and more nearly elliptical, as is described later in this paper.

Another instance of the same effect, but this time with the direct current so adjusted that extinction occurs every period, is illustrated in Fig. 2, which was taken by the authors under the following conditions:—

Arc length 1 mm
Arc voltage (R.M.S.) 47·5 volts
Arc current (R.M.S.) 5·0 amps.
Alternating current (R.M.S.) 3·1 amps.
Direct current (R.M.S.) 4 amps.

The dotted line in this diagram indicates the static d.c. characteristic which had been previously determined for the same arc. It serves to illustrate the effect which is supposed to be covered by the third term in the arc equation.

The present paper does not deal with arcs other than those taking place between carbon electrodes in air, but it may be remarked that special dynamic characteristics, differing in shape from those illustrated, are found when the arc takes place between metal electrodes or when special means are provided for rapid extinction, as in the Poulsen arc; or, again, when the anode is water-cooled, or when the arc is deflected by an air blast. The peculiar conditions existing in these special examples have been investigated by the authors as well as by many other writers,[*] but they belong to a different category and will not be referred to further.

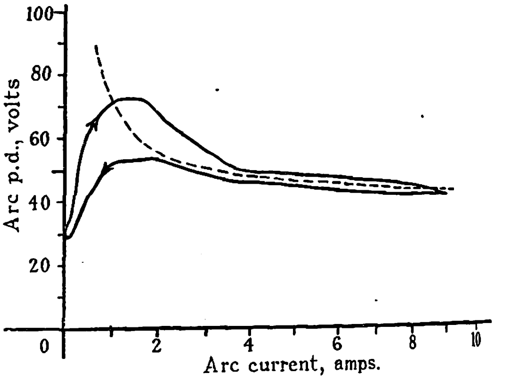

Fig. 2.

(1) An Arc with Parallel Resistance.

It is well known that a d.c. carbon arc cannot be maintained from a constant-potential supply without a series resistance; and the laws governing the magnitude of this resistance in terms of the arc volt-ampere characteristic have been clearly set out by Mrs. Ayrton.[†] It is not, however, so well known that when a resistance is in parallel with the arc the circuit can *only* be stable if the value of the shunt resistance exceeds a certain critical limit. The conditions governing this relationship have an important bearing upon the oscillations of the musical arc, and indeed form a convenient starting-point for the study of that phenomenon. The difficulty of dealing with the oscillations of an arc arises from the fact that a solution of the differential equations is not possible if the equation to the true arc characteristic be adopted. Beginning, however, with the consideration of a parallel resistance, a solution by geometrical methods can be developed whatever the shape of the arc volt-ampere curve may be. Moreover, the method is applicable to many other systems in which oscillations arise from an analogous cause, and is therefore of wide practical application. The oscillations of some musical arcs are maintained by the negative slope of the volt-ampere curve. If this curve be treated as a straight line (which is only justifiable over a very small range) the equations are easily solved. The main deductions, based on this assumption, are given for reference in the Appendix, where the arc characteristic is expressed in the form $V_a = K_0 - ri_a$, K_0 being the hypothetical value of the arc p.d. V_a when the current through the arc, i_a, is zero. Mrs. Ayrton's researches on the open carbon arc show that the static characteristic for a given length is more nearly expressed by the relationship $V_a = A + B/i_a$, while Steinmetz (with some theoretical justification) prefers the form $V_a = A + B/\sqrt{i_a}$, A and B being constants. But whichever of these alternatives be adopted, the same difficulty still arises with the equations and the geometrical analysis is useful as displaying the cause of this difficulty.

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[*] H. T. Simon: *Physikalische Zeitschrift*, 1906, vol. 7, p. 437.

[†] S. Norberg: *Ingeniörs-Vetenskaps-Akademiens Handlingar*, 1925, No. 44.

[*] See, for example, J. T. Morris: *Electrical Review*, 1907, vol. 61, p. 912.

[†] "The Electric Arc," chap. 8.

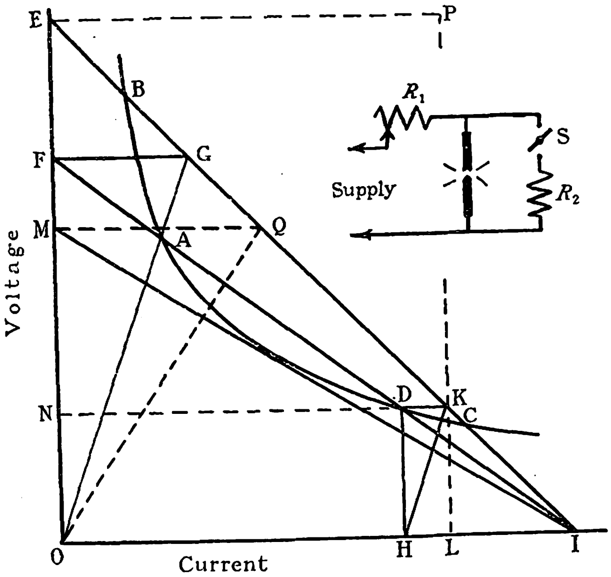

FIG. 3.—Arc with parallel resistance.

Suppose then that a carbon arc (Fig. 3) is fed from a constant-pressure source with a resistance R_1 in series and a switch S and resistance R_2 in shunt. Let OE and OI represent the axes of voltage and current respectively, and let the line ADC express the arc static characteristic. Then, following Mrs. Ayrton's construction, and with switch S open, if the line EI be drawn so that the tangent of the angle EIO represents R_1, the point C, where EI cuts the arc characteristic, is the stable point of working for the system. The other point of intersection, B, is unstable because dV_a/di_a is there negative and greater than E/I, so that Kauffman's conditions for stability are not fulfilled.[*]

Draw now a horizontal line FG in such a way that OF/FG represents the resistance R_2, and join FI. Then FI is the locus of the right-angled apex of all triangles within the triangle EIO that are similar and similarly placed to the triangle OFG. For example, in the triangles HDK, OFG:—

because FG is parallel to DK, FG: DK = FI: DI
and since FO is parallel to DH, FO: DH = FI: DI = FG: DK.
And the angle OFG = the angle HDK.
Therefore the triangles HDK and OFG are similar.

If the line FI also cut the arc curve, as at D, then the arc is stable at the point D with R_1 in series and R_2 in shunt. For since the triangle KDH is similar to the triangle GFO, DK is a current through R_2 corresponding to DH volts; and DH is also the voltage across the arc for the arc current DN, because D is common to the arc curves and to FI. Thus, if the arc is started with the current C, the switch S being open, the current will fall to NK when S is closed, and will divide so that ND passes through the arc and DK through R_2. If now the value of R_2 be reduced, the point F will approach O, and the angle FIO will decrease with corresponding changes in ND and DK. This process may be continued until F reaches the point M when MI just touches the curve ADC. If F is lowered still further, it is impossible for the necessary conditions to be fulfilled and the arc must be extinguished. Thus the lowest possible value of R_2 is OM/MQ. The following test proves this construction.

Using an experimentally determined characteristic for a 4-mm arc [approximately $V_a = 44 + (75/i_a)$] and a supply pressure of 220 volts, with a feed resistance $R_1 = 15{\cdot}1$ ohms, the current at point C was $i_a = 11{\cdot}2$ amperes, and the voltage $V_a = 52$ volts, whilst OI was 14·55 amperes, giving the line IM cutting the voltage axis at OM = 90 volts. Thus the resistance represented by OM/MQ is 90/8·6 = 10·45 ohms. By running this arc with a variable resistance R_2 in shunt, the arc continued to burn so long as R_2 exceeded about 10·5 ohms. By making R_2 large and gradually cutting it out, a condition was always arrived at when the arc was extinguished, and the average value of R_2 at which this occurred was 10·36 ohms. Having regard to the rapidity with which changes occur in the arc, this compares well with the theoretical figure of 10·45 given above.

It is evident that by an appropriate combination of R_1 and R_2 the arc characteristic could be experimentally determined with considerable accuracy.

It has been remarked that points such as A and B do not fulfil the conditions for stability. Consequently the composite circuit of Fig. 1 is only stable when:—

(1) FI cuts the arc characteristic, i.e. $\tan \angle FIO$ is greater than $\tan \angle MIO$.

(2) $\delta V_a/\delta i_a$ at the point of intersection with FI is less than $\tan \angle FIO$.

Now the slope of FI

$$= -FO/OI = -(OE - EF)/OI = -\frac{E - ER_1/(R_1 + R_2)}{E/R_1} = -\frac{R_1 R_2}{R_1 + R_2}$$

and for stability this must be greater than $\delta V_a/\delta i_a$.

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[*] *Göttinger Nachrichten*, 1899, p. 243; also *Annalen der Physik*, 1900, vol. 2, p. 168.

If we adopt the straight-line relationship $V_a = K_0 - ri_a$ (see Appendix), then $dV_a/di_a = -r$; so that the limiting condition is $r = R_1R_2/(R_1 + R_2)$, which is the same as the condition for limiting steady operation of a musical arc, as given in the Appendix. If, on the other hand, we use Mrs. Ayrton's equation, $V_a = A + B/i_a$, then $dV_a/di_a = -B/i_a^2$, so that in the limit $B/i_a^2 = R_1R_2/(R_1 + R_2)$, or $i_a = \sqrt{[B(R_1 + R_2)/R_1R_2]}$.

Constant-Current Feed with Parallel Resistance.—In oscillating circuits the feed current is often maintained approximately constant by a large self-induction in the feed circuit. The construction just given may easily be extended to cover such conditions. If, for example, in Fig. 3, OL represents the selected constant current, then when $R_2 (= OF/FG)$ is in parallel with the arc, the arc current will be ND as before, and DK will be the current through R_2, NK being the line current because it lies on the perpendicular through L. Before the switch is closed the arc current is, in this instance, OL, and afterwards it is ND. The change in the arc current and voltage consequent upon the addition of a shunt resistance is therefore different, according to whether the feed current is or is not constant. If from the point L a tangent be drawn to the arc curve, the ratio of the ordinate at the point of contact to the horizontal intercept between the curve at that point and the line LP gives the minimum possible value of R_2 for the chosen current. It is a function of A, B and I, where I is the constant current, and its value is

$$R_2 = A^2/(AI + 2B) - 2\sqrt{[(B^2 + ABI)]}$$

As regards stability, the conditions appear to be similar to those in the circuit with constant feed volts. The authors hesitate to dogmatize, since they have made no experiments on this question.

(2) APPLICATION TO THE OSCILLATING ARC.

These expressions at once suggest the analogy between an oscillating arc and an arc with a shunt resistance. For in the former a capacity C, inductance L and resistance r_2 (Fig. 4) replace the shunt resistance in the latter, and only an alternating current can flow through the shunt circuit. Applying these considerations to Fig. 3 we obtain Fig. 4, and it follows that, if N_1C is the stable arc current before oscillation begins, then a half-wave of charging current through the condenser in the positive direction will be represented by a current rising from zero at C to a maximum at, say, DK and down again to C. The reverse half-wave is similarly represented by a discharge current from C to PQ and back to C. The feed current meanwhile goes from N_1C down to NK and back to N_1C; then from N_1C to N_2P and back. Similarly, the arc p.d. during charge goes from N_1 up to N and back; and during discharge from N_1 down to N_2 and back. Thus by means of this diagram the whole cycle can be studied. It is obvious that the change in arc p.d. synchronizes with that of the oscillating current; in other words, the a.c. circuit must operate at the resonant frequency. It is clear, also, that during the charge period the average p.d. is higher than during discharge. This accounts for the growth and maintenance of the oscillations.* For consider a maximum high-frequency current DK. At this instant the voltage across the resistance R_1 has fallen from EN_1 to EN, so that the difference NN_1 represents a rise of pressure from the mains on the oscillating circuit, which must be equal to or greater than the product of the current DK and resistance r_2. On discharge the current through R_1 has risen to N_2P and the corresponding pressure across the oscillating circuit has fallen to N_2, so that the condenser may be able to discharge itself against the resistance r_2. If the values NN_1 and N_1N_2 are greater than the product of r_2 into the corresponding values DK, PQ, the remainder is available for increasing the oscillating current exponentially until balance is established.

Hitherto the argument has proceeded on the assumption that the line DCQ is almost straight; but in fact the slope of CD is always a little greater than CQ, and moreover it increases rapidly beyond D towards B. Consequently if N_1N_2 is the resistance-drop in the a.c. circuit for the discharge current PQ, N_1N must be more than sufficient to produce the charging current DK, and the oscillations cannot be stable but must continually tend to an increase, due to the departure of the arc characteristic from the straight line. It is just here that the differential equations fail, and we arrive at the conclusion that the musical arc in which oscillations take place about C, without extinction of the arc, must be an exceedingly unstable phenomenon, if the arc characteristic is the assumed static curve.

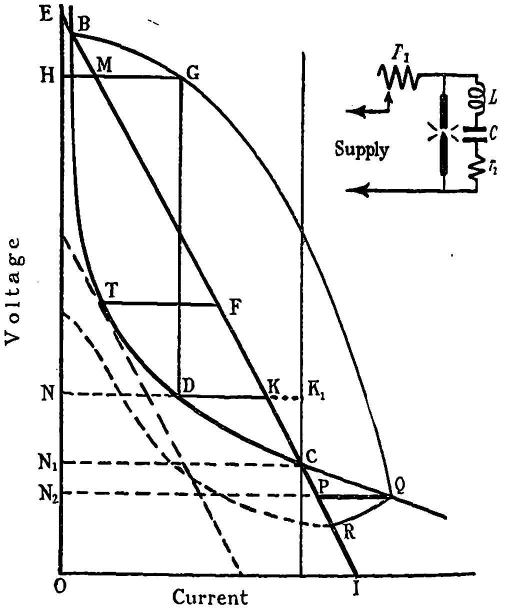

FIG. 4.

Before pursuing this further, we may note that if growth in succeeding cycles takes place, then the point D during each successive cycle travels further up the line QCD until it reaches the position where the horizontal difference between this line and EI is a maximum.

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* These deductions are not in accord with the theory of Blondel (see *L'Eclairage Electrique*, 1905, vol. 44, p. 41). They are, however, supported by the equations in the Appendix.

This occurs at the point T where a line parallel to EI is a tangent to the curve TCQ. The conditions there are that $\delta V_a/\delta i_a = -R_1$. Adopting Mrs. Ayrton's equation, the maximum possible instantaneous value of the high-frequency current in the direction of charging the condenser is derived as follows:—

$$dV_a/di_a = -B/i_a^2 = -R_1$$

whence i_a under these conditions is $\sqrt{(B/R_1)}$. Now $E = (i_a + i_c)R_1 + V_a$, where i_c is the high-frequency or oscillating component of current; and so

$$E = (i_a + i_c)R_1 + A + B/i_a$$

On substituting for the value of i_a we get, for the maximum possible instantaneous value of i_c under these conditions,

$$i_{c_{max.}} = \left[E - A - 2\sqrt{(BR_1)}\right]/R_1$$

And, if we regard $i_{c_{max.}}$ as having a simple harmonic variation,

$$i_c = i_{c_{max.}}/\sqrt{2}$$

The point C in Fig. 4 is given by

$$i = \left[E - A + \sqrt{\left\{(A - E)^2 - 4R_1B\right\}}\right]/2R_1$$

Thus i_c/i, the ratio of high-frequency to direct current, is

$$2\left\{E - A - 2\sqrt{(BR_1)}\right\}/\left[E - A + \sqrt{\left\{(A - E)^2 - 4R_1B\right\}}\right]$$

If we take the values used in Fig. 6 for an arc 1 mm long, where $E = 248 \cdot 5$, $V_a = (41 + 30/i_a)$, $R_1 = 50$, then $i_{c_{max.}} = 2 \cdot 6$, $i_c = 1 \cdot 84$, $i = 4 \cdot 00$, $i_c/i = 0 \cdot 46$. Or, again, using the values of Table 1 and assuming the same equation for V_a, we find: $i_c = 0 \cdot 825$, $i = 2 \cdot 25$, $i_c/i = 0 \cdot 365$. In both instances the results are of the right order as compared with experiment, which is as much as can be expected when it is remembered that the wave-form and the arc equation are not likely to remain the same for many instants.

Stability of Excursions about C. Dynamic Characteristics.—It has been remarked that these oscillations must be unstable if they are dependent entirely upon the conditions hitherto assumed. But in fact they are more stable than this theory allows, and the cause of their stability is the so-called "hysteresis" of the arc. During discharge of the condenser the arc current is far larger than during its charge period; e.g. N_2Q in Fig. 4 is far greater than NK. Consequently the electrode temperature (upon which the shape of the arc characteristic depends) is different when the current is falling from N_2Q to NK as compared with the converse case. The result is that the line DQ becomes roughly elliptical, yielding the dynamic characteristic as illustrated in Fig. 5, which shows part of Fig. 4 enlarged. On the upward swing, then, when steady conditions have been reached, the current lines lie between TV and TK, instead of between CD and CK. After the maximum current has been reached at V, the horizontal intercepts travel round through D and lie between DS and KS. The reverse oscillation is represented by lines which lie between SI and SQ up to Q, and then by lines between TI and TQ. The chief effect of this modification is that the maximum high-frequency p.d. occurs at D, while the maximum current occurs at V, so that a phase displacement is introduced. The phenomenon may be easily understood by reference to the simple linear steady conditions given in the Appendix, where

$$i_c = K\sqrt{\frac{C}{L}} \sin \frac{t}{\sqrt{(LC)}}$$

and $$i_a = -\frac{R_1 + r_2}{R_1} i_c + K_1$$

Then $$I = \text{feed current} = K_1 - \frac{Kr_2}{R_1}\sqrt{\frac{C}{L}} \sin \frac{t}{\sqrt{(LC)}}$$

and $$V_a = E - R_1K_1 + Kr_2\sqrt{\frac{C}{L}} \sin \frac{t}{\sqrt{(LC)}}$$

The variable parts of arc voltage and current are thus in antiphase, as would be expected from the resonance conditions, and the mean high-frequency power is $(K^2r_2C)/(2L)$. If now V_a and i_a have an angular displacement other than O or π, the path described will be an ellipse with its major axis lying nearly along the original straight line; and for the same amplitudes the high-frequency power will be reduced in the proportion of $1 : \cos \phi$, where ϕ is the angular displacement from π. This ellipse is the simple counterpart of the loop in Fig. 5, caused by the quasi-reactance term $(K/i_a)(di_a/dt)$ mentioned in the introduction. Its effect is threefold, viz.:—

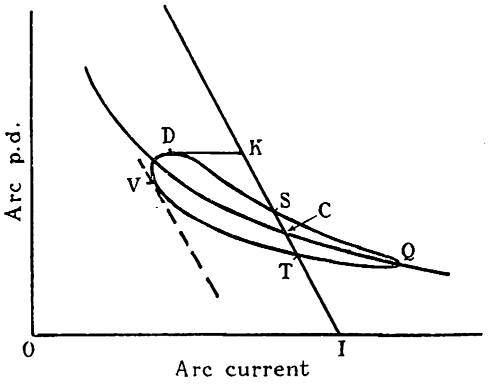

FIG. 5.

(1) It causes a change in the effective ratio of L/C because it is similar to a reactance.
(2) It alters the natural period of the whole circuit and disturbs the resonant condition so that the high-frequency current and arc voltage are no longer in phase.
(3) It tends to limit the high-frequency power and therefore the growth of the oscillation; in other words, it gives to this type of oscillation a stability which otherwise it would not possess.

The arc hysteresis loop, or dynamic characteristic, occurs to some extent in all instances, but it is only when the excursion is about some point where dV_a/di_a is small that it assumes the elliptical shape, and then the ellipse is of small importance. When the amplitude of the excursion is greater the dynamic characteristic is far less regular. The upper curve in Fig. 9 is deduced from the oscillogram shown in Fig. 7, and may be compared with Fig. 1, which it closely resembles; but it will be noted that from A to B the return curve lies above the outgoing line. This is not usual, but it often happens. It is due to the fact that in this region dV_a/di_a is small and i_a large. Consequently, in the p.d. equation

$$V_a = A + B/i_a + K/i_a \times di_a/dt,$$

the shape is controlled largely by the first two terms and any slight alteration of arc position or length (upon which A and B depend) is enough to interchange the two lines. On the other hand, the loop ACD is always present and lies in a region where dV_a/di_a is large and i_a small, and consequently it is much affected by the second and third terms. The physical explanation is simple if the peaks AD be joined as suggested by the dotted line in Fig. 7. Then the voltage curve follows the normal current line, i.e. represents the resistance-drop in a tuned circuit, while, in Fig. 9, C disappears and DAB becomes the ordinary characteristic. The hollow at C is entirely due to the response of the high-frequency inductance and feed inductances and resistances to the first change at A. In the present instance, the d.c. feed circuit had considerable inductance, which accounts for the rounded form at C. The authors have observed that when this is not the case the point C is lower and the curve far sharper. The twin peaks of Fig. 7 appear in almost all oscillograms. The opinions advanced hitherto upon the arc phenomena are not in accordance with the views of Blondel,* nor do they entirely agree with those of Pedersen,† but the present authors believe that they will bear close investigation.

Effect of Constant Current Feed.—Here, as in the preceding section, the behaviour of the arc when the feed current is kept constant may be inferred. Suppose, for instance, the vertical line through C (Fig. 4) represents the selected constant-current feed. Then when the arc current is ND, the current in the high-frequency circuit will be DK_1 instead of DK; and we conclude that for a given oscillating arc voltage greater high-frequency currents will flow with constant feed current. On the other hand, this greater current NK_1 will only correspond to the same voltage-rise N_1N as did DK; so that r_2 must be smaller. In other words, to cause the arc to oscillate with a high high-frequency resistance r_2, a high feed-voltage and external resistance are preferable to a constant-current feed. This is entirely borne out by experiment. It may be added that constant feed-current conditions are obtained in practice by making the resistance R_1 smaller but very inductive. Such an arrangement has the advantage that the damping introduced by high-frequency currents flowing in the feed circuit is reduced, and therefore a higher efficiency is attainable.

(3) DISCONTINUOUS OSCILLATION.

When, as in Fig. 4, the current has grown to the value TF, it must of necessity continue to flow, not by moving from TF towards C, but towards B; because beyond T the charging current actually falls with a rising voltage. Thus the harmonic oscillation about C is now superseded by a transient towards B. It will be seen later that B may never be reached, on account of differences between the static and dynamic conditions.

In order to show the theoretical manner in which this growth will take place, it is possible, for any given characteristic, to integrate the differential equations step by step, and this has been done, starting from the fundamental equations for an arc of 1 mm. They are as follow:—

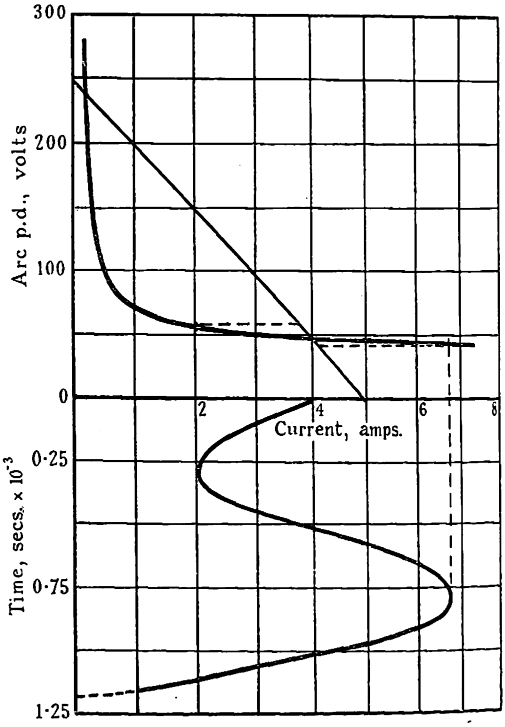

FIG. 6.—Predicted oscillation. Supply voltage 248·5; feed resistance 50 ohms.

(*a*) Feed circuit $V_a = E - IR_a$
(*b*) Arc circuit $V_a = 41 + 30/i_a$
(*c*) Oscillating circuit $V_a = r_2 I_c + \frac{Ldi_c}{dt} + \frac{1}{C}\int i_c\,dt,$

and $I = i_a + i_c$.

The conditions chosen for the calculation were:—

Applied volts = 248·5
Arc length = 1 mm
Feed resistance = 50 ohms
High-frequency inductance (L) = 5 066 μH
High-frequency resistance (r_2) = 1 ohm
High-frequency capacity (C) = 5 μF.

The natural period of the circuit is therefore about 1 000 periods per sec., and Fig. 6 shows in rectangular co-ordinates the growing wave and the original characteristic.

If the growth of the oscillation just described does not lead to complete arc extinction, it at least results in a current so small as to be incapable of maintaining anything more than a glow. Experiment shows, however, that, when once these conditions have been established and a point such as B in Fig. 4 has been reached, oscillation continues. We may assume, if we wish, that on approaching B the arc is extinguished and the pressure on the condenser circuit rises until it reaches the full line voltage OE, but it is not possible then for discharge to take place, for by hypothesis the arc current must be on the line TDC, and the line current on EI. Horizontal intercepts between these two are charging currents for the condenser. Discharge can only occur below C, as at PQ. In other words, the discharge region must lie to the right of EI, and so long as the arc characteristic is of the shape shown there is no such region between C and B. How then can the arc voltage travel from B to C again? The answer to this question is obtained from oscillograms, of which Fig. 8 is a typical example. From this it is seen that the condenser charging current is always near its maximum value when extinction occurs; i.e. to obtain this form of oscillation the circuit must be so arranged as to bring about extinction near the maximum intercept

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* A. BLONDEL: *L'Eclairage Electrique*, 1905, vol. 44, pp. 41 and 81.

† P. O. PEDERSEN: *Proceedings of the Institute of Radio Engineers*, 1917, vol. 5, p. 255.

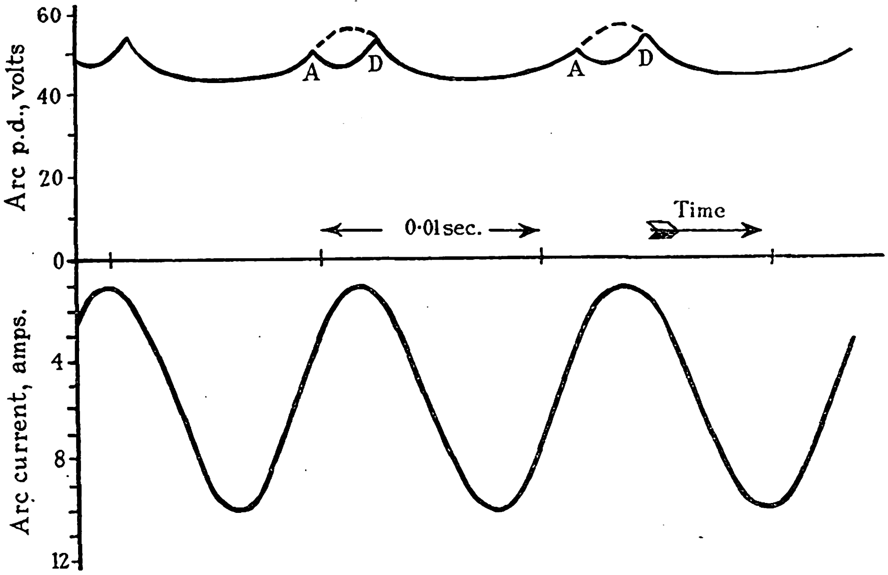

FIG. 7.—Non-extinguishing arc. Supply voltage 240; scales approximate.

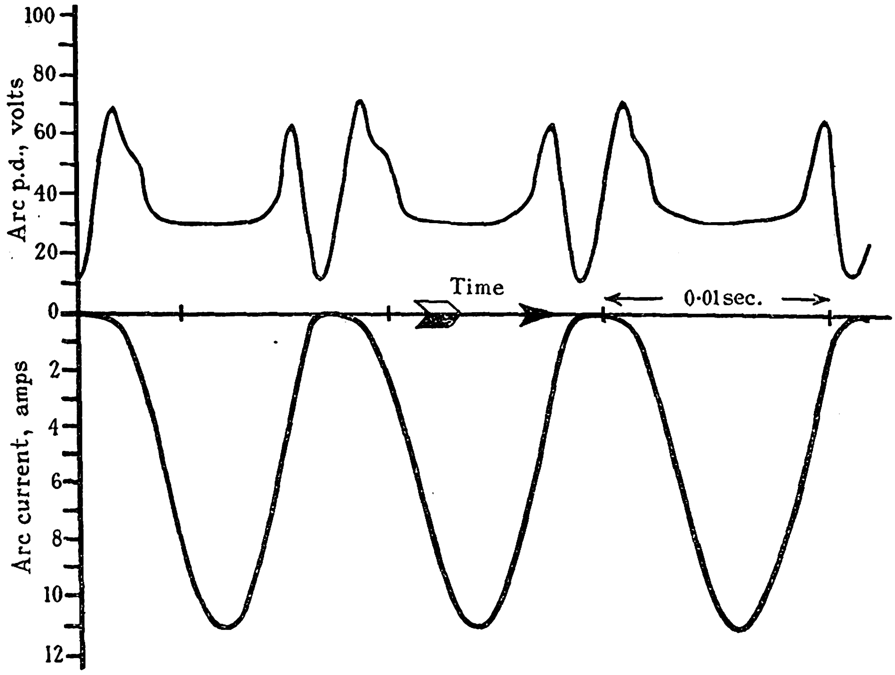

FIG. 8.—Extinguishing arc. Supply voltage 210; scales approximate.

TF (Fig. 4), so that on re-ignition the diminishing charging current may continue towards C. This condition means that when the arc current is small enough for extinction to occur the slope of the characteristic must not be greater than the slope of the resistance line. Now the shorter the arc the flatter the portion CDT. For example, to the family of curves derived by Mrs. Ayrton * the following equation applies:—

$$V_a = 38\cdot88 + 2\cdot074\, l + \frac{11\cdot66 + 10\cdot54\, l}{i_a}$$

where l is the arc length in mm. Thus, for constant l,

$$\frac{dV_a}{di_a} = -\frac{11\cdot66 + 10\cdot54\, l}{i_a^2}$$

If $l = 5$ and $i_a = 1$

$$\frac{dV_a}{di_a} = -64 \text{ (nearly).}$$

If $l = 1$ and $i_a = 1$

$$\frac{dV_a}{di_a} = -22 \text{ (about).}$$

If then the 5-mm arc be arranged on a 220-volt circuit with 40 ohms in series the stable current will be about 4 amperes. It cannot, however, oscillate with an amplitude exceeding 2·8 amperes, as at this current $dV_a/di_a = -40$. Its minimum current when oscillating will thus be 1·22 amperes, and it will almost certainly not be extinguished. It is an example of Fig. 7. If, however, with the same circuit conditions the arc length be reduced to 1 mm, the minimum arc current may fall to 0·74 before $dV_a/di_a = -40$, and the arc will most likely be extinguished. It approaches Fig. 8. Thus for a given circuit the discontinuous oscillation is more likely to occur with short arcs, its high-frequency current will be greater, and since the arc is extinguished the high-frequency amplitude must approach the value of the direct current, and the ratio of R.M.S. alternating- to direct-current feed must be about 0·7.

Table 1 gives details of two experiments which have almost the same circuit conditions and serve to confirm these contentions. The words "type A" and "type B" serve to distinguish the non-extinguishing and extinguishing arc respectively.

The last difference in this comparison is very clear to a musical ear, and can be traced immediately the change of type occurs. It is significant that the figures given by Duddell in his original paper on the musical arc † indicate that type B was his discovery, for the ratios of high-frequency to arc current in the two instances that he quotes are 0·86 and 0·9 respectively, under which conditions the arc must surely have been extinguished *every period*.

As further evidence of the two types of oscillation, reproductions of two sets of oscillograms are shown in Figs. 7 and 8, the former being type A. The conditions appropriate to these diagrams are given in Table 2.

Dynamic Characteristics of Extinguishing Arc.—The form of loop appropriate to an arc extinguished by a forced sinusoidal oscillation has been given in Fig. 2. When the oscillation is natural it is more complex. The lower curves of Fig. 9 are deduced from Fig. 8 and the physical explanations are exactly in line with those advanced for the upper curves. The intersection of the "go" and "return" curves is more pronounced than usual, but the authors have observed it on many occasions, and, having regard to the rapidity with which the arc changes its position on the electrodes, it is not surprising that these irregularities should occur. The ignition voltage need not be the d.c. supply voltage; it may be lower or higher, but, if higher, then the feed circuit as well as the high-frequency circuit must contain inductance.

TABLE 1.

Data of Two Oscillating Arcs. Carbons: Apostle, Solid, diameter 18 mm and 11 mm.

	Experiment 1, Type A	Experiment 2, Type B
Arc length	1 mm	0·25 mm
Supply voltage ..	220	220
L	14·7 mH	14·7 mH
C	5·26 μF	5·26 μF
r_2	0·5 ohm	0·5 ohm
R_1	73·3 ohms	71·7 ohms
D.C. feed	2·1 amps.	2·3 amps.
High-frequency current	1·1 amps.	1·65 amps.
Ratio of high-frequency to direct current	0·524	0·718
Frequency	590 periods per sec.	595→608 periods per sec.
Quality of sound ..	Mellow	Harsh

TABLE 2.

Data of Two Oscillating Arcs.

	Fig. 7, Type A	Fig. 8, Type B
Supply voltage	240	210
Feed current (I)	5·1 amps.	4·3 amps.
V_a (R.M.S.)	47 volts	35 volts
i_c (R.M.S.)	3·1 amps.	4·4 amps.
Ratio i_c/I	0·6	1·02
L	24·4 mH	24·4 mH
C	154 μF	154 μF
r_2	0·6 ohm	0·6 ohm

Since the authors, in their interpretation of these arc figures, differ from other investigators, it is important that strong evidence to support them should be forthcoming. They have said:—

(1) That when the arc is extinguished by a natural swing, the slope of the characteristic must not exceed that of the resistance line.

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* "The Electric Arc," Fig. 61.

† *Journal I.E.E.*, 1900–1, vol. 30, p. 251.

(2) That the dynamic loop may be caused by a heat change which simulates a reactance.

(3) That departures from such a loop, when not due to irregular working of the arc, are caused by the high-frequency and feed inductances.

The first point they think they have proved above. Fortunately, they have also found means of proving the other two by experiments upon an arc with no high-frequency inductance whatsoever.

The argument is as follows:—If an arc can be caused to oscillate with capacity but no inductance in shunt, the arc voltage can never rise above that of the supply, and there is no possibility of a swing about the point C, Fig. 4. Thus if, in Fig. 4, the inductance L be omitted and the arc oscillates, then the charging current will lie between BTDC and BMKC, but no discharge whatever can lie in this region. Therefore, charging will continue up to the point B, and if the arc extinguishes it will go on up to E, or to some lower point at which re-ignition occurs. Again, since the charging current will be large at first, but will tend to decrease, the di_a/dt term will at first be large and negative, and the dynamic characteristic should be well to the left of the static curve during charging, as, for example, the dotted curve in Fig. 4. On ignition the discharge will be extremely rapid and *must lie entirely to the right of* EI. This can happen if the di_a/dt term exists and is large enough to produce such an effect, as, for example, is suggested in Fig. 4 by the line BGQ. Then on discharge, for a feed current = HM, the current through the arc would be i_a = HG, and $k/i_a \times di_a/dt$ would be positive and represented by DG. Thus departures on both sides of the static curve will be expected, but the form of the loop cannot be predicted beyond saying that the arc current will increase to a maximum, say N_2Q when di_a/dt is zero, and because of this condition Q must be on or near the static curve and still to the right of EI. Then as the high-frequency current decreases di_a/dt will be negative until some point representing the minimum arc voltage is reached at R which corresponds to zero high-frequency current and must therefore be on EI. Beyond R the high-frequency current reverses, but di_a/dt is still negative because it is now the difference between the high-frequency current and the direct current which feeds the arc, and this term remains negative until the maximum reverse high-frequency current is reached. Thus the outward curve might be BGQR, and the return curve from R to B would be a line such as the dotted curve lying to the left of, or below, CDB. We must therefore consider the possibility of an oscillation with no high-frequency inductance.

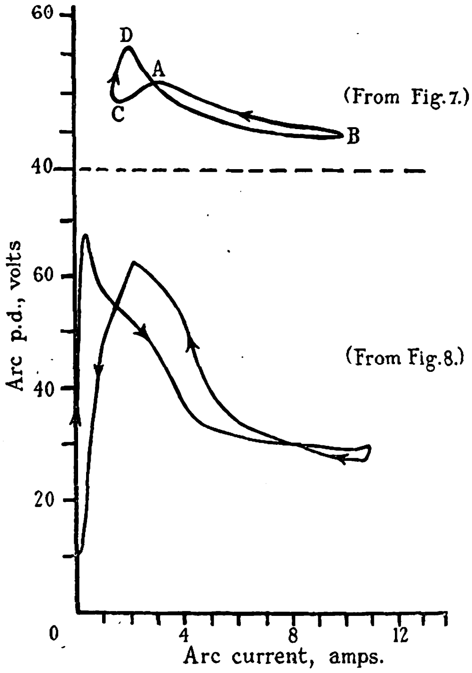

FIG. 9.—Dynamic characteristics.

(4) Oscillations with No Inductance.

It is obvious that if a condenser and a short-circuiting device in parallel be fed through a series resistance from a d.c. supply, the condenser can automatically charge and discharge, provided that the short-circuiting device operates at a high voltage and ceases to operate at a lower voltage. A well-known example is the behaviour of the neon lamp as determined by Pearson and Anson.[*]

Now although the characteristic of the arc is quite dissimilar from that of the neon lamp, the two have this much in common, that a higher voltage is necessary to start than to maintain the discharge. An arc, therefore, fed in the above manner, with no inductance whatever, should play the part of a short-circuiting device and show itself capable of giving out a musical note. This experiment was tried and the prediction was verified. It is interesting to note that Duddell's first oscillation was produced with no inductance other than that of a pair of long leads, but his effect disappeared when these leads were twisted together, so that he thought that the swing could only take place if inductance were present. The authors' experiments, however (made with very short leads to the condenser and a short arc), show that the high-frequency inductance is unnecessary and serves only to improve the wave-form and to fix the frequency. For when the inductance is omitted the frequency is determined for a given condenser, arc length and supply pressure, by the series feed resistance, just as it is with the neon lamp. The phenomenon is in fact a series of violent single-energy transients, of practical importance to the power engineer, since it illustrates the fact that destructive oscillations—probably the most destructive oscillations—may arise from a short-circuit in a cable system where no ordinary resonance exists at all. The example in Table 3 gives the conditions for an arc behaving in this manner.

Fig. 10 shows an enlargement of an oscillogram taken under the following conditions:—Line voltage 215, mean line current 5·2 amps., condenser current 25 amperes (R.M.S.), feed resistance 31·6 ohms, capacity 216·1 μF, arc length 1 mm. The action may easily be traced. At time T_1 the arc proper is extinguished momentarily, but the inter-electrode space (being ionized) continues to conduct, and the current through the arc rises from T_1 to T_2 while the condenser charges. The voltage curve

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[*] *Proceedings of the Physical Society of London*, 1922, vol. 34, pp. 175 and 204

TABLE 3.

Oscillations with Condenser Only Across the Arc.

Direct feed current, amps.	1·6	1·9	2·15	3·0	3·1	5·6
High-frequency current, amps.	8·6	9·4	10·7	15·0	15·0	22·0
Arc voltage, volts	65	60	65	55	50	50
Resistance voltage, volts	190	192	185	175	180	180
Feed voltage, volts	250	250	250	225	225	220
Capacity, μF	5	5	5	20	40	40
Feed resistance, ohms	119	101	86	58	58	32
Ratio of high-frequency to direct current	5·37	4·95	4·98	5·0	4·84	3·92
Frequency, periods per sec.	1 890	2 280	2 520	1 800	940	1 080

during this period has the usual shape for a condenser charged through a resistance from a source at nearly constant p.d. The small arc current, as measured from the diagram, averages about 1·76 amperes and therefore accounts for a fall of the applied p.d. from 215 to 150·2 volts. The condenser voltage at the beginning of charge is about 8·35, and at the end only 61·0, so that clearly the gap resistance breaks down at this low pressure. The calculated time required to charge the condenser from 8·35 to 61·0 volts with an applied p.d. of 150·2 through the resistance of 31·6 ohms is 32×10^{-4} sec. A similar calculation from the current wave gives about 51×10^{-4} sec. The corresponding time, as measured from the diagram, is about 40×10^{-4} sec. There are many possible causes for such discrepancies, e.g. the difficulty of making exact measurements from the oscillogram, the doubt as to the exact instants at which charge and discharge begin, variations in successive cycles, etc., so that it cannot be expected that the results should be of more than the right order.

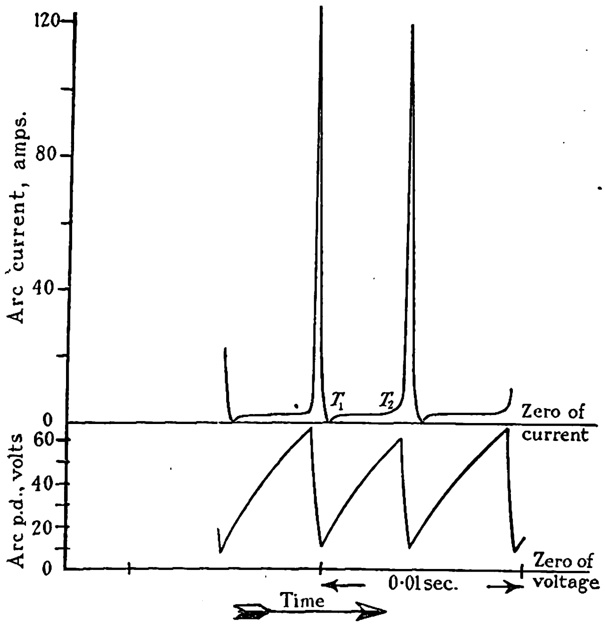

FIG. 10.—Arc with condenser in parallel.

As regards discharge, assume the time to be so short that the line-current variation is small. Then if V_a represents the arc voltage, i.e. the instantaneous condenser voltage, and V_1 and V_2 are its initial and final values,

$$V_a = A + B/i_a \quad \text{and} \quad i_a = -C(dV_a/dt)$$

So $$Bt = \tfrac{1}{2}C\left(V_1^2 - V_2^2\right) - AC(V_1 - V_2).$$

Taking, for instance, in this arc, $A = 33$, $B = 15$, we find $t = 0{\cdot}001$ sec., which might easily be true for the oscillogram. But such a calculation is really useless, depending, as it does, on an exact knowledge of A and B, and omitting the thermal term. If, for instance, $(V_1 + V_2) < 2A$, t is negative, which is absurd. We cannot therefore predict even roughly the time of discharge, or the maximum current. But the value of the latter, as measured, is no less than 126 amperes, and the R.M.S. value is 25, so that the ratio of maximum to R.M.S. value is about 5. Now, regarding the discharge wave as being roughly triangular, and remembering that the periodic time is about 45×10^{-4} sec., the time of discharge must be of the order of 5×10^{-4} sec. From the oscillogram it measures about $6{\cdot}0 \times 10^{-4}$ sec., so that the ratio of time of charge to time of discharge is 40/6·0 or 6·3, and the agreement with the rough theory is as good as can be expected. The main point to be noticed is that the average charging current is small and the time long as compared with that of discharge; also that, although extinction occurs every period, it is immediately followed by a time during which a small but increasing current flows, such as might occur if a glow remained between the electrodes. In many experiments the authors have found similar evidence, accounting for the low re-ignition voltage.

Oscillograms such as Fig. 10, involving the use of a condenser only, form an excellent method of studying arc transients, because the arc and condenser voltages are always the same. By the gradual introduction of inductance into the high-frequency circuit the change of the wave form may be traced, as well as the alteration from a frequency controlled by the feed resistance to one that is determined by the natural high-frequency period, and such records have been obtained. They involve, however, too long a discussion for this paper and must be postponed for some future occasion. It should be noted that for these experiments the arc length must be kept very short (which is probably why the phenomena were overlooked), and that the frequency is dependent upon and very sensitive to the length, because both of the constants A and B involve the length l of the arc. Thus if we write, with Mrs. Ayrton, $A = A_1 + A_2l$ and $B = B_1 + B_2l$ and substitute in the equation for discharge we get:—

$$t = \frac{C(V_1^2 - V_2^2)}{2(B_1 + B_2l)} - \frac{(A_1 + A_2l)C}{B_1 + B_2l}(V_1 - V_2)$$

showing that, in general, greater arc length results in shorter times of discharge.

Finally, Fig. 10 shows how high the ratio of R.M.S. high-frequency current to the d.c. feed current may be for these single-energy transients. In that example it is 25/5·2, or 4·8, as against 0·524 and 0·718 in Table 1. This is, however, by no means the limit. Instances could be cited in which the ratio was far higher, approaching 20; but of course a comparatively small resistance in the high-frequency circuit quickly reduces this large figure.

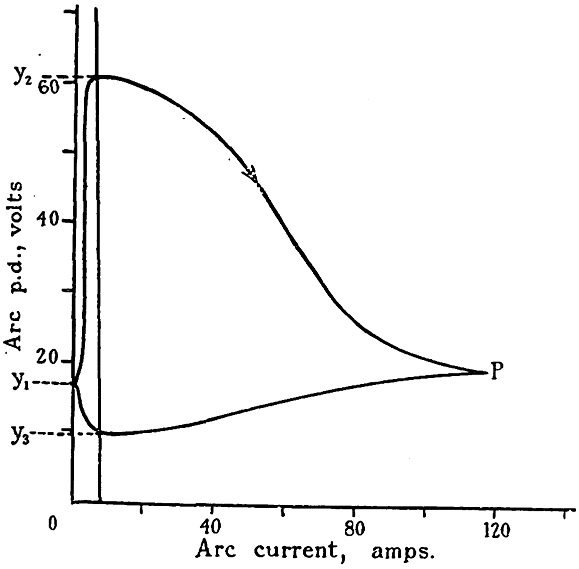

FIG. 11.—Dynamic characteristic of arc with condenser in parallel.

Fig. 11 shows the dynamic characteristic deduced from Fig. 10 by direct measurement of corresponding ordinates. Referring to this diagram, at y_1 the arc is extinguished. At y_2 re-ignition begins and y_3 marks the minimum condenser pressure. Thus charging takes place from y_3 through y_1 to y_2. The remainder of the curve is discharge. The line Py_3 in the dynamic characteristic is extremely difficult to deduce with precision from the arc-current/arc-voltage waves. The authors believe that as drawn it is as nearly as possible correct, having regard to the fact that the resistance line must, in their view, pass through y_2 and y_3, as shown.

The area of the loop has no great significance; it must not be confused with an indicator diagram or a hysteresis loop, for it does not represent work. The loop does, however, illustrate the mechanism of oscillation and it has a particular value in that it enables a link to be established between Duddell oscillograms and dynamic characteristics obtained by a cathode ray; but that also must be dealt with on a future occasion.* It shows, too, the immense effect on the arc characteristic of the rate of change of current, and confirms the likelihood of the general arc equations. From such a figure the current and voltage waves upon a time base may be derived. For if i_c represents the condenser current, then $i_c = CdV_a/dt$; and $dt = CdV_a/i_c$. Now each abscissa in Fig. 11 between the resistance line and the curve is a value of i_c, so that if the curve be intersected by a number of equally spaced horizontal lines representing δV_a the corresponding increment of time may be obtained by multiplying δV_a by the capacity C and dividing it by the appropriate value of i_c. Adding successively the time increments, we may plot them against i_c and thus invert the process by which Fig. 11 was obtained. Since for very high frequencies the cathode-ray oscillograph must be used, and since with that instrument it is possible to take the dynamic characteristic, the value of the above process is evident. When there is inductance in the high-frequency circuit, other methods must be substituted, which again emphasizes the value of the single-energy transient as a starting point for the examination of the arc.

CONCLUSIONS.

There are three ways in which a d.c. solid carbon arc may oscillate. Of these, the first or " A " type consists of excursions about a point upon a straight-line characteristic. The second (or " B " type) and commonest is a set of double-energy transients involving arc extinction every period or every few periods. The authors have found experimentally that a train, consisting of a growth from the straight-line condition, ending every two or more periods with arc extinction, does frequently occur. The third type is obtained with no inductance in the high-frequency circuit, and consists of a train of rapid single-energy transients around a wide loop.

The geometrical solution of the problem shows that, on the basis of the static characteristic, the maximum value attainable by an oscillation of the first and second kind is indicated by the value TF in Fig. 4. It is certain, however, that a loop due to the thermal term exists in these discharges also, with the result that oscillation about C takes place not along, but around, the line DCQ (see Fig. 5). This departure from the static curve is not very pronounced when the oscillations are small and the frequency low; but, as the oscillating currents increase or the frequency rises, di_a/dt becomes larger and the loops more important. In every instance the moment of extinction (or of minimum arc current) is almost certainly dependent upon the modification of the characteristic introduced by the thermal term. The fact that with small currents and low frequencies the behaviour of the arc can be fairly estimated from the equations of the Appendix shows that the departures from the static characteristic cannot, under those conditions, be serious. In short, no loop is theoretically necessary for oscillations of the A or B types, though it may exist; but without such a loop the third type would appear to be impossible.

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* See *Electrical Times*, 1930, vol. 77, p. 1066: " The Indicator Diagram of an A.C. Circuit."

The authors wish to acknowledge the assistance rendered by Mr. E. G. Ashton, B.Sc., in connection with some of the oscillograms analysed in the course of their work.

APPENDIX.

Referring to Fig. 4, let E be the constant applied pressure, V_a the voltage across the arc, i_a the arc current, i_c the current in the high-frequency or condenser circuit, and I the sum of i_a and i_c. Then we have the following equations:—

$$V_a = E - IR_1 = E - R_1(i_a + i_c) = L\frac{di_c}{dt} + r_2 i_c + \frac{1}{C}\int i_c\,dt$$

Now let the arc have a straight-line negative characteristic so that $V_a = K_0 - ri_a$. Then K_0 is the hypothetical value of V_a when the arc is extinguished, and $di_a/dV_a = -1/r$.

Thus
$$\frac{dV_a}{dt} = \frac{R_1 r}{R_1 - r}\cdot\frac{di_c}{dt}$$

and
$$i_a = -\frac{R_1 i_c}{R_1 - r} + K_1$$

K_1 being the steady value of the arc current when $i_c = 0$. This equation shows also that i_a increases as i_c decreases. We thus obtain as the general equation for the oscillating circuit:—

$$\frac{d^2 i_c}{dt^2} + P\frac{di_c}{dt} + Qi_c = 0,$$

where $P = \frac{1}{L}\left(r_2 - \frac{R_1 r}{R_1 - r}\right)$ and $Q = \frac{1}{CL}$.

Assuming $P^2/4$ to be less than $1/(LC)$, oscillations are possible in the condenser circuit. Further, if K is the value of V_a when $t = 0$, and $q = \sqrt{\left[\frac{1}{CL} - \frac{1}{4}P^2\right]}$

then
$$i_c = \frac{K}{qL}\sin qt\epsilon^{-\frac{1}{2}Pt}$$

which will increase indefinitely if P be negative, i.e. if $R_1 r/(R_1 - r)$ is greater than r_2. For operation at a steady value of i_c, $r_2 = R_1 r/(R_1 - r)$ or $r = R_1 r_2/(R_1 + r_2)$, a difficult condition to maintain. Then

$$i_c = \frac{K}{qL}\sin qt$$

and
$$i_a = -\frac{r_2}{r}i_c + K_1 = -\frac{R_1 + r_2}{R_1}i_c + K_1$$

also
$$I = -\frac{r_2}{R_1}i_c + K_1$$

Thus K and K_1 are the co-ordinates of the characteristic at which the arc works with the given values of E and R_1, and with the high-frequency circuit open; also the feed current I cannot be steady but varies with a slope that is the inverse of the slope of i_c.

THE THERMAL RESISTIVITY OF SOLID DIELECTRICS.*

[REPORT (REF. L/T41) OF THE BRITISH ELECTRICAL AND ALLIED INDUSTRIES RESEARCH ASSOCIATION]

(*Paper first received 3rd July,* 1929, *and in final form 17th January,* 1930.)

PREFACE.

As part of its comprehensive programme of Researches on Dielectrics, the Association has carried out an experimental investigation on the thermal resistivity of dielectrics.

Before undertaking this research a questionnaire was sent to all interested members, and the replies received showed that there was a serious lack of data on this subject and that the results obtained by other investigators did not apply sufficiently accurately to the materials at present in use in this country, neither did they take into account some of the many variables which are introduced during the manufacture of electrical machinery and apparatus.

The experimental investigations made for the E.R.A. were undertaken by the National Physical Laboratory, and for obtaining the required data new methods of test were developed and are described in this report.

During the progress of the investigation the Research Laboratories of the Metropolitan-Vickers Electrical Co., Ltd., carried out a separate investigation on the thermal resistance of air films. The results of this research were kindly placed at the disposal of the Association and have been included as part of this report.

Although there are many other features connected with the thermal resistivity of dielectrics which have not yet been investigated, it is felt that a description of the new methods of test specially developed for this work by the National Physical Laboratory and the valuable data already obtained will be of considerable practical use.

In the present report a detailed record has been given of the results obtained. This, it is considered, is required by those wishing to make a close study of the subject.

The Director of the E.R.A. will be pleased to receive comments from those who may have occasion to use the data recorded in this report.

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Acknowledgments.
Appendix I.—Estimation of the Thermal Conductivity of the Insulation on a Rectangular Bar.
Appendix II.—Bibliography.

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* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

INTRODUCTION.

In electrical machinery and apparatus a large proportion of the heat resulting from energy losses in the copper and iron has to pass through the electrical insulating materials. As the latter are also heat insulators, a considerable difference in temperature on the two sides of the insulation may be required to cause the passage of the heat from the copper or iron to the cooling medium. As both the rating and reliability of the machine is largely determined by the maximum temperature of its insulation, a study of the thermal resistivity of electrical insulating materials is of considerable importance.

Tables recording values for the thermal resistivity of dielectrics are of little use without some knowledge of the degree of success with which they may be applied to practical cases. For this reason a study has been made of the features which usually affect the flow of heat through electrical insulation as applied in practice.

After reviewing the work of other investigators, new methods of test were developed. These have enabled the required features to be studied with an accuracy believed to be greater than has been obtained during any previous research on the subject.

After investigating the effect of such features as the degree of contact, mechanical pressure, temperature range, repeated heating, uniformity of resistivity over large areas, numbers of layers, etc., the true thermal resistivity of a large number of typical samples of various classes of solid dielectrics was determined.

Tests were then made on bars insulated in members' works by the same processes and with the same materials as are used for turbo-stator bars. The effect of different manufacturing processes on the thermal resistivity was determined.

Another section of the research was devoted to a study of different types of insulation used between sheet-steel stampings. These tests were also made on commercial samples supplied by members.

Part IV of the report records the results of an experimental investigation carried out by the Research Laboratories of the Metropolitan-Vickers Electrical Co., Ltd.

In researches on the transfer of heat through bodies, it has usually been the practice to express the results in terms of thermal conductivity.

A material has unit thermal conductivity when it conducts one gramme calorie of heat per second across opposite sides of a centimetre cube, the difference in temperature between the sides being 1° C.

In considering heat transference in electrical machinery and apparatus it is more convenient to express the above-mentioned property in terms of thermal resistivity.

In its report on the heating of buried electric cables, Ref. F/T12, the E.R.A. used the symbol K to express thermal resistivity, and defined it as the temperature-difference in degrees Centigrade to cause a transfer of energy at the rate of one watt * between opposite faces of a centimetre cube.

As in previous publications by the E.R.A., the thermal resistivity K of the materials is in this report always expressed in terms of watts, degrees Centigrade and centimetres.

When it is required to express the thermal resistivity in terms of an inch cube, the values given for K must be divided by $2 \cdot 54$.

When it is required to compare the values given for K, the thermal resistivity, with thermal conductivity values k expressed in gramme calories per second per centimetre cube, the following conversion formula may be used:—

$$\text{Thermal conductivity } k = \frac{0 \cdot 24}{\text{Thermal resistivity } K}$$

Part I.

A STUDY OF THE THERMAL RESISTIVITY OF SOLID DIELECTRICS WHEN TESTED IN SHEET FORM, AND OF THE FACTORS WHICH INFLUENCE THE FLOW OF HEAT THROUGH THEM.

(a) *Materials.*

The materials examined in this section of the research included typical samples of the following classes of solid dielectrics obtained from members:—

Papers and pressboards.
Varnished cloths and silks.
Vulcanized fibres of thicknesses ranging from $\frac{1}{8}$ in. to $1\frac{1}{8}$ in.
Varnished paper boards.
Ebonite.
Mica, micanite and micafolium.

(b) *Methods of test.*

For obtaining information on the true and on the apparent resistivity of the above range of types and thicknesses of dielectrics it was found necessary to develop more than one method of test. Whenever feasible, both the heat input and the heat output are measured independently. This is an important feature of the methods employed, for it enables a check to be kept on the accuracy of the thermal measurements.

The tests developed and the purposes for which they were mainly employed are given below:—

(i) *Apparatus No.* 1.

The first apparatus is shown diagrammatically in Fig. 1. It was constructed for the study of the thinner materials ranging in thickness from $0 \cdot 002$ cm up to $0 \cdot 05$ cm.

A $1\frac{3}{4}$-in. diameter copper rod 8 in. long was hollowed out to a depth of 4 in. and a heating coil inserted, as shown in the diagram. The specimen under test rested on the top surface of this rod, and superimposed was a water-cooled copper rod 4 in. in length pressed down by a spring. The top rod was surrounded on its outer surface by a copper spiral, through which a steady stream of water flowed. The temperature-rise of the water was measured by a set of differential thermo-junctions of copper-constantan. One degree rise in temperature of the water corresponded to 250 micro-volts in the differential flow couples. When the specimen

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* One watt = 1 joule (or $0 \cdot 24$ gramme-calorie) per sec.

NOTE: Some idea of the order of magnitude of the values given in the various tables can be obtained from the following values taken from *Smithsonian Physical Tables* (7th ed.). When temperature is in the vicinity of 100° C., k for pure copper is $0 \cdot 908$. Therefore $K = 0 \cdot 264$. At a similar temperature k for wrought iron is $0 \cdot 143$. Therefore $K = 1 \cdot 68$.

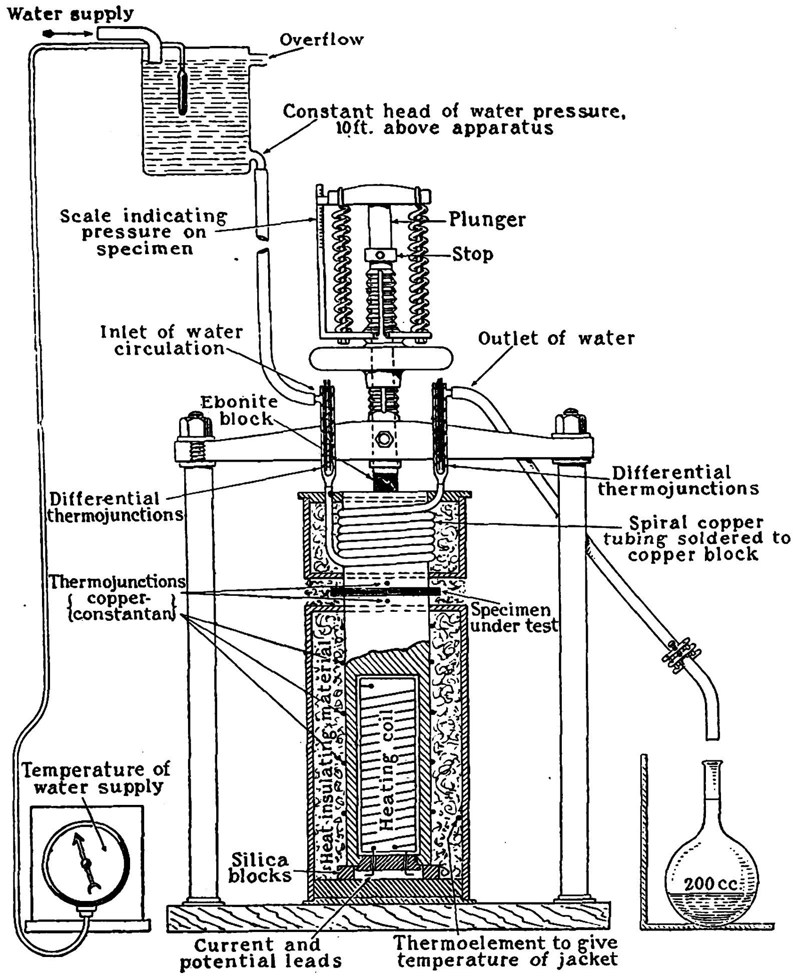

Water supply
Overflow
Constant head of water pressure, 10ft. above apparatus
Scale indicating pressure on specimen
Plunger
Stop
Inlet of water circulation
Outlet of water
Ebonite block
Differential thermojunctions
Differential thermojunctions
Spiral copper tubing soldered to copper block
Thermojunctions {copper-constantan}
Specimen under test
Heat-insulating material
Heating coil
Temperature of water supply
Silica blocks
200cc
Current and potential leads
Thermoelement to give temperature of jacket

FIG. 1.—Apparatus No. 1 *for testing thin specimens.*

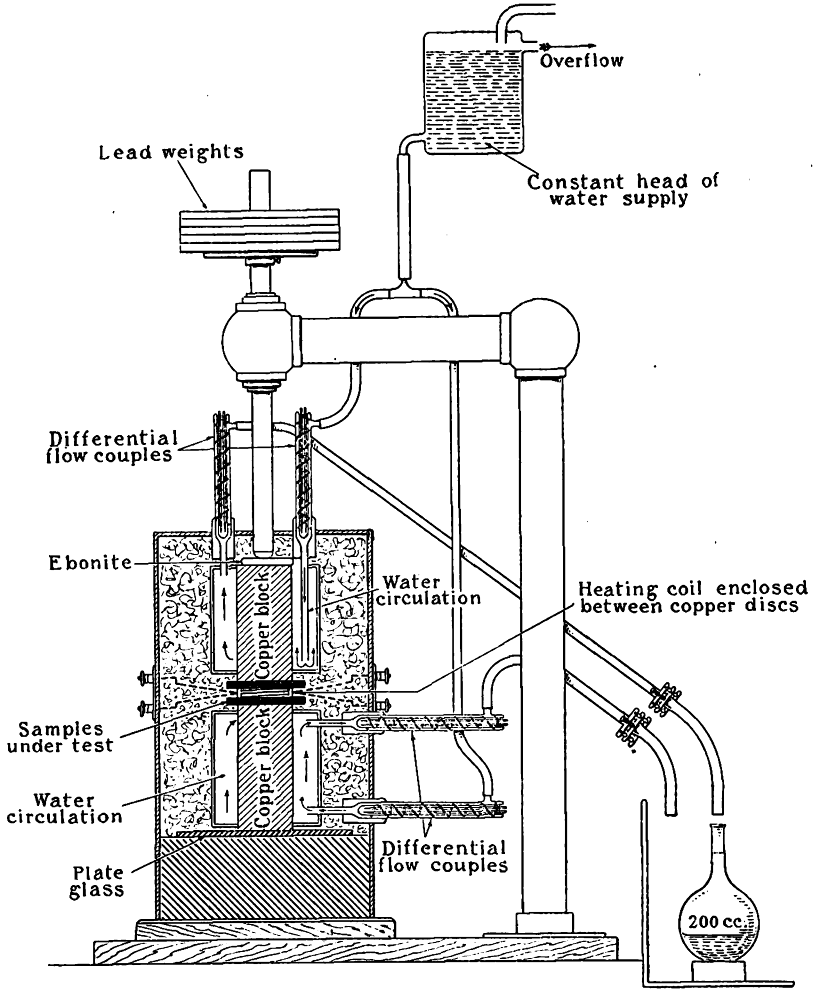

Overflow
Lead weights
Constant head of water supply
Differential flow couples
Ebonite
Water circulation
Copper block
Heating coil enclosed between copper discs
Samples under test
Copper block
Water circulation
Differential flow couples
Plate glass
200 cc.

FIG. 2.—Apparatus No. 2 for testing thick specimens.

had been inserted between the blocks pressure was applied by means of the spring plunger and the magnitude of this pressure determined by the scale reading. Most of the tests with this apparatus were carried out under a pressure of 24·8 lb. to the square inch.

To reduce heat loss both the hot and the cold bars were enclosed in metal cases packed with insulating material. The surfaces of the copper bars were ground plane to an accuracy of 1/10 000th of an inch. By making the surface to this degree of accuracy, contact resistance between the copper rods and the material under test would be due to the irregularities of the specimen and not the irregularities of the bar surfaces.

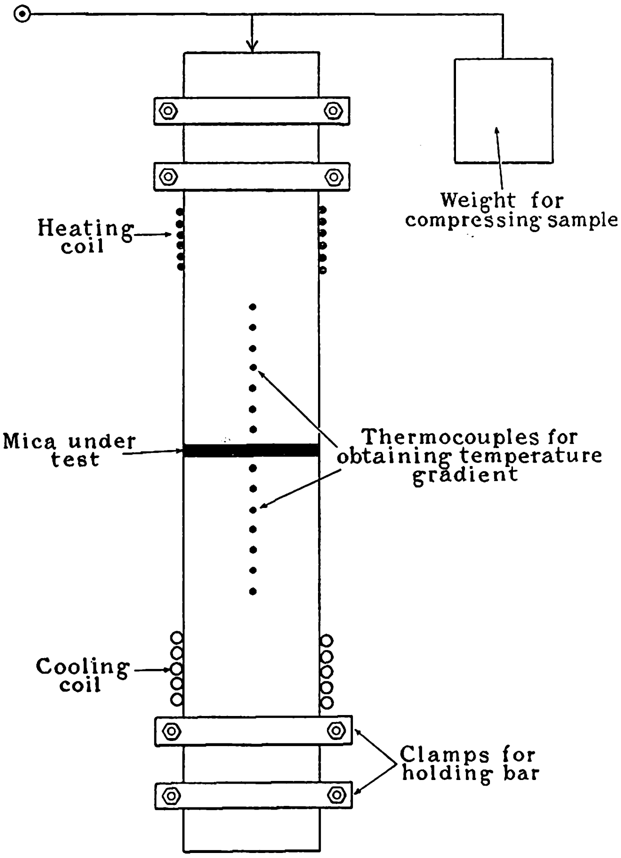

Heating coil
Weight for compressing sample
Mica under test
Thermocouples for obtaining temperature gradient
Cooling coil
Clamps for holding bar

FIG. 3.—Apparatus No. 3 for testing thin specimens by comparison of temperature gradients.

(ii) *Apparatus No.* 2.

For the thicker material another apparatus was constructed, which is shown in Fig. 2. In this the heating coil is in the form of a flat disc, and two samples of the material are employed in the test. The advantage of this arrangement is that a considerable reduction in the magnitude of the correction for the heat loss from the heating coil is effected.

Thermo-couples were attached to the shallow copper case around the heating coil and also to the two " cold " bars. Each " cold " bar was water-cooled, and the temperature-rise of the water observed by differential thermo-couples disposed as shown in Fig. 2. The arrangement for applying pressure was a " dead-weight " plunger carrying lead weights amounting to 57 lb., which was equivalent to a pressure of 23·5 lb. per sq. in. In both No. 1 and No. 2 apparatus the plunger was thermally insulated by the interposition of a distance piece of ebonite. The metallic surfaces which came into contact with the specimen were ground true, the accuracy being within 1/10 000th of an inch to a true plane. In assembling the apparatus for an experiment a simple form of gauge was required to ensure that the axes of the two copper blocks and the heating coil were in line.

The tests were made at a series of steady temperatures up to the maximum specified for the class of material under investigation, and one or more repeat readings taken when cooling down. In the majority of cases the repeat readings differed by a few per cent from the values obtained initially.

This may be due to some permanent physical change in the properties of the material due to heating or hygroscopic changes. It is also possible that some of the materials soften slightly on heating, and the applied pressure would then bring the copper surfaces into more intimate contact with the material.

A number of experiments were made to ascertain whether there was any systematic difference in the results obtained from the two forms of apparatus; the differences were negligible. For example, a test on paper board, L. 135 (thickness, 0·51 mm), gave on No. 1 apparatus a resistivity value *K* of 615, and on No. 2 apparatus 590, at a mean temperature of 30° C. A specimen of treated silk, No. L. 120 (thickness, 0·12 mm), gave on No. 1 apparatus the value 715, and on No. 2 apparatus 712, at a mean temperature of 30° C.

(iii) *Apparatus No.* 3.

As shown in Fig. 3, this differed somewhat from the two described above. It consisted of two copper bars each 14 in. in length. One was provided with a heating coil and the other with a cooling coil. These were attached to the extreme ends of the bars. Thermocouples were arranged at regular intervals along both bars so that the temperature gradient could be observed. The bars were supported vertically, the lower one being fixed while the top one was movable. Definite pressures could be applied to the top bar by means of a lever and weights.

In this apparatus the quantity of heat flowing into the specimen and out of it was obtained by observations of the temperature gradient along the copper bars and a knowledge of the thermal conductivity of the copper. The two surfaces were amalgamated so that good thermal contact with the specimen was ensured. In order to determine the thermal resistivity of the two mercury films, which were always present when a specimen was interposed between the bars, some tests were made using a sheet of iron instead of the specimen. This sheet of iron was of uniform thickness, amounting to only 0·002 in. From observations of the discontinuity in the temperature gradient across the mercury joints and the thermal conductivity of the iron specimen it was calculated that the thermal resistivity *K* of the mercury film amounted to 0·067 for an energy transference at the rate of 1 watt per cm^2 of area.

With this apparatus two thicknesses of a sample of mica were tested, one being 0·005 in. and the other 0·01 in. The results obtained were in good agreement, as shown below:—

Thickness of specimen	Thermal resistivity K
0·005 in.	177
0·010 in.	174

These results were obtained with the ends of the bars in contact with the specimen well amalgamated. This apparatus is not well adapted for the study of anything but thin materials. If the thermal resistivity of the material is high, then the temperature-drop across the specimen is large and the gradient along the two bars small. As it is necessary to measure the gradient along the bar in order to obtain the conductivity, the use of this simple form of apparatus is limited.

(iv) *Apparatus No.* 4.

The irregular nature of the surfaces of most of the materials as supplied commercially was a serious obstacle to the use of plain contact plates, and necessitated recourse to amalgamated plates, so a form of apparatus was then devised with the object of facilitating assembly when the surfaces were flooded with mercury.

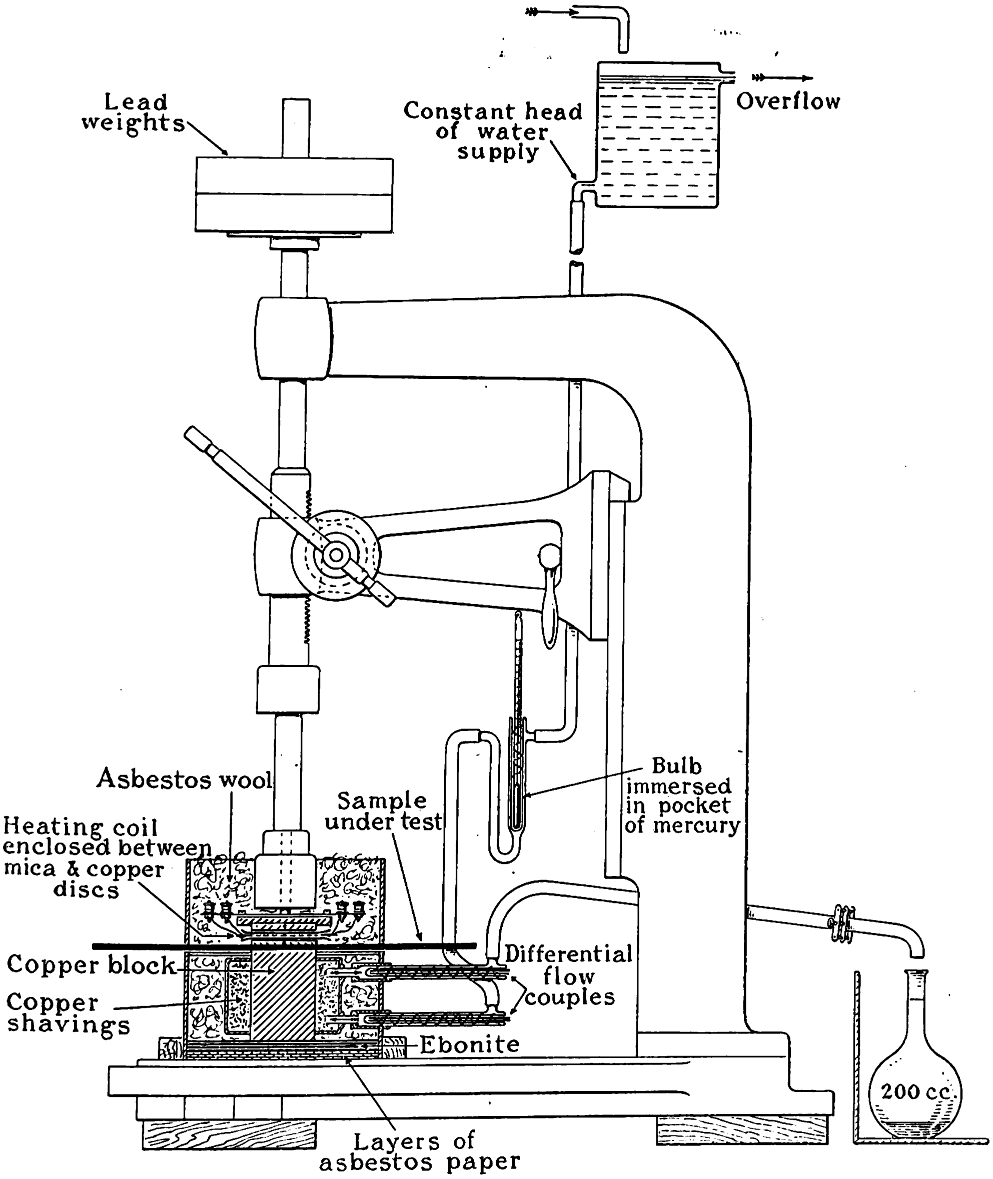

Lead weights
Constant head of water supply
Overflow
Asbestos wool
Sample under test
Bulb immersed in pocket of mercury
Heating coil enclosed between mica & copper discs
Copper block
Copper shavings
Differential flow couples
Ebonite
200 cc.
Layers of asbestos paper

FIG. 4.—Apparatus No. 4 for general-purpose testing. Suitable for specimens of large area.

The same instrument also served for the study of the variation in conductivity over the area of a large sheet, and proved to be of general utility.

Owing to the difficulty of assembly when two test specimens are employed, it was decided that the design should be such as to require but one sample, and, further, that the hot and cold surfaces should align automatically without any further manipulation once they had been brought into contact with the faces of the specimen.

A study of Fig. 4 shows how these aims have been achieved. The heating coil is clamped between two flat copper discs partially embedded in a block of ebonite; the amalgamated face is horizontal and face downwards. The complete heating unit is carried on a spindle working in guides, and once it is properly aligned with the cold plate these guides ensure that the hot face registers correctly with the cold face. This automatic alignment of the two surfaces is essential when point-to-point tests have to be made on large-sized sheets, as shown in Fig. 4, although it is more usual for the test specimen to be in the form of a circular disc of the same diameter as the hot and cold plates.

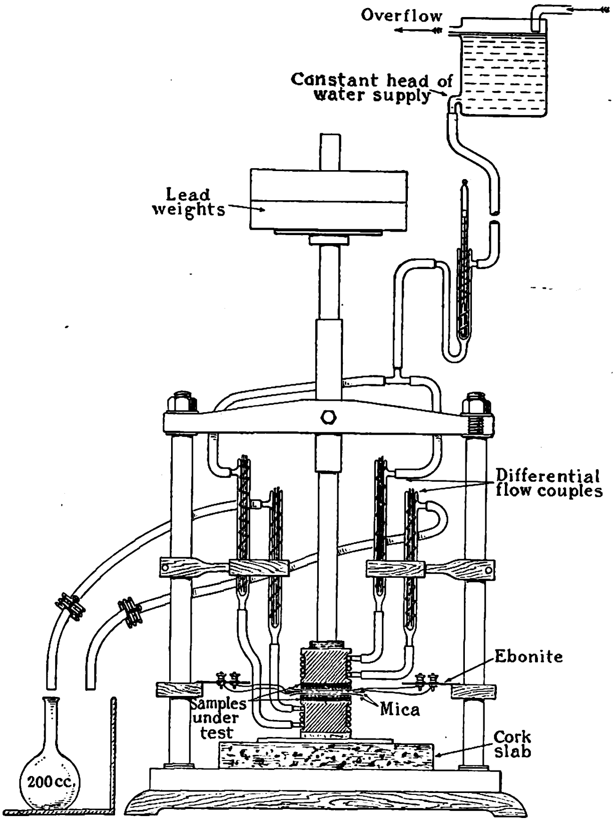


Fig. 5.—Apparatus No. 5 for testing without mercury films.

The cold surface is the end of a cylindrical block of copper maintained at a constant temperature by the steady circulation of water.

The temperature of the inlet water to the "cold" block is so adjusted that the mean of the inlet and outlet temperature is equal to the temperature of the surrounding atmosphere; this eliminates the correction for heat loss or gain from the block.

The temperature-rise of the water is measured by a pair of differential flow couples.

The watts dissipated in the heating coil are determined by observations of volts and amperes. After correction for the small heat leakage through the back of the hot plate, the energy dissipated in the heating coil is very nearly equal to the heat absorbed by the water flow. The data obtained in a typical experiment, such as those for light grey fibre (see table 11), will show the order of agreement obtained.

Experiment on Light Grey Fibre L. 113.

Pressure	21 lb. per square inch
Temperature of hot face ..	39·7° C.
Temperature of cold face ..	19·9° C.
Correction for gradient through mercury film	0·1 deg. C.
Hence true temperature difference ($t_1 - t_2$)	19·7 deg. C.
Amperes in hot plate resistance coil	0·5791
Volts at terminals	12·78
Watts	7·40
Correction for heat transmitted through back of hot plate	1·20 watts
Hence watts supplied to hot face of specimen (W) ..	6·20
Rate of water flow	200·0 cm³ in 126 secs.
Temperature-rise of water ..	0·93 deg. C.
Hence watts absorbed by water flow	6·15
Area of specimen (A)	15·59 cm²
Thickness of specimen (d) ..	0·141 cm

$$\text{Thermal resistivity } (K) = \frac{A \times (t_1 - t_2)}{W \times d}$$

$$= \frac{15 \cdot 59 \times 19 \cdot 7}{6 \cdot 20 \times 0 \cdot 141} = 351$$

(v) *Apparatus No.* 5.

Apparatus No. 5 is illustrated in Fig. 5. It resembles apparatus No. 2, but has a different arrangement of thermo-elements and an improved heating coil. The thermo-elements are so arranged that the difference between the hot and cold faces can be directly observed with greater accuracy than is possible by measuring the hot and cold face temperatures independently and taking the difference. A diagram of the connections is given in Fig. 6.

(*c*) *Contact resistance between electrode and specimen.*

One fact that became evident at the outset was that the surfaces of the specimens were not perfectly flat, and consequently when tested in an apparatus between perfectly flat metallic plates there was a certain resistance to the heat flow, due to air films at the contact faces.

While it would be possible to eliminate this resistance by amalgamating the metal surfaces, it was deemed advisable to carry out a series of experiments with the material clamped between plain metal plates, since in practice it will be necessary to take account of the surface resistance in any calculations in connection with the design of electrical machinery. A material which has a low resistivity, but whose surfaces are irregular and of an unyielding nature, may not be as useful as one of higher resistivity but with flatter surfaces, for it may happen that in certain thicknesses the total resistance to the heat flow will be higher with the former material than with the latter. Although it is advisable to endeavour to ascertain for each material its true thermal resistivity, some information is necessary on its contact resistance when clamped between two flat metallic plates under definite pressure.

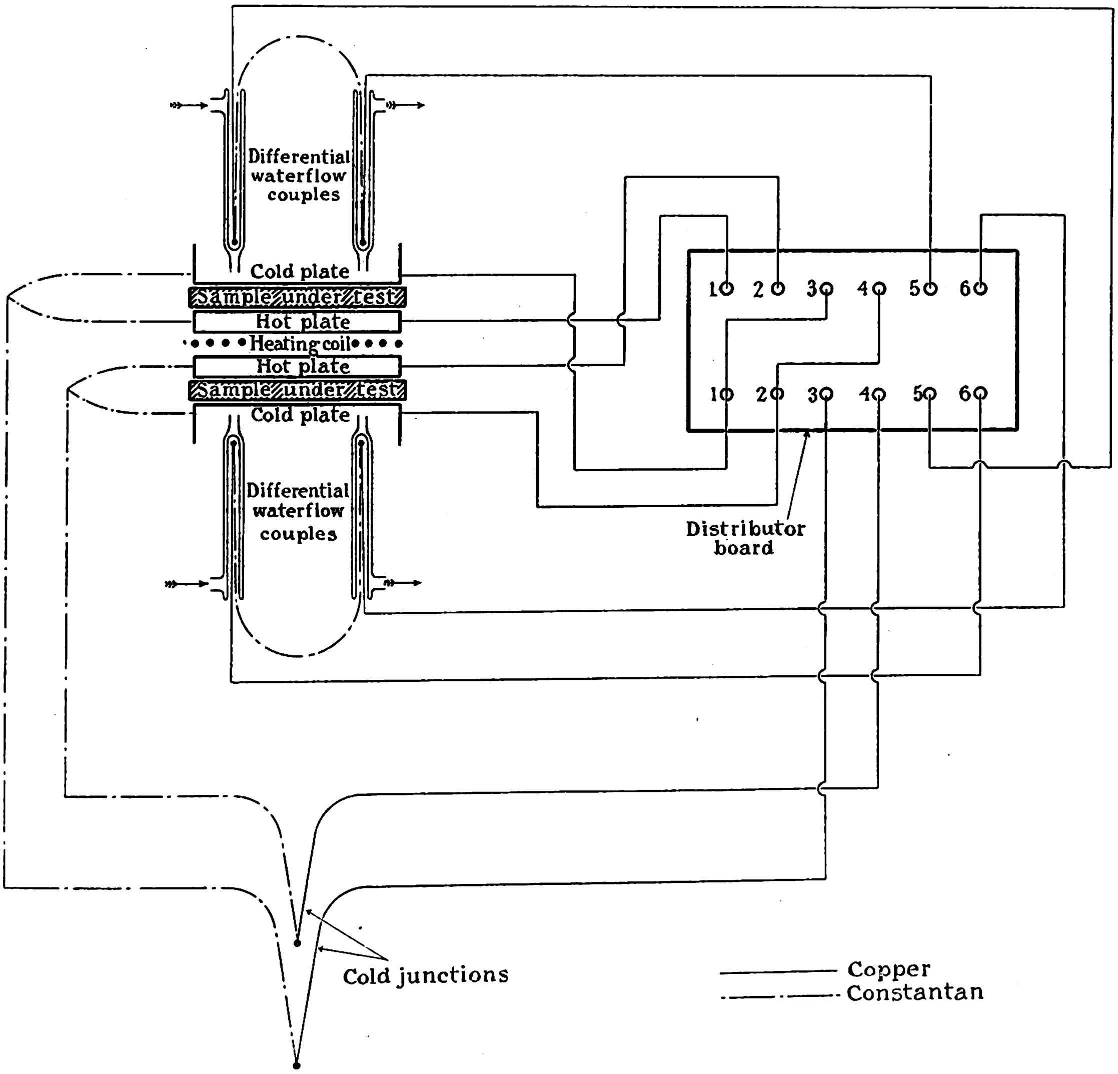


FIG. 6.—Diagram of the connections of Apparatus No. 5.

Another factor which has to be taken into consideration is the variation of the conductivity and the compressibility of the material under load.

In the earlier tests attempts were made to use electrodes of comparatively large area. During some tests with amalgamated copper electrodes measuring 4 in. × 4 in. the following results were obtained:—

The sample of dielectric consisted of two sheets of mica each 0·7 mm in thickness. When the apparatus was set up in the usual manner with a hot plate sandwiched between the two mica slabs it was found that the resistivity K for a pressure of 3·75 lb. per sq. in. was 273, and when the pressure was increased to 75 lb. per sq. in. the resistivity fell to 228.

Measurements of the thickness of the samples at definite points show that they were not absolutely uniform, so it appeared that the amalgamated surfaces were not capable of eliminating the effect of variations in thickness of a sample measuring 16 sq. in. in area. As the result of this experiment much smaller areas were used, and apparatus No. 3 was constructed where the surfaces of contact were only 1·65 sq. in. in area. Messrs. Wiggins & Son very kindly supplied a series of mica samples 1½ in. in diameter and about 1/100th of an inch in thickness, which were uniform in thickness to 1/10 000th of an inch. The results obtained with these micas are quoted in Table 1. Some of the materials tested in apparatus Nos. 1 and 2 were also tested in No. 3. The difference in the results due to the reduction of contact resistance by the mercury was very marked, notably in the case of micafolium (see Table 2).

Some tests were made to ascertain whether the amount

TABLE 1.

True Thermal Resistivity of Mica Determined with Apparatus No. 3. Thickness, 0·254 Millimetre. Pressure, 120 lb. per Square Inch.

Description of mica	Mean temperature, ° C.	Thermal resistivity K
No. 17: Brazilian Muscovite, ruby mica	50	185
No. 6	51	188
No. 7: Indian Muscovite, clear green	48	177
No. 5: Indian Muscovite, stained green	48	182
No. 10: Indian Muscovite, stained ruby	50	180
No. 9: Indian Muscovite, clear green	54	176
No. 8: Indian Muscovite, clear green	50	173
No. 12: Indian Muscovite (altered), white mica	53	184
No. 15: Canadian Phlogopite (amber)	55	216
	54	210
No. 14: Indian Muscovite, clear ruby	63	177
	72	174

TABLE 2.

Comparison of Results with Plain and Amalgamated Surfaces.

Materials	Thickness, in cm	Apparent thermal resistivity					
		Mean temperature, ° C.	Thermal resistivity K. Plain surfaces	Mean temperature, ° C.	Thermal resistivity K. Fully amalgamated surfaces	Mean temperature, ° C.	Thermal resistivity K. Amalgamated surfaces wiped free of excess mercury
Micafolium, L. 132	0·014	71	936	48	360	51	568
1/32-in. amber micanite, L. 125	0·085	42	594	57	358	56	407
						118	276
Mica-cambric, L. 142	0·0265	50	1 120	61	590	—	—
1/32-in. pressboard, L. 139	0·087	65	534	—	—	76	452
20-mil pressboard, L. 135	0·051	67	556	—	—	66	485
1-mil jap tissue, L. 143	0·002	57	3 000	—	—	43	2 670
7-mil yellow varnished cloth, L. 105 ..	0·019	58	638	—	—	52	575
Varnished silk, L. 120, 7 per cent silk ..	0·012	52	704	—	—	51	577
Varnished silk, L. 119, 9 per cent silk ..	0·0166	60	714	—	—	50	565
Untreated silk, L. 146	0·005	36	2 270	—	—	48	1 680

TABLE 3.

Comparison of Results Obtained with Nos. 1 and 4 (the Surfaces of both Nos. 1 and 4 Apparatus were Amalgamated). Pressure, 21 lb. per Square Inch.

Material	Apparatus No. 1		Apparatus No. 4	
	Mean temperature, ° C.	Resistivity K	Mean temperature, ° C.	Resistivity K
Treated silk, L. 119	37·6	516	30·0	494
	83·7	494	33·0	500
	52·0	502	—	—
Pressboard, L. 135	65·0	490	38·0	512
	46·0	503	40·0	499

of excess mercury used on the surfaces had an appreciable influence on the results.

The material employed in this investigation was a paper board 0·5 mm in thickness. In the first test the amalgamated copper surfaces were flooded with mercury, test sample inserted, and more mercury added to form two large flattened drops of mercury.

When the surface had been lowered into contact the excess mercury around the edges was removed. In the second test no special care was taken to flood the surfaces; a few drops were placed on both copper surfaces. The experiments were repeated several times, but no measurable difference in the conductivity was observed.

A small correction was always applied for the thermal resistance of the mercury film. This was determined by blank experiments, using a thin sheet of steel instead of the specimen.

(*d*) *Comparison of results obtained with two different forms of apparatus.*

It is of interest to compare data obtained on two forms of apparatus differing very considerably in details of construction, but both employing amalgamated surfaces. An inspection of the data in Table 3 will show the order of the agreement obtained.

When data obtained with and without amalgamation of the surfaces are compared, it is found that good agreement is obtained if the samples are of a slightly compressible nature and tested in thicknesses of the order of 1 to 2 mm.

This is illustrated by the data given in Table 4 obtained with apparatus Nos. 4 and 5 for pressboard, glazed and unglazed.

TABLE 4.

Comparison of Results Obtained with No. 4 Apparatus (Amalgamated) and No. 5 Apparatus (Unamalgamated).

Material	Number of layers	Apparatus No. 4		Apparatus No. 5	
		Mean temperature, ° C.	Resistivity *K*	Mean temperature, ° C.	Resistivity *K*
Unglazed pressboard, L. 149	1	30·9	598	27·3	577
Glazed pressboard, L. 152	1	24·1	570	23·6	576
		50·3	560	55·0	563

TABLE 5.

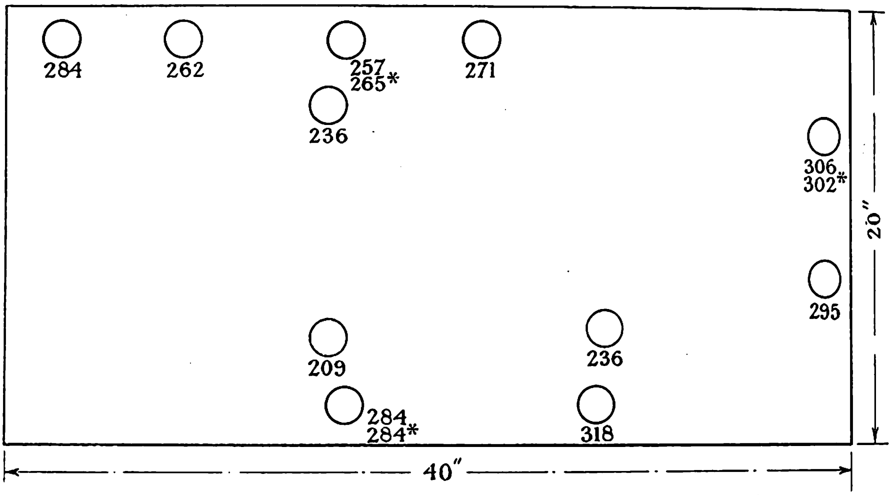
Comparison of Results Obtained with No. 4 Apparatus (Amalgamated) and No. 5 Apparatus (Unamalgamated).

Material	Number of layers	Apparatus No. 4		Apparatus No. 5	
		Mean temperature, ° C.	Resistivity *K*	Mean temperature, ° C.	Resistivity *K*
Treated silk, L. 162	1	21·0	580	21·0	702
	3	21·0	566	21·0	607
	5	21·0	520	21·0	602
	8	21·0	501	21·0	557
Micafolium	1	22·5	570	—	—
		37·5	516	—	—
		49·2	482	—	—
	10*	21·0	534	24·8	763
		32·5	521	33·8	726
		46·5	505	50·9	670

* These were superimposed layers heated and compressed.

In the case of very thin samples of the order of 0·09 to 0·15 mm (3 to 6 mils), it is questionable whether the true thermal conductivity of the material can be measured accurately by either type of apparatus. Even when the sample is pressed between amalgamated plates it is improbable that perfect thermal contact is effected over the entire area; and as the resistivity of the thin layer of material is small, the residual contact-resistance may be of appreciable magnitude in comparison with the true resistance of the material.

There is indirect evidence to support this view, since



*Denotes repeat reading

FIG. 7.—Variation of thermal resistivity over the area of specimen.

the conductivity of superimposed thin layers increases with the number of layers tested. Reference might be made to Fig. 13, where the results of such experiments are shown graphically.

In the case of hard materials with irregular surfaces the difference between the results obtained with amalgamated and unamalgamated surfaces is considerable, and there is no doubt that the junction from the plain metal surface to the specimen offers appreciable resistance to the heat flow. This is illustrated by the data in Table 5, obtained for a solid block made of ten superimposed layers of micafolium heated and pressed to form a hard sheet.

Thus the general conclusion was that the most satisfactory procedure was to prepare samples from 1 to 2 mm in thickness and test between amalgamated plates. When the material was of such a nature that specimens of this thickness could not be prepared, the test was carried out with unamalgamated plates in apparatus of the type illustrated in Fig. 5.

(*e*) *Variation of the resistivity from point to point over the area of a sheet.*

A sheet of micanite 20 in. by 40 in. was tested at various points of its surface by means of the apparatus illustrated in Fig. 4.

The positions for the test were selected as those showing the widest variation in opacity when the sheet was examined by transmitted light.

The results obtained are shown diagrammatically in Fig. 7.

It will be seen that the variations from point to point in certain areas are very considerable, which is not surprising, taking into consideration the structure of the material.

(*f*) *Measurement of the thickness of the specimens.*

In order to obtain the thickness of the specimens under different loads the apparatus shown in Fig. 8 was constructed.

It consists of a micrometer head clamped to the vertical pillar. The specimen is laid on the table with a disc of steel resting on top of it. The surfaces both of the table and the steel disc are ground accurately

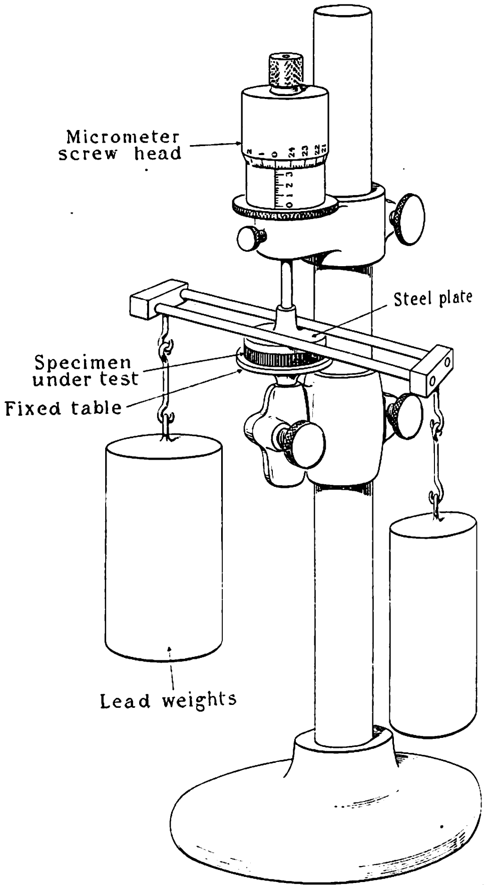


FIG. 8.—Apparatus for measuring decrease of thickness under pressure.

plane. Pressure can be applied by the arrangement of weights shown in the diagram.

The effect of a gradually increasing pressure on the samples for the first time was to produce a permanent deformation, after which loading and unloading gave a reproducible curve (see Fig. 9 and Table 6).

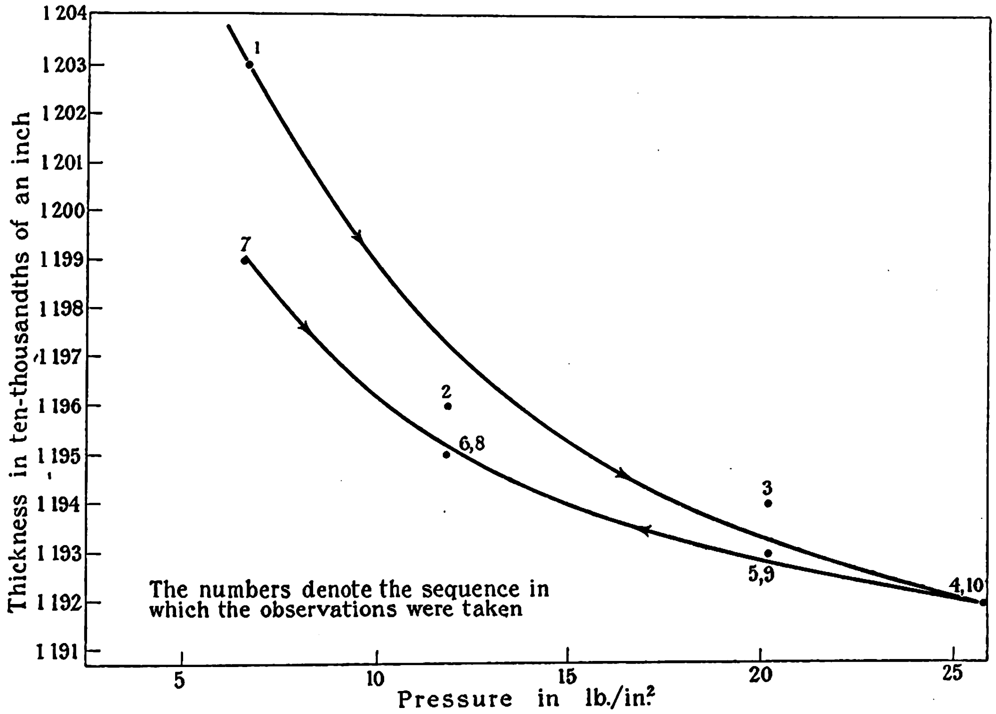


FIG. 9.—Curves showing effect of pressure upon thickness of specimen.

TABLE 6.

Compression Test. Material Tested: Unglazed Grey Pressboard, L. 149.

Pressure, lb. per sq. in.	Thickness in inches	Pressure, lb. per sq. in.	Thickness in inches
6·6	0·1203	11·8	0·1193
11·8	0·1196	6·6	0·1199
20·2	0·1194	11·8	0·1195
25·8	0·1192	20·2	0·1193
20·2	0·1193	25·8	0·1192

(*g*) *Effect of pressure on the thermal conductivity.*

A sample of unglazed grey pressboard was tested under various loads between 8 and 23 lb. per sq. in. The material was of a compressible nature, as the data in Fig. 9 show.

In calculating the resistivity, the appropriate thickness corresponding to each load was taken from Table 6. The results show that there is a small decrease in the thermal resistivity with pressure (see Fig. 10 and Table 7).

(*h*) *Tests on samples taken from sheets of different thickness, but nominally of the same composition.*

A series of samples of glazed and unglazed grey pressboard, varying in thickness from 1/32 in. to ⅛ in., also varnished silk in thicknesses from 3 mil to 6 mil were supplied. The data are summarized in Table 8.

In the case of the unglazed pressboard there appears to be a very slight decrease of resistivity with thickness (see Fig. 11).

The results obtained with the three thicknesses of glazed pressboard are abnormal; the sample taken from L. 152 (⅛ in. in thickness) gives a result 20 per cent less than those obtained for materials labelled L. 150 and L. 151 (1/32 in. and $\frac{1}{16}$ in. respectively). So it appears that the three sheets are not identical in physical properties.*

Sample L. 152 was tested in two different forms of apparatus, amalgamated and unamalgamated, with identical results.

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* These were supplied as being the same grade of material and from their colour and surface appeared similar. The cause of the anomalous results was traced to the following difference in density:—

1/32 in. .. 1·27; 1/16 in. .. 1·22; ⅛ in. .. 1·08

The low density of the ⅛-in. sample explains the low conductivity. The makers stated that a finer pulp was used in the manufacture of the 1/32-in. and 1/16-in. sheets than for the ⅛-in. material. The same material was used in all three, but the method of manufacture was different.

The four samples of treated silk show a very slight decrease of resistivity with thickness (see Fig. 12), but the change is probably well within the limits of possible variation in the physical properties of the samples, even if prepared from the same raw materials.

(*j*) *Resistivity of a number of superimposed layers of thin material.*

Two samples of treated silk, L. 119 and L. 162, were tested in single and superimposed layers. All the measurements were made at a mean temperature of 21° C.

It will be observed from an inspection of Fig. 13 that the apparent resistivity decreases with increasing number of layers, but probably tends asymptotically to a constant value.

When a number of thicknesses of the treated silk are superimposed the layers tend to bed into each other, and thus effect good contact at the interfaces, so that the decrease in resistivity with increasing thickness of the test sample may be due to the contact resistance at the metal-specimen surfaces becoming relatively less important in comparison with the total resistance of the sample. That there is appreciable contact resistance at the contact surfaces is shown by the difference between the unamalgamated- and amalgamated-surface curves in Fig. 13.

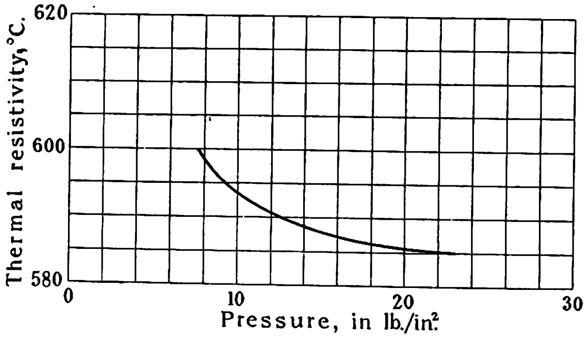

FIG. 10.—Curve showing influence of pressure upon thermal resistivity of unglazed pressboard.

It is thus seen that with a material like treated silk, even when tested between well-amalgamated plates, it is not possible to effect perfect thermal contact.

TABLE 7.

Effect of Pressure on the Thermal Resistivity. Apparatus No. 5 (Unamalgamated Surfaces).

Material	Pressure, lb. per sq. in.	Mean temperature, ° C.	Thickness of sample, in.	Thermal resistivity K
Unglazed grey pressboard, L. 149, $\frac{1}{8}$ in.	23·0	25·2	0·1192	588
	17·7	25·4	0·1193	584
	10·8	25·7	0·1195	587
	7·7	26·0	0·1198	600
	10·8	26·3	0·1195	597
	17·7	26·3	0·1193	588
	23·0	26·4	0·1192	583

(*k*) *Effect of temperature and pressure on the thermal resistivity of two samples of varnished cloth.*

NOTE.—The object of the investigation described below was to determine, under certain conditions, the effect of temperature and pressure on the transmission of heat through two sheets of varnished cloth, which were labelled L. 600 and L. 601 respectively. This did not form part of the main investigation, but was carried out at the N.P.L. at a later date.

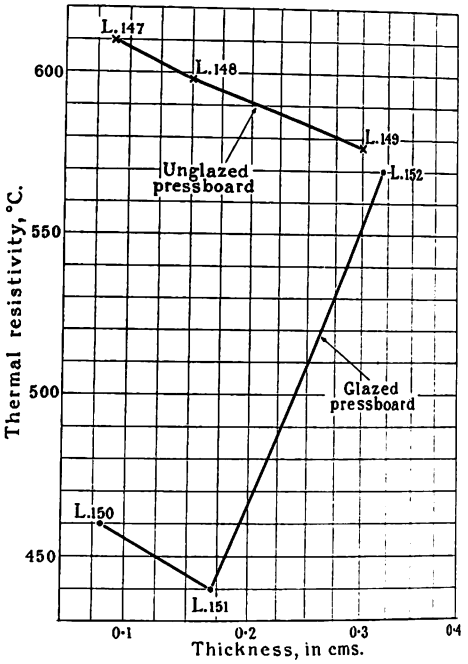

FIG. 11.—Variation of thermal resistivity with thickness of specimen (pressboard).

Method of experiment.

The method employed was identical in principle with that adopted in the main investigation into the resistivity of dielectrics, which forms the subject of this

TABLE 8.

Single Layers of Various Thickness. Apparatus Nos. 4 and 5. Pressure, 21 lb. per Square Inch.

The thick samples were tested in Apparatus No. 5, and the thin ones in No. 4. Table 4 on page 1320 shows that, subject to the reservations made in clause (*d*) (pages 1311 and 1312), test results obtained on the two forms of apparatus are comparable.

Material	Apparatus No.	Thickness, in cm.	Mean temperature, ° C.	Thermal resistivity K
Unglazed grey pressboard L. 147, 1/32 in.	4	0·084	31·8	614
			36·5	604
			50·2	611
			60·3	611
			49·6	607
			30·7	618
L. 148, 1/16 in.	4	0·150	30·9	598
			38·3	600
			63·5	582
			50·1	588
			35·0	592
			31·4	591
L. 149, $\frac{1}{8}$ in.	5	0·303	19·3	585
			27·3	577
			35·6	577
			58·9	561
			47·9	570
Glazed brown pressboard, L. 150, 1/32 in.	4	0·082	25·2	468
			30·6	459
			54·7	446
			58·7	451
			50·8	456
Glazed brown pressboard, L. 151, 1/16 in.	4	0·169	32·8	457
			43·0	442
			51·4	412
			64·6	423
			44·6	434
			34·2	446
Glazed brown pressboard, L. 152, $\frac{1}{8}$ in.	5	0·322	20·0	576
			23·6	576
			39·6	562
			55·0	563
			30·0	591
	4	0·149	24·1	570
			50·3	560
Treated silk	4	0·015	29·8	548
L. 162 *		0·015	29·8	548
L. 163 †		0·012	30·0	552
L. 164 †		0·012	31·7	578
L. 165 †		0·0091	32·5	580

* Made from 6 Momme silk.

† Made from 3 Momme silk.

TABLE 9. APPARATUS No. 1.

Apparent Thermal Resistivity Results. Pressure, 24·8 lb. per Square Inch.

Material	Thickness, in cm	Temperature, in degrees Centigrade			Thermal resistivity *K*
		Hot face	Cold face	Mean	
Cotton, L. 140, 5-mil untreated cambric	0·015	126	25	75	1 130
		116	28	72	1 230
		68	17	43	1 330
		33	13	23	1 430
		30	12	21	1 270*
Silk, L. 146, 2-mil untreated jap silk	0·005	123	37	80	2 020
		93	30	61	2 100
		53	19	36	2 270
		29	13	21	2 450
		26	13	20	2 230*
Treated silk, L. 119, varnished silk containing 7 per cent of silk	0·0166	128	32	80	694
		94	25	60	714
		51	16	34	723
		26	11	18	721
		27	13	20	638*
Treated silk, L. 120, varnished silk containing 9 per cent of silk	0·012	119	38	78	697
		76	26	51	704
		46	18	32	732
		23	12	18	778
		21	12	17	629*
Treated cotton, L. 105, 7-mil yellow varnished cloth	0·019	97	23	60	638
		75	19	47	626
		65	16	40	697
		39	12	25	746
		20	9	14	812*
Micanite, L. 125, 1/32-in. amber micanite ..	0·085	224	22	123	583
		159	18	89	590
		71	12	41	594
		34	10	22	613
		41	10	25	611
		41	11	26	617*
Paper, L. 141, sulphite kraft paper	0·004	124	36	80	1 990
		93	28	60	2 190
		53	19	36	2 300
		32	14	23	2 390
		31	14	23	2 450*
Paper board, L. 135, 20-mil pressboard	0·051	124	23	73	557
		113	22	67	556
		89	19	54	557
		39	12	26	601
		49	14	32	681*
Mica paper, L. 132, micafolium	0·014	171	42	107	719
		115	27	71	936
		41	12	27	816
		29	13	21	773*

* Denotes repeat readings.

TABLE 9. APPARATUS NO. 1—*Continued.*

Apparent Thermal Resistivity Results. Pressure, 24·8 *lb. per Square Inch.*

Material	Thickness, in cm	Temperature, in degrees Centigrade			Thermal resistivity K
		Hot face	Cold face	Mean	
Mica cloth, L. 142	0·0265	193	31	112	768
		124	21	72	891
		85	16	50	1 120
		47	13	30	1 460
Mica paper, L. 144	0·009	194	54	124	940
		120	32	76	1 170
		80	22	51	1 420
		29	11	20	2 560
		26	13	20	1 520*
Mica silk, L. 145	0·022	197	29	113	927
		150	24	87	1 030
		96	17	56	1 290
		52	12	32	1 490
		40	11	25	1 860
		33	11	22	1 320*
Paper, L. 143, 1-mil jap tissue	0·002	108	43	75	2 980
		82	33	57	3 000
		52	21	37	3 320
		28	14	21	3 530
		23	13	18	2 900*

* Denotes repeat readings.

TABLE 10. APPARATUS NO. 2.

Apparent Thermal Resistivity Results. Pressure, 23·55 *lb. per Square Inch.*

Material	Thickness, in cm	Temperature, in degrees Centigrade			Thermal resistivity K
		Hot face	Cold face	Mean	
Fibre, L. 130, from Firm A	0·375	125	15	70	276
		97	14	56	296
		70	12	41	293
		35	11	23	326*
Fibre, L. 114, from Firm B	0·340	128	15	72	349
		99	13	56	349
		36	11	24	351
		39	11	25	354*
Fibre, L. 128, from Firm A	0·16	146	20	83	332
		123	19	71	346
		106	16	61	364
		81	15	48	388
		31	12	21	430
		23	10	16	450*

* Denotes repeat readings.

TABLE 10. APPARATUS No. 2—*Continued.*

Apparent Thermal Resistivity Results. Pressure, 23·55 *lb. per Square Inch.*

Material	Thickness, in cm	Temperature, in degrees Centigrade			Thermal resistivity K
		Hot face	Cold face	Mean	
Varnished paper board, L. 122, from Firm D ..	0·320	124	15	70	320
		100	14	57	326
		81	13	47	319
		31	11	21	323
		28	11	19	337*
Varnished paper board, L. 121, from Firm C ..	0·286	126	15	71	351
		104	14	59	365
		80	13	46	362
		33	11	22	397*
$\frac{1}{8}$-in. pressboard, L. 133, 90 per cent jute and hemp, hard pressed, Grade I	0·266	121	13	67	356
		103	13	58	365
		61	11	36	350
		31	10	20	351
		24	9	17	318*
$\frac{1}{8}$-in. pressboard, L. 134, 66 per cent jute and hemp, 34 per cent cotton	0·335	126	12	69	471
		101	12	56	457
		74	11	42	473
		41	10	25	422*
Fibre, L. 117, from Firm E	0·313	126	13	70	473
		88	12	50	446
		34	11	22	462
		89	12	51	480*
$\frac{1}{8}$-in. pressboard, L. 138, 66 per cent jute and hemp, 34 per cent cotton, soft pressed	0·335	123	11	67	570
		95	10	52	640
		63	9	36	546
		33	9	21	418
		59	10	34	583*
1/16-in. pressboard, L. 137, 90 per cent cotton, soft pressed	0·168	122	15	68	615
		93	13	53	606
		48	10	29	633
		29	10	19	670
		62	12	37	631*
$\frac{1}{8}$-in. pressboard, L. 136, 90 per cent cotton ..	0·342	120	12	66	633
		52	10	31	655
		36	10	23	673
		76	11	44	625*
1/32-in. pressboard, L. 139, Continental manufacture	0·087	117	13	65	534
		89	17	53	531
		51	14	32	552
		26	11	19	545
		59	13	36	529*
		49	13	31	583*

* Denotes repeat readings.

TABLE 11.

True Thermal Resistivity Obtained on Single Thicknesses with No. 4 Apparatus (Amalgamated Surfaces). Pressure, 21 lb. per Square Inch.

Material	Thickness, in cm, of sample tested	Mean temperature, ° C.	Thermal resistivity *K*	Material	Thickness, in cm, of sample tested	Mean temperature, ° C.	Thermal resistivity *K*
Red fibre, L. 154, ¼ in. ..	0·176	25·0	269	White fibre, L. 109, ⅛ in.	0·146	24·1	382
		38·0	271			29·6	373
		44·7	268			47·4	367
		63·0	266			57·0	369
		45·0	274*			45·3	373*
		31·2	273*			40·0	379*
Red fibre, L. 155, ½ in. ..	0·214	27·6	285	Light grey fibre, L. 113, ⅛ in.	0·141	25·0	356
		39·2	279			29·8	353
		50·0	279			46·2	355
		63·2	278*			59·4	341
		48·3	284*			45·6	349*
						31·6	359*
Red fibre, L. 156, ¾ in. ..	0·169	26·3	448				
		38·3	452	Red fibre, L. 115, ⅛ in. ..	0·133	46·9	307
		55·5	434			32·0	311
		67·0	434			22·0	312
		58·8	442*			26·4	317*
		45·3	442*				
Red fibre, L. 157, 1⅛ in. ..	0·153	31·0	433	Red fibre, L. 129, ⅛ in. ..	0·104	48·5	279
		50·6	435			27·9	286
		53·6	440			21·1	290
		64·9	432			20·9	289*
		44·2	451*				
		36·5	448*	Red fibre, L. 107, ⅛ in.	0·113	44·5	452
						33·3	460
Black fibre, L. 158, 1 in. ..	0·221	31·7	427			21·6	458
		46·7	417			23·4	452*
		49·4	417				
		70·2	422	Black fibre, L. 112, ⅛ in.	0·124	36·7	313
		52·6	432*			28·0	313
		32·8	455*			19·6	312
						47·2	306
Red fibre, L. 131	0·282	30·4	302			28·3	325*
		39·1	296				
		58·5	295	Grey fibre, L. 108, ⅛ in.	0·087	50·4	351
		62·3	294			36·7	357
		50·6	298*			31·5	356
		33·6	298*			24·6	359*
						31·0	354
Red fibre, L. 111, ⅛ in. ..	0·191	24·8	370				
		31·3	363	Grey fibre, L. 118, ⅛ in. ..	0·171	44·9	249
		49·7	356			36·9	247
		67·9	353			25·7	250
		40·0	361*			28·7	258*
Grey fibre, L. 110, ⅛ in. ..	0·113	22·5	285	Whalebone, L. 116, ⅛ in.	0·124	27·1	228
		28·6	288			31·6	240
		47·5	276			46·3	236
		61·9	278			60·2	233
		40·1	288*			41·8	240*
		28·4	300*			36·9	232*

* Denotes repeat readings.

TABLE 11.—*Continued.*

True Thermal Resistivity Obtained on Single Thicknesses with No. 4 Apparatus (Amalgamated Surfaces). Pressure, 21 lb. per Square Inch.

Material	Thickness, in cm, of sample tested	Mean temperature, ° C.	Thermal resistivity *K*
Unglazed grey pressboard, L. 147, 1/32 in.	0·084	31·8	614
		36·5	604
		50·2	611
		60·3	611
		49·6	607*
		30·7	618*
Unglazed grey pressboard, L. 148, 1/16 in.	0·150	30·9	598
		38·3	600
		63·5	582
		50·1	588
		35·0	592*
		31·4	591*
Glazed brown pressboard, L. 150, 1/32 in.	0·082	25·2	468
		30·6	459
		54·7	446
		58·7	451
		50·8	456*
Glazed brown pressboard, L. 151, 1/16 in.	0·169	32·8	457
		43·0	442
		51·4	412
		64·6	423
		44·6	434*
		34·2	446*
Unglazed dark brown pressboard, L. 159, 1/32 in.	0·106	24·3	312
		38·1	297
		55·8	299
		65·6	299
		43·0	306*
		32·0	306*
Unglazed dark brown pressboard, L. 160, 1/16 in.	0·200	27·9	301
		43·6	301
		52·5	296
		62·2	302
		44·7	316*
		31·6	275*
Commutator micanite, L. 126	0·078	45·7	219
		29·8	262
		19·5	267
		26·5	247*
Flexible micanite, L. 127	0·023	40·2	382
		27·9	445
		21·3	507
Ebonite, 9471	0·145	37·0	632
		28·6	627
		34·4	622
Ebonite, 9471	0·145	44·9	617
		37·8	638*
		26·6	628*
Ebonite, 9472	0·148	21·5	626
		28·1	628
		35·4	616
		45·7	624
		35·0	638*
		27·2	662*
Ebonite, 9473	0·134	24·9	549
		29·5	547
		34·9	543
		42·5	550
		29·7	555*
		26·9	570*
Ebonite, 9474	0·128	20·3	544
		29·4	541
		34·0	572
		43·2	542
		28·4	564*
		24·1	537*
Varnished paper board, L. 123, ⅛ in.	0·149	21·1	373
		33·8	374
		47·5	378
		22·6	373*
Treated cotton, L. 105 ..	0·0194	30·0	348
		40·5	344
		51·6	350
		74·0	326
		34·0	352*
Unglazed grey pressboard, L. 149, ⅛ in.	0·303	19·3	585
		27·3	577
		35·6	577
		58·9	561
		47·9	570*
Glazed brown pressboard, L. 152, ⅛ in.	0·322	20·0	576
		23·6	576
		39·6	562
		55·0	563
		30·0	591
Unglazed dark brown pressboard, L. 161, ⅛ in.	0·334	26·1	378
		28·5	375
		53·0	370
		18·3	364

* Denotes repeat readings.

report. Six discs of each material were cut, and arranged so that three were piled on each side of an electrically-heated plate of the same area as the samples. The whole was then clamped between two cold plates maintained at the same temperature. A measurement of the energy input into the hot plate and of the temperature-difference between the hot and cold plates, subject to a small correction for the lateral escape of heat, served to give the thermal resistivity.

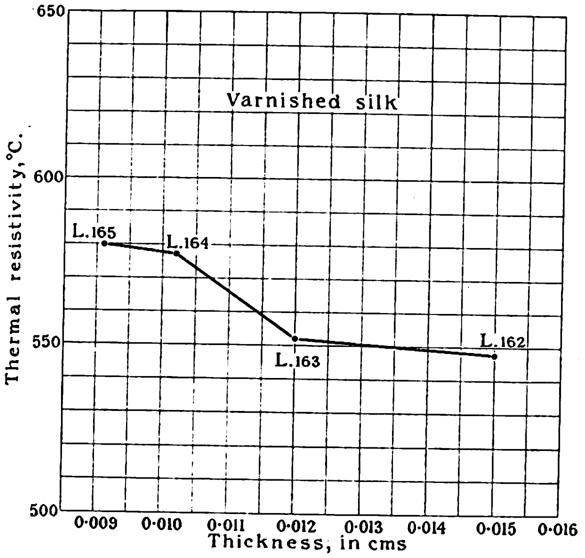

FIG. 12.—Variation of thermal resistivity with thickness of specimen (varnished silk).

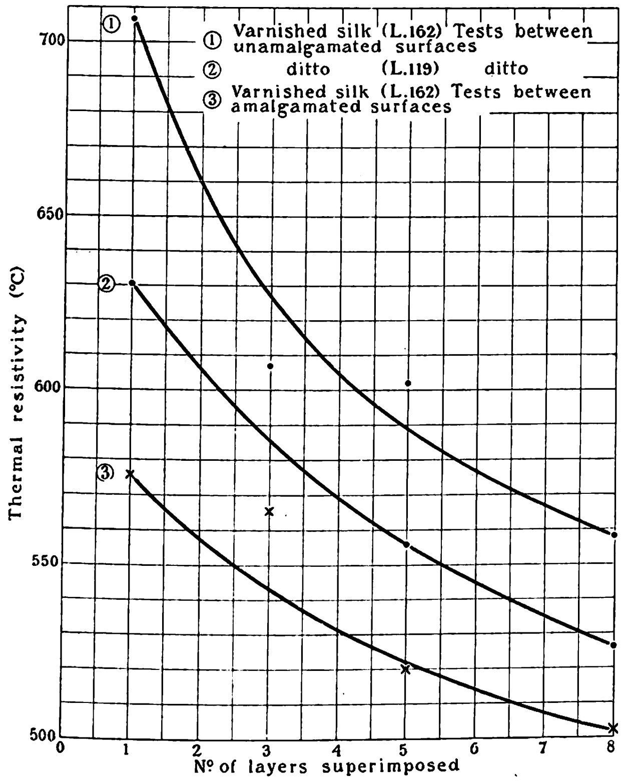

FIG. 13.—Curves showing decrease of thermal resistivity with number of layers of laminated material.

The hot plate consisted of a flat heating coil insulated with mica and clamped between brass discs.

The following procedure was adopted for the test on each specimen:—

The resistivity was measured at a series of increasing pressures for a mean temperature of 20° C.

When the maximum load had been reached the resistivity was measured at various mean temperatures up to 90° C. The resistivity was finally re-determined at a mean temperature of 20° C. An indication was thus obtained of the effect of high temperatures on the thermal resistivity.

Results of Experiments.

The results of the experiments are set out in Tables 12 to 15.

TABLE 12.

Variation of Thermal Resistivity with Pressure. Varnished Cloth: Sheet labelled L. 600. At a mean Temperature of 20° C.

Pressure, in lb. per sq. in.	Thermal conductivity (k) in gramme calories per cm^2 per sec., for 1 cm thickness and 1 deg. C. difference of temperature between faces	Thermal resistivity K
0·15	0·00028	855
3	0·00036	665
10	0·00041	585

TABLE 13.

Variation of Thermal Resistivity with Temperature. Varnished Cloth: Sheet labelled L. 600. Tested under a Pressure of 10 lb. per Square Inch.

Mean temperature °C	Thermal conductivity (k) in C.G.S. units	Thermal resistivity K
20	0·00041	585
50	0·00045	530
90	0·000495	485
20	0·000495	485

TABLE 14.

Variation of Resistivity with Pressure. Varnished Cloth: Sheet labelled L. 601. At a Mean Temperature of 20° C.

Pressure, in lb. per sq. in.	Thermal conductivity (k) in C.G.S. units	Thermal resistivity K
0·15	0·00040	600
3	0·00043	555
10	0·00046	520

TABLE 15.

Variation of Thermal Resistivity with Temperature. Varnished Cloth: Sheet labelled L. 601. Tested under a Pressure of 10 lb. per Square Inch.

Mean temperature °C	Thermal conductivity (k) in C.G.S. units	Thermal resistivity K
20	0·00046	520
50	0·00049	490
90	0·000535	445
20	0·000535	445

It will be observed that the effect of pressure on the resistivity is less pronounced in the case of L. 601 than in the case of L. 600. This may be related to the fact that the surface of L. 600 is rougher than that of L. 601.

The resistivity is permanently reduced after exposure to a temperature of 90° C., and the repeat value at lower temperatures is in close agreement with that found at the highest temperature. This was confirmed in an independent test when another specimen of the material was heated to a maximum temperature of 75° C., the subsequent determination at 20° C. agreeing with the value obtained at 75° C.

(*l*) *Shape of the test specimen.*

Another factor studied was the shape of the test specimen. It was not always convenient to cut the specimen in the form of circular discs of the exact diameter of the copper rods, so larger-size specimens of rectangular shape were generally used. A test was made with one of these large specimens, and the experiment repeated after the specimen had been cut down to a circular disc of the exact diameter of the copper rods. The differences in the values obtained for the resistivities were quite negligible, being well within the limits of the experimental error. Hence the practice of using reasonably large-size plates is legitimate.

(*m*) *Results obtained during the main series of tests on materials studied in sheet form.*

The results of the preliminary tests are recorded in Tables 1, 9, and 10. It must be remembered, however, that these results are not strictly comparable, as those recorded in Tables 9 and 10 are "apparent" resistivities, contact resistance being included. The data in Table 1 are "true" resistivities obtained by experiments in which the contact faces were amalgamated. The small size of the mica specimens, 1½ in. in diameter, prevented tests being made in apparatus Nos. 1 and 2, which require specimens at least 1¾ in. in diameter.

Table 11 summarizes the data obtained during the determination of the true thermal resistivities of the materials included in the investigation.

It will be observed that each class comprises substances differing very considerably in thermal resistivity. The sixteen samples of fibre range in resistivity from 478 to 266.

The sample of whalebone gave the lowest resistivity of all the materials studied, the value being about 10 per cent lower than that for the best fibre.

The five samples of treated silk have a high apparent resistivity which may be in part due to residual contact resistance.

Part II.

A STUDY OF THE THERMAL RESISTIVITY OF SOLID DIELECTRICS WHEN APPLIED ON TO BARS BY THE USUAL SHOP PROCESSES OF WRAPPING.

(*a*) *General.*

The preceding section of the report has been concerned with the thermal resistivity of a number of materials tested between flat plates. Frequently it is not possible to apply the results directly to the conditions under which the materials are used in electrical machinery and apparatus, owing to factors which may complicate the estimation of heat flow. Examples of such factors are the shape of the body to be insulated, the effects of air-gaps and slots, and the conditions of fixing or winding the insulating medium. Consequently it was considered desirable to investigate the thermal resistivity of selected materials after they had been applied by the usual shop processes to conductors of such shape and dimensions as are employed in practice.

This investigation was confined to the materials and processes used particularly for the insulation of the slot portions of machine windings, such as turbo-alternator stators,* as the heat flow through the insulation of these parts is a matter of considerable importance in the design of such windings.

Preliminary experiments were made with bars of rectangular and circular sections insulated with micafolium (not pressed), using an apparatus employing air cooling, the insulation on the bars not being supported.

For the main investigation, however, bars insulated with micafolium and mica tape were tested by two different methods: one similar to that used in the preliminary tests, and the other designed to simulate as closely as possible the conditions existing in the slot of a machine. In the latter case the bar was held between water-cooled clamping plates, so that the insulation was prevented from swelling when heated. Tests were also made by this method, using different clamping pressures applied to the water-cooled plates, to determine the effect of variations in these pressures on the thermal resistivity of the insulations.

The insulation on the bars was applied by the usual shop processes, e.g. wrapping, hot pressing, etc., and some of the bars were tested before and after an artificial "ageing" at a temperature of 100° C., to determine the effect of this treatment on the thermal resistivity values.

(*b*) *Preliminary tests on bars of various section insulated with micafolium.*

The first case taken was that of a rectangular bar insulated with a wrapping of micafolium. Imitation stator bars were constructed; one, by joining together, face to face, two flat bars of copper in which longitudinal grooves had been milled, the other, built up of flat strips into a box form. The hollow bars thus formed were slightly rounded along the edges, in accordance with the usual practice, and were wrapped with micafolium to a thickness of 0·2 cm.

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* Further investigations are in hand on the thermal resistivity of insulation on bars representing the materials and methods used on "end-windings" of machines.

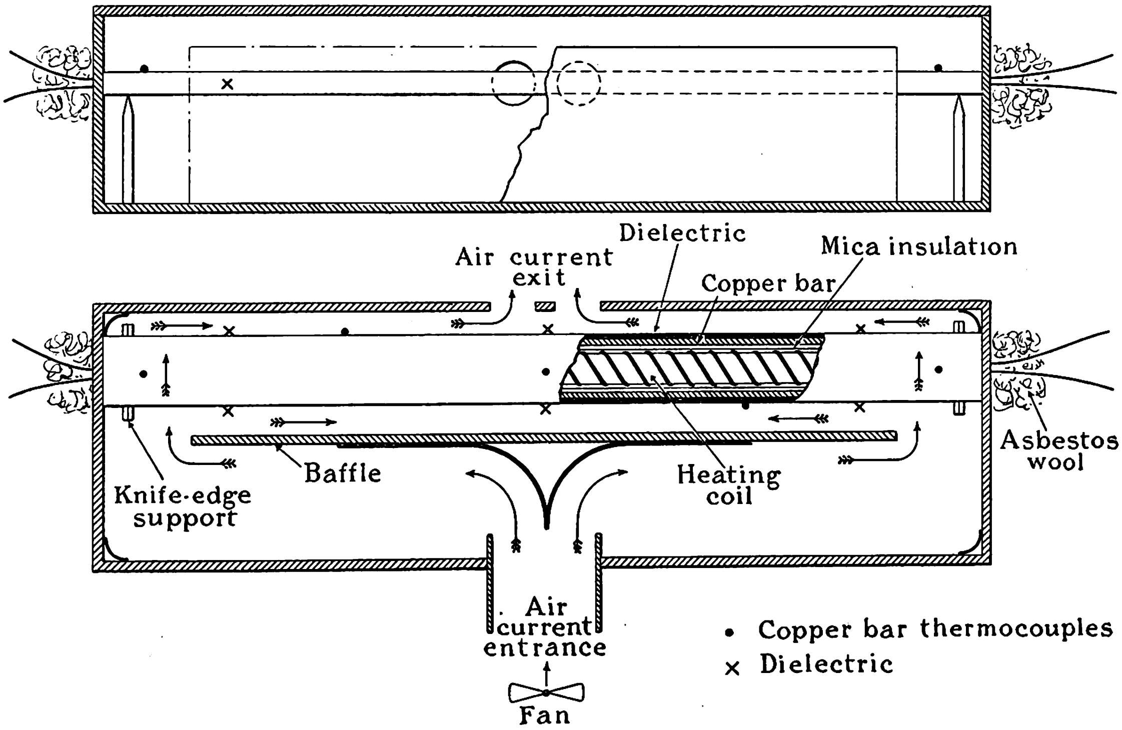

Fig. 14.—Apparatus for the study of the thermal resistivity of insulated copper bars.

The arrangements for carrying out a test were as follows:—

A long heating coil of nichrome wire or strip was inserted into the interior of the bar. A series of thermocouples pegged into the copper or fixed to the outside of the insulation served to give the temperature distribution of the hot and cold surfaces. To facilitate the temperature measurement of the cold surface the outside of the insulation was sprayed with zinc. In order to obtain a sufficiently large gradient of temperature through the insulation, the bar was placed in an enclosure and air was blown on the surface of the specimen. A section and plan of the apparatus are shown in Fig. 14.

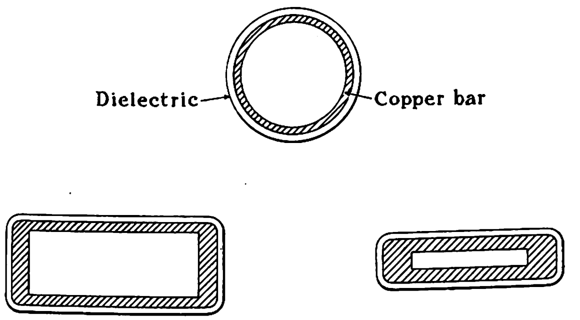

Fig. 15.—Sections of the insulated copper bars used in test.

Experiments were made on two bars, each a metre long and of cross-sections $5 \times 1\cdot2$ cm and $6\cdot1 \times 2\cdot5$ cm respectively. The micafolium was wrapped tightly on the bars, but was not pressed. For purposes of comparison a cylindrical bar wrapped in the same way with micafolium was also tested; the thickness of the insulation in all cases was about 0·2 cm. The sections of the bars are shown in Fig. 15.

In conducting an experiment the energy required to maintain a steady difference in temperature was determined. If E is the energy and T the temperature-difference, then in order to obtain the resistivity K it is necessary to know the value of the constant S in the equation:—

$$E = \frac{S \times T}{K}$$

The constant S depends entirely on the dimensions, and has been called the " shape factor."

The evaluation of the shape factor in the case of a bar of a rectangular section does not admit of exact mathematical treatment, but a graphical solution of the problem is given in Appendix I. The assumptions there made are that the insulator is of uniform resistivity and that the inner and outer surfaces of the insulation are isothermals.

Two cases are considered, namely, that in which the outer surfaces of the bar and insulation are rectangular in section, and that in which the edges of the bar and insulation are rounded.

It is estimated that these cases give almost identical results, the shape factor being approximately:—

$$S = \left(\frac{2(b+c)}{t} + 2\cdot2\right)l \quad . \quad . \quad . \quad (1)$$

where l, b and c are respectively the length, breadth, and depth of the bar and t the thickness of the insulation. To appreciate the significance of formula (1) it may be compared with that given by a flat sheet of material of thickness t and of area equal to the inner surface of the insulation on the bar, or, alternatively, the mean of the inner and outer surfaces of the insulation on the bar.

The shape factors of these two cases would be respectively:—

$$S = \left(\frac{2(b+c)}{t}\right)l \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$S = \left(\frac{2(b+c)}{t} + 4\right)l \quad . \quad . \quad . \quad . \quad (3)$$

It will be seen that (1) lies between (2) and (3).

Reverting to the experiments on the bars, the temperature measurements indicated that there was considerable gradient in temperature from the centres to the ends of the bars. The temperatures of the surfaces of the insulation were more uniform. Under these circumstances it was only possible to arrive at an approximate estimation of the mean temperature gradient through the insulation. The results obtained with the three bars are given in Table 16 and are plotted in Fig. 16. For purposes of comparison the resistivity of small specimens of micafolium were also determined with apparatus Nos. 4 and 5. A single layer as well as a sample made from ten superimposed layers of material pressed together and heated at 140° C. for 5 hours was tested. The values are given in Table 17 and in Fig. 16.

TABLE 16.

Summary of Results on Copper Bars Insulated with Micafolium (Unpressed). Bars not Clamped during Tests.

Description of copper bars	Mean thickness of insulation, in cm	Mean temperature of hot surface, ° C.	Mean temperature of cold surface, ° C.	Mean temperature-difference, deg. C.	Thermal resistivity K
Small rectangular bar	0·204	42·0	32·3	9·7	920
		77·0	51·0	26·0	920
		78·0	51·0	27·0	920
		51·5	35·4	16·1	1 080
		68·3	44·1	24·2	1 130
		78·4	49·8	28·6	1 130*
		95·0	59·0	36·0	1 080
		97·7	62·4	35·3	1 040
Large rectangular bar	0·219	50·5	34·9	15·6	1 080
		70·5	46·5	24·1	1 040
		79·0	51·4	27·6	990
		64·0	43·8	20·2	990*
Cylindrical bar	0·227	28·0	22·2	5·8	750
		62·5	41·4	21·1	720
		83·0	53·9	29·1	720
		80·0	52·0	28·0	750*

* Denotes repeat reading.

Where the thickness of the insulation is small as compared with the other dimensions the differences between the above formulæ are unimportant. Thus, in the case of the bar used in the present experiments, which had a cross-section 5 × 1·2 cm, the insulation being 0·2 cm thick, formulæ (2) and (3) would give a result within about 3 per cent of that given by formula (1).

For the cylindrical bar the shape factor is:—

$$S = \frac{2\pi l}{\log_e \dfrac{b}{a}} = \frac{2 \cdot 73 l}{\log_{10} \dfrac{b}{a}}$$

b and a being the outer and inner diameters. As in the case of the rectangular bar, the treatment of the insulation as flat and of area equal to that of the inner surface of the insulation on the bar, or of the mean of the inner and outer surfaces, does not introduce a large error.

Whilst the experiments on the bars were regarded as being merely of a preliminary character, the following conclusions may be drawn:—

It will be noticed that the lowest apparent resistivity is given by the apparatus with amalgamated surfaces, and that the values obtained with the unamalgamated surfaces and the round bar are in fair agreement and are less than those given by the rectangular bars. The explanation of this order of values would appear to lie in the fact that the resistivity of a number of layers of a material like micafolium depends, to a considerable extent, on the closeness of the contact between the successive surfaces through which the heat has to pass. The greatest flow of heat would be expected where the layers are kept in contact by pressure and the bounding surfaces are in contact with mercury films; while, with an unsupported rectangular bar (as distinct from one tightly wedged in a slot as in service), good contact between the layers would only be expected in the neighbourhood of the corners, and the heat flow would therefore be less than in the other cases, including that of the cylindrical bar. It was noticeable that after the experiments the insulation on the rectangular bars could be depressed by the pressure of the fingers on the flat surfaces, thus showing that air-gaps were present.

TABLE 17.

Summary of Results on Micafolium Tested with Apparatus No. 4 (Amalgamated) and Apparatus No. 5 (Unamalgamated).

Number of thicknesses	Thickness, in cm, of sample tested	Mean temperature, ° C.	Thermal resistivity K
No. 4 Apparatus (amalgamated surfaces).			
Single layer	0·018	22·5	570
		37·5	516
		49·2	482
10 superimposed layers	0·091	21·0	534
		32·5	521
		46·5	505
No. 5 Apparatus (unamalgamated surfaces).			
10 superimposed layers	0·091	24·8	763
		33·8	726
		50·9	670

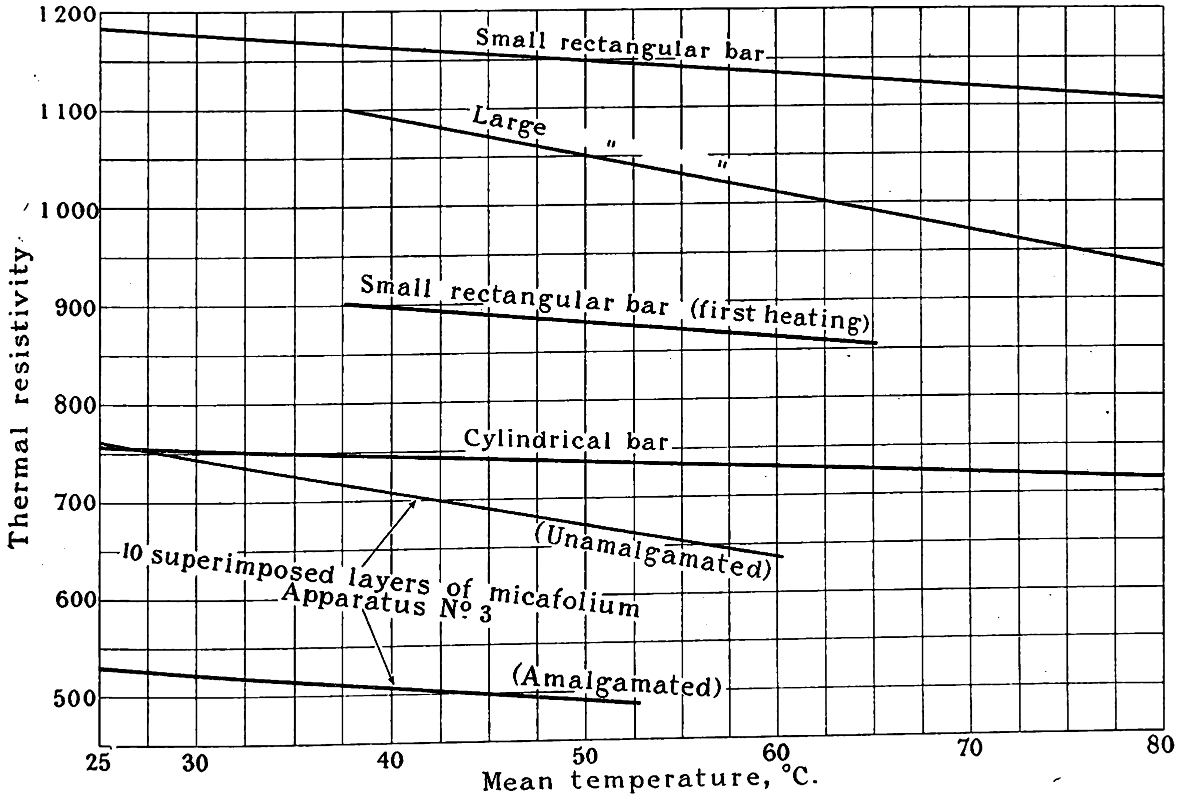

FIG. 16.—Thermal resistivity values from Tables 16 and 17.

It is also significant that the results obtained for the small rectangular bar on first heating were decidedly lower than those subsequently obtained, suggesting that the insulation slackened off when raised to higher temperatures. No such effect was observed in the case of the round bar.

(c) *Main series of tests on bars insulated with micafolium and mica tape.*

The object of the investigation was to determine the effective resistivity of wrappings of micafolium and mica tape on turbo stator bars under conditions similar to those prevailing in actual practice. For this purpose the thermal resistivity has been measured after the application of the insulation to the stator bar.

Two investigations were made, using the following methods of testing:—

Method (I)—Bars unclamped—air-cooled.

Method (II)—Bars clamped between water-cooled plates.

(i) *Method (I)—Bars Unclamped—Air-cooled.*

General.

In this investigation, tests were made by means of an apparatus similar to that used for the preliminary experiments, i.e. the bars were not clamped during the test.

In the case of micafolium, since two distinct processes are involved, namely, " machine-wrapping " and " hot-pressing," the value of the resistivity was determined after each process. Both materials were then artificially " aged " by heating for a week at a temperature of 100° C., the bars on which they were wound being clamped during this period between iron plates so as to correspond to the case of a stator bar wedged in the slot of an actual machine. The effect of the " ageing " process was gauged by a re-determination of the resistivity. It should be added that, since it is usual to apply a layer of cotton tape on the outside of the mica-tape wrapping, the resistivity after first winding was determined with and without this layer. It was hoped also to determine the effect of " ageing " the cotton-tape layer, but as time and funds did not permit, the effect of " ageing " the mica tape only was investigated.

The following determinations of thermal resistivity were thus made on the micafolium and mica tape:—

Micafolium.

After machine-wrapping, after hot-pressing and after " ageing."

Mica tape.

After wrapping, with and without the layer of cotton tape, and after " ageing " without the layer of cotton tape.

The bars were insulated by standard works processes in members' works. The ageing was also carried out by the members, who kindly co-operated by insulating the bars.

Method of experiment.

The method of test used was developed from the method employed for the preliminary experiments on stator bars described in (*a*) above. As in the previous tests, a hollow bar was made up by joining together thick strips of copper so that the outer dimensions were typical of those of a stator bar. The length of the bars used was 60 cm, the cross-section was 6 × 1·6 cm, and the thickness of the test insulation about 3 mm. A section of the bar is shown in Fig. 17. The hollow interior of the bar was filled by a flat heating coil consisting of nichrome wire wound on micanite and insulated externally by micanite.

For the purpose of determining the resistivity of the insulation the bar was placed transversely in a steady stream of air which removed the heat dissipated in the internal heating coil. When steady conditions of temperature have been reached, a measurement of the energy supplied to the coil, of the temperatures of the inner and outer surfaces of the insulation, and of the dimensions of the insulation, suffices to give the resistivity. Thus, if Q is the rate of heat supply, T the temperature-difference between the outer and inner surfaces of the insulation whose resistivity is K, then:—

$$Q = \frac{ST}{K}$$

where S is a constant depending on the shape and dimensions of the insulation. As explained in section (*a*) above, the following solution for the constant S given in Appendix I has been used as representing the best available approximation to the conditions of the experiment:—

$$S = \left(\frac{2\,(b+c)}{t} + 2\cdot 2\right)l$$

where l, b and c are respectively the length, breadth and depth of the bar, and t the thickness of the insulation.

Of the quantities involved in obtaining the thermal resistivity only the measurement of the thickness t and the temperature-difference T presented any difficulty. The thickness was obtained by measuring with a micrometer the overall thickness of the bar with and without the insulation. It was estimated that the measurement of thickness could not be made better than to the nearest 0·1 mm on a total of 3 mm.

As regards the measurement of the temperature-difference, the difficulties in dealing with materials in the form used in the present experiments are very considerable. The inner temperature was taken to be that of the copper bar and was measured by means of a series of copper-constantan couples pegged into it at various points along its length. By a suitable adjustment, by means of vanes, of the distribution of the air flow, a practically uniform temperature along the whole length of the bar was obtained, the thermo-couples giving readings agreeing to about 0·2 deg. C.

For measuring the temperature of the outer surface the use of thermo-couples attached to copper discs was first tried, but was abandoned as, owing to irregularities in the distribution of temperature, a large number would have been required to obtain the mean value of the temperature. The thermometric device finally used for the purpose was a platinum resistance thermometer consisting of a wire 0·2 mm in diameter, 6·5 metres long, and about 40 ohms in resistance, which was wound in a spiral along the outer surface of the insulation, the whole being cased in a wrapping of rubber tape. A plan of the apparatus is shown in Fig. 17.

Measurements of the resistance of the thermometer were obtained by comparing the volt-drop, for a constant current of the order of 100 micro-amperes, on the thermometer and a standard resistance arranged in series with it. The resistance thermometer was used differentially as follows:—

It was first calibrated in terms of the thermo-couples attached to the bar by comparing their readings when the bar was encased in a thick layer of cotton wool about 4 in. deep and maintained at a constant temperature by means of the internal heating coil. Under these conditions the temperature gradient through the thin layer of micafolium or mica tape was assumed to be negligible in comparison with that induced by placing the bar, without the protecting layer of cotton wool, in a rapid current of air. The difference in the readings of the resistance thermometer from those of the thermocouples under the conditions of the actual experiment was taken to give the temperature-difference induced by the air current in the test layer of micafolium or mica tape.

It may be mentioned that alternative and doubtless more precise methods were considered for dealing with the problem of temperature measurement and of cooling the external surface, but the method described above was adopted as probably giving a close approximation to the desired conditions for the minimum expenditure of time and money.

Results obtained by Method I.

The results of the experiments are set out in Table 18, and the values are shown graphically in Fig. 18.

For purposes of comparison, two sets of values which were obtained in previous experiments for a number of superimposed layers of micafolium have also been plotted in Fig. 18.

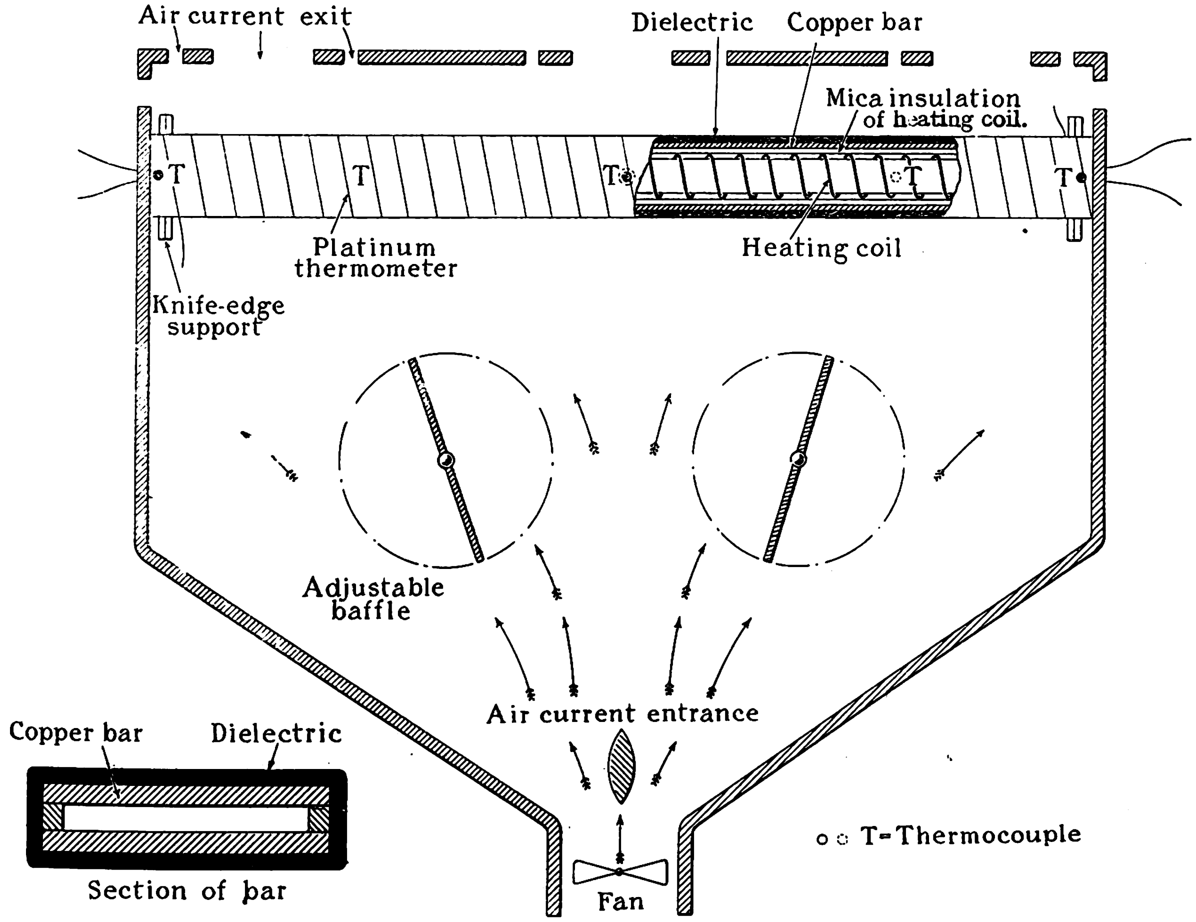

FIG. 17.—Apparatus for the determination of the thermal resistivity of insulated bars—unclamped.

In the previous experiments the specimen sheets of micafolium were clamped between flat copper plates, the surfaces of which in one case were amalgamated and in the other unamalgamated. It will be seen that the effect of improving the surface contact by amalgamation has been to lower the resistivity from about 760 to 530. This is ascribed to the irregular nature of the surface.

In the present experiments a big decrease in the resistivity of the micafolium is produced by the hot-pressing process, due, presumably, to the improvement in contact between the successive layers by the elimination of air films. On the other hand the subsequent "ageing" process has produced an apparent rise in resistivity of the order of 20 per cent. The reason for this result is not obvious, since the material has been subject to great pressure in the process of "ageing." However, it should be mentioned that the combined effect of the pressure and a temperature of 100° C. has been to squeeze out a considerable amount of shellac.

In the case of the mica tape experiment the resistivity with and without the layer of cotton tape is somewhat more than that of the micafolium in the first stage (hand-wrapped). The material in the first state was noticeably springy, indicating imperfect contact between successive layers. The pressures involved in "ageing" have evidently improved the contact since the material shows a decrease in resistivity of the order of 40 per cent.

TABLE 18.

Thermal Resistivity of Stator Bars Tested Unclamped—Air Cooled.

Description of wrapping	Mean thickness of wrapping, cm	Hot surface temperature, ° C.	Cold surface temperature, ° C.	Mean temperature, ° C.	Thermal resistivity K
Micafolium (hand-wrapped)	0·30	40·5	29·3	34·9	1 152
		49·3	34·4	41·8	1 120
		63·2	40·0	51·6	1 165
		51·5	34·4	42·9	1 131
		32·6	25·6	29·1	1 152†
Micafolium (hot-pressed)	0·27	38·6	32·3	35·5	516
		47·6	37·4	42·5	531
		60·6	46·8	53·7	521
		51·6	41·5	46·5	522
		36·8	30·2	33·5	549†
Micafolium (aged)	0·27	37·0	29·8	33·4	702
		38·9	31·3	35·1	702
		43·8	33·9	38·9	690
		49·9	37·5	43·7	675
		56·8	42·4	49·6	660
		22·9	19·3	21·1	715†
Mica tape with cotton tape covering (before ageing)	0·40	40·3	22·5	31·4	1 364
		52·1	27·7	39·9	1 270
		64·1	31·8	47·9	1 211
Mica tape without cotton tape covering (before ageing)	0·30	40·8	24·3	32·5	1 262
		51·0	28·9	39·9	1 255
		64·6	36·6	50·6	1 211
Mica tape without cotton tape covering (aged)	0·29	21·3	17·8	19·5	872
		34·0	26·8	30·4	853
		44·9	33·6	39·3	829
		27·8	22·8	25·3	878†

† Denotes repeat reading.

In considering the results obtained during the tests on the insulated stator bars it is important to note that during the tests the insulation on the bars was not subjected to any external pressure, as always occurs under service conditions. In considering the results of the preliminary series of tests (see page 1330) it was recorded that the resistivity of a number of layers of a material like micafolium depends to a considerable extent on the closeness of the contact between the successive surfaces through which the heat has to pass, and that the tests on bars on rectangular section had shown that, unless the bar was subjected to pressure, good contact between the layers could only be expected in the neighbourhood of the corners.

In the tests carried out by Method II, this feature has been recognized and provision has been made for the determination of the thermal resistivity of insulated stator bars, the specimens being clamped as in the case of insulated bars tightly wedged in the slots of a machine.

(ii) *Method (II)—Bars Clamped between Water-cooled Plates.**

The tests in this series were carried out with the bars tightly clamped between water-cooled plates, the pressure applied being approximately that which it was considered would be obtained in the slot of a machine.

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* This part of the investigation was carried out by the British Thomson-Houston Co., Ltd.

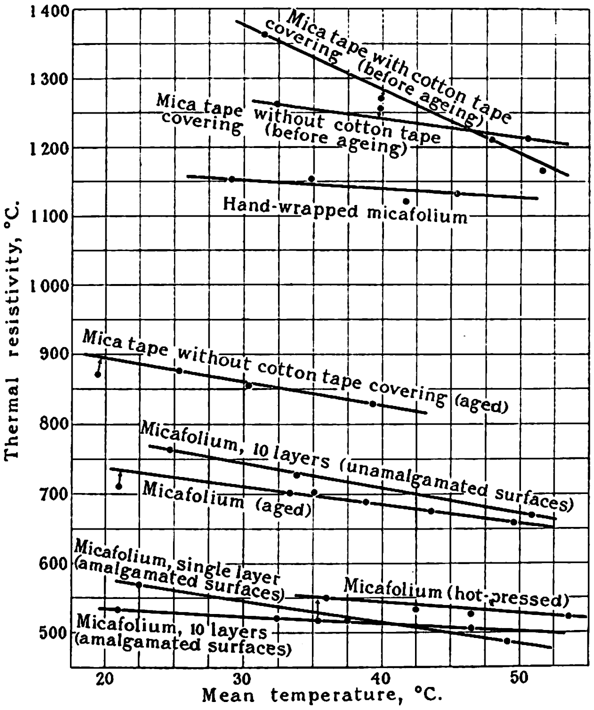

FIG. 18.—Curves showing the variation of thermal resistivity with temperature.—Method I.

The bars were rectangular, the dimensions being similar to those of a conductor used in regular windings. Thermal resistivity tests were made on bars insulated with paper-backed mica tape, and also on a bar insulated with micafolium.

In order to determine the effect of variations in the pressure applied to the clamping plates, on the thermal resistivity results and with a view to correlating the results obtained in this investigation with those obtained by Method I, further tests were carried out using different pressures applied to the clamping plates. These pressures were determined by means of calibrated springs fixed between the clamping plates and the screws.

Description of Insulated Bars.

The bars used for these tests were hollow and of rectangular section, built up of flat strips of copper, the outside dimensions being 2·438 in. × 0·75 in. and 19 in. long. Thermo-couples were attached to the outside surface of the bars in the positions shown in Fig. 19, and an electrical heating unit was fixed inside the bar.

The insulation on the bars was applied by the usual shop processes, including wrapping and hot pressing, etc. In the case of the mica-tape insulated bars, the insulation included an outside layer of cotton tape, the thermal resistivity measurements being made with this tape in position.

Description of Apparatus.

The test bar was held between four copper cooling plates, cooling water being circulated through the latter. Pressure was applied to the clamping plates by means of screws, and for the tests carried out to determine the effect of varying this pressure special clamps were used in which calibrated springs were inserted between the clamping screws and the plates, in order that the applied pressure could be determined.

In order to measure the temperature-drop across the insulation, thermo-couples were also fixed on the surfaces of the clamping plates adjacent to the insulation, and in positions corresponding with the thermo-couples on the insulated bar (see Fig. 19). The thermo-couples consisted of Eureka wires soldered to the copper bars, these being connected as shown in Fig. 20. The temperature-drop across the insulation was obtained by balancing the e.m.f.'s of the external junctions against

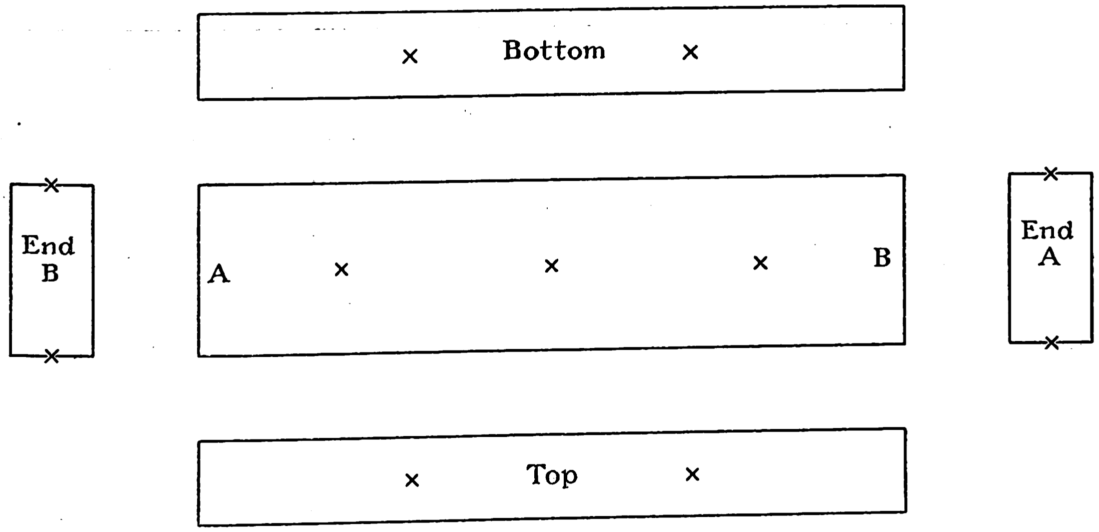

FIG. 19.—Showing location of the thermo-couples on test bar.

the e.m.f.'s of the thermo-junctions on the bars and clamping plates, by varying the temperature of the external hot junction.

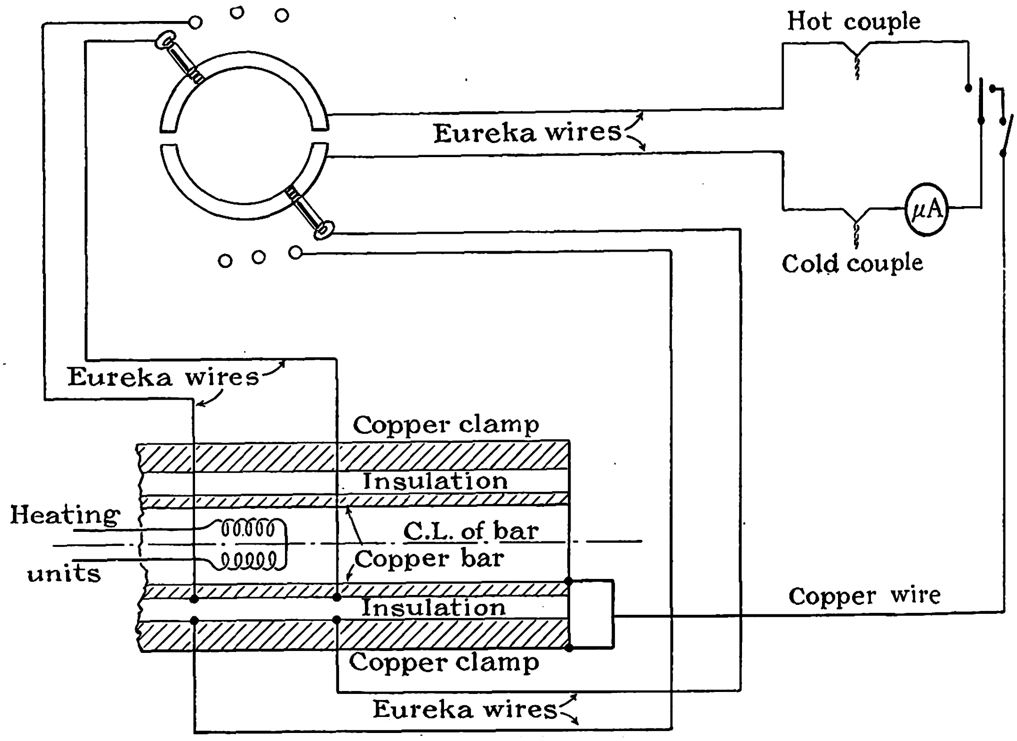
Hot couple
Eureka wires
μA
Cold couple
Eureka wires
Copper clamp
Insulation
Heating
units
C.L. of bar
Copper bar
Insulation
Copper wire
Copper clamp
Eureka wires

FIG. 20.—Diagram of connections of thermo-couples.

TABLE 19.

Thermal Resistivity of Mica Tape and Micafolium Wrapped on Bars (Bars Clamped During Tests).

Insulation on bar	Mean thickness of insulation, cm	Mean thickness of insulation, in.	Mean temperature, ° C.	Temperature-difference, deg. C.	Thermal resistivity *K*
Mica tape (with cotton tape)	0·65	0·256	25·5	18·6	404·0
			27·0	26·0	424·0
			26·1	28·2	459·5
			30·2	34·5	449·0
			33·3	40·6	441·0
			39·7	49·4	429·0
Micafolium	0·36	0·142	22·7	12·4	453·0
			26·5	19·9	454·0
			28·6	24·2	442·0
			28·6	24·4	446·0
			30·9	29·0	441·5
			34·9	35·7	434·0

Method of Test.

(*a*) *Bars tightly clamped.*—In the first series of tests, the results of which are given in Table 19, the bars were clamped by means of the clamping screws. They were clamped tightly so as to get a pressure on the insulation which was considered to be equivalent to that obtaining in the slot of a machine. The bars were heated by supplying current to the heating units, the power supplied to the units being measured and adjusted to values which would give various temperature-differences across the insulation, the thermal resistivity being determined from the temperature measurements made under these various conditions.

(*b*) *Tests for effect of variation of clamping pressure.*—In the tests made on the bars to determine the effect of variation of clamping pressure on thermal resistivity, two sets of readings were made under each pressure, the method of test being otherwise as described above. The results of these tests are given in Table 20, in which corresponding figures taken from Table 19 are also included.

TABLE 20.

Variation of Thermal Resistivity of Mica Tape and Micafolium (Wrapped on Bars) with Pressure Applied to Clamping Plates.

Insulation on bar	Mean thickness of insulation,		Approx. pressure. lb. per sq. in.	Mean temperature, ° C.	Temperature-difference, deg. C.	Thermal Resistivity K
	cm	in.				
Mica tape (with cotton tape)	0·462	0·182	0	30·6	27·7	866
			0	48·6	62·9	820
			½	29·4	26·0	798
			½	45·7	57·7	752
			1	28·7	24·1	753
			1	44·8	55·0	717
			7	26·7	20·7	648
			7	42·2	50·4	606
			14	26·7	18·7	584
			14	44·4	53·1	553
			20	25·4	17·1	535
			20	42·7	51·3	505
			(Bar tightly clamped;	25·5	18·6	404
			see Table 19)	39·7	49·4	429
Micafolium	0·36	0·142	0	28·8	18·7	683
			0	45·6	52·3	630
			½	27·2	16·3	597
			½	37·8	46·5	565
			½	42·4	45·5	553
			2	27·3	15·6	541
			2	26·9	15·3	533
			2	40·6	42·6	514
			10	26·0	13·9	508
			10	39·4	40·0	486
			13	26·2	13·2	482
			13	39·7	37·9	462
			(Bar tightly clamped;	22·7	12·4	453
			see Table 19)	34·9	35·7	344

Determination of Thermal Resistivity K.

In order to fall into line with the way in which the data is to be used in practical calculations, the thermal resistivity, expressed by symbol K, is defined as the ratio of the temperature-difference (expressed in deg. C.) across opposite faces of a centimetre cube, to the resulting heat flow (expressed in watts).

If, therefore, in an experiment on a particular sample:—

e is the energy transferred through the insulation in watts,
T is the observed temperature-difference in degrees Centigrade,
t is the thickness of the insulation,
L is the length of the sample,
C is the equivalent circumference,

then the resistivity K is given by the expression:—

$$\frac{T \times L \times C}{e \times t}$$

The only quantity which cannot be directly measured is the equivalent circumference of the sample, as a complication arises owing to the peculiar distribution of heat flow at the corner. However, if

b = depth of bar upon which the insulation is formed, and
w = the corresponding width,

then the equivalent circumference may be taken as:—

$$2(b + w + 1{\cdot}1t)$$

The value of the thermal resistivity K is therefore given by the expression:—

$$K = \frac{T \times L}{e \times t} \times 2(b + w + 1{\cdot}1t)$$

TABLE 21.

Variation of Thermal Resistivity of Mica Tape with Clamping Pressure for a Mean Temperature of 35° C.

Insulation on bar	Pressure lb. per sq. in.	Thermal resistivity K for mean temperature of 35° C.	Remarks
Mica tape (with cotton tape) (unaged) ..	0	1 325	Results obtained by N.P.L. tests (Fig. 18)
Mica tape (without cotton tape) (aged) ..	0	840	Results obtained by N.P.L. tests (Fig. 18)
Mica tape (with cotton tape)	0	850	
	½	765	
	1	735	Figures interpolated from curves based on Table 20
	7	617	
	14	564	
	20	513	
	(Pressure unknown)	447	Figures from curves based on Table 19

TABLE 22.

Variation of Thermal Resistivity of Micafolium with Clamping Pressure for a Mean Temperature of 35° C.

Insulation on bar	Pressure lb. per sq. in.	Thermal resistivity K for mean temperature of 35° C.	Remarks
Micafolium (hot pressed)	0	550	Results obtained by N.P.L. tests (Fig. 18)
Micafolium	0	655	Figures interpolated from curves based on Table 20
	½	569	
	2	519	
	10	490	
	13	468	
	(Pressure unknown)	435	Figures from curve based on Table 19

Results obtained by Method II.

From the results given in Tables 19 and 20 curves were plotted from which the values corresponding to an average insulation temperature of 35°C. were interpolated. These figures are given in Tables 21 and 22, in which are also included the values obtained by the

National Physical Laboratory. These values are also plotted in Figs. 21 and 22, from which the relationship between thermal resistivity and applied pressure can be readily seen.

ably higher than that of micafolium. The present investigation demonstrates that there is little difference between the thermal resistivities of the two wrappings under service conditions.

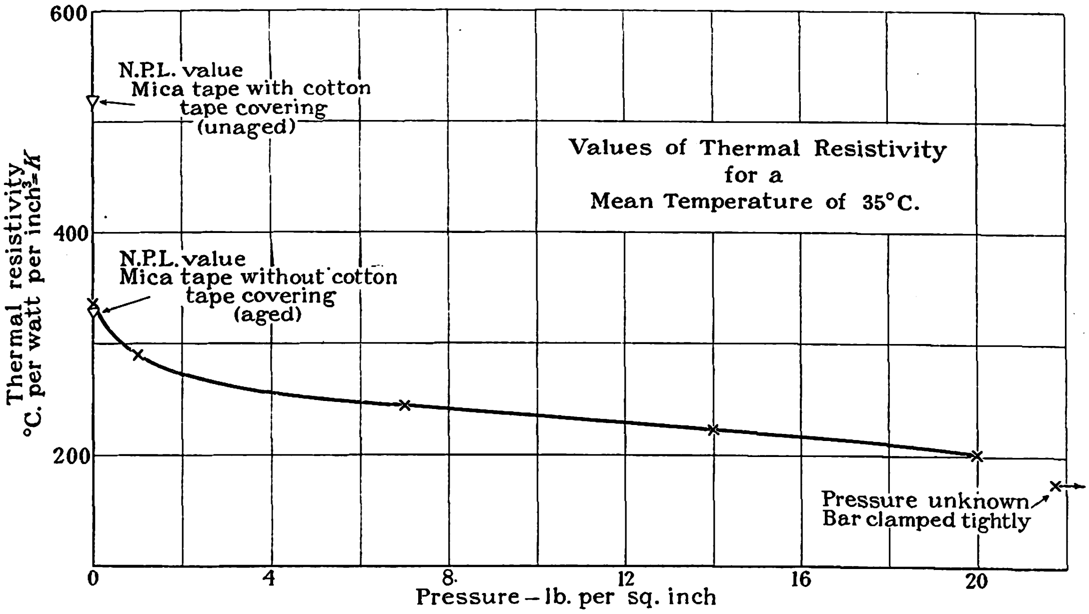

FIG. 21.—Showing the influence of mechanical pressure on the thermal resistivity of mica tape.

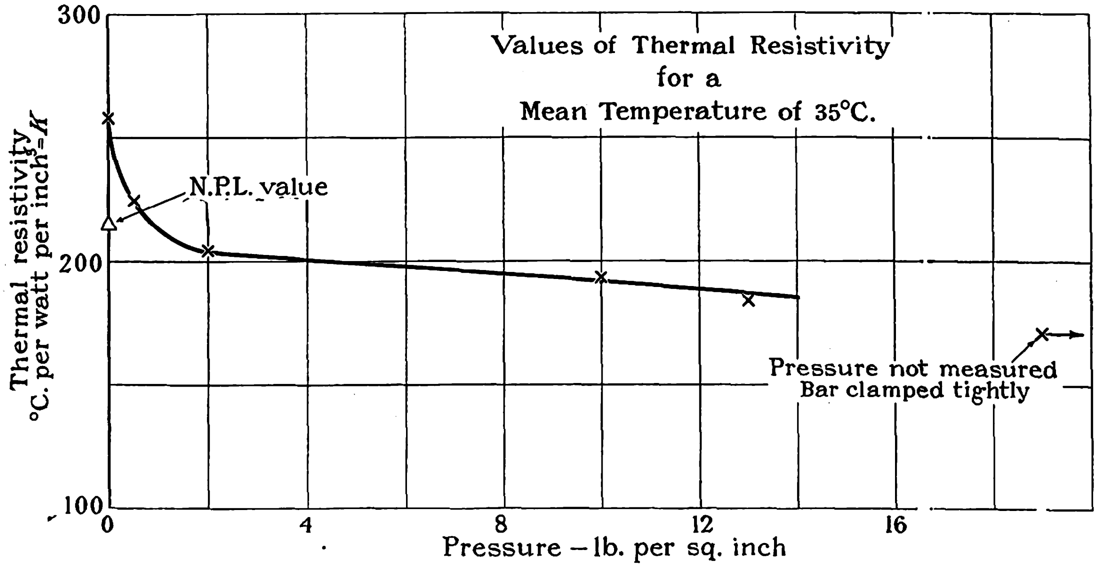

FIG. 22.—Showing the influence of mechanical pressure on the thermal resistivity of micafolium.

The thermal resistivity of both mica tape and micafolium wrapped on bars is found to be lower when the insulation is supported between plates, as in the slot of a machine, than when measured without support or clamping means.

Conclusions.

The previous investigation (Method I) showed that with the insulation unsupported during the test, the mica tape wrapping had a thermal resistivity consider-

Part III.

A STUDY OF THE THERMAL RESISTIVITY OF SHEET-STEEL STAMPINGS TRANSVERSE TO THE LAMINATIONS.

(*a*) *General.*

The object of the investigation was to determine under certain conditions the effect of pressure and temperature on the transmission of heat through various types of stampings as used in electrical machines. A number of firms were invited to submit specimens, the description of which, together with the identification numbers used in this report, are indicated below, viz.:—

Firm	Description of stamping	Specimen No.
A	Dynamo iron 0·16 in. thick, insulated with core plate japan ..	1
A	Dynamo iron 0·016 in. thick, insulated with core plate varnish ..	2
B	Stampings coated with insuline ..	3
B	Stampings coated with paper ..	4
C	0·2 per cent Si steel paper-covered	5
C	1·5 per cent Si steel paper-covered	6
C	4·5 per cent Si steel paper-covered	7

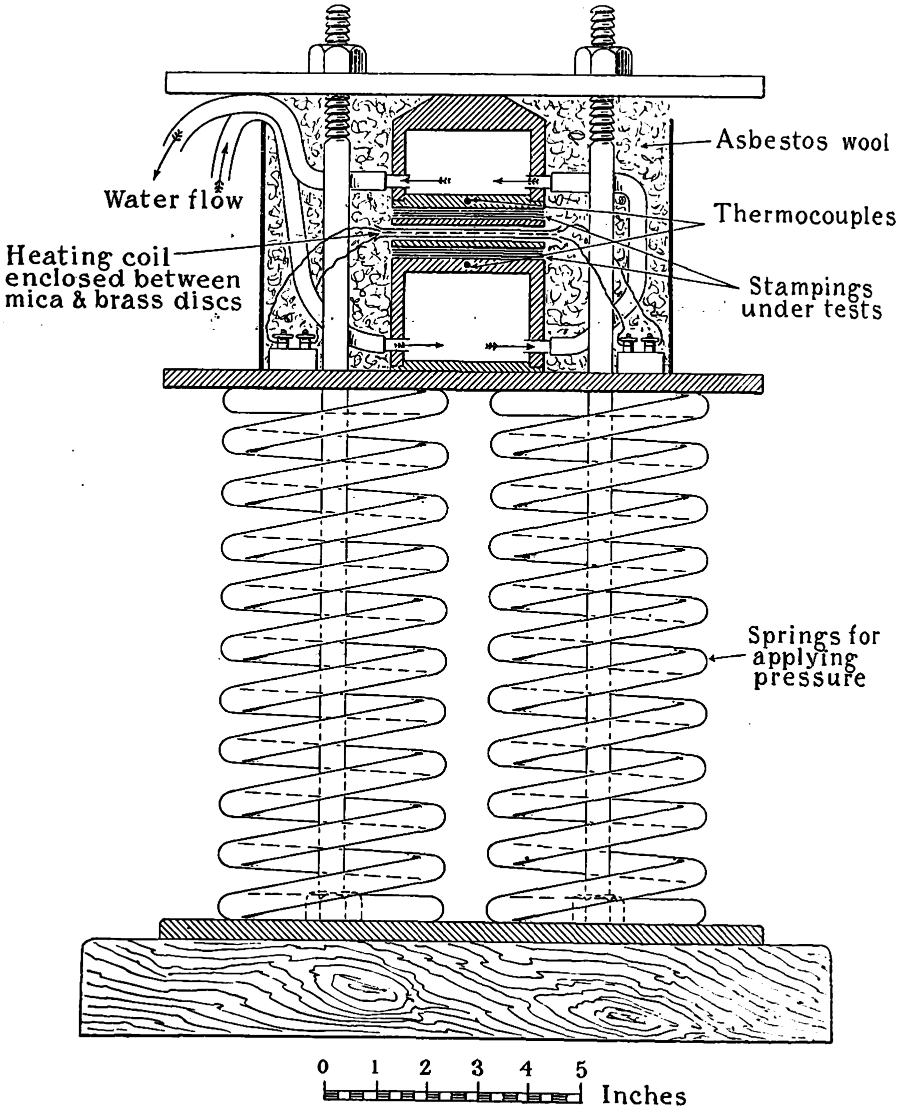
Asbestos wool
Water flow
Thermocouples
Heating coil enclosed between mica & brass discs
Stampings under tests
Springs for applying pressure
0
1
2
3
4
5
Inches

FIG. 23.—Apparatus for the determination of the thermal resistivity of sheet-steel stampings.

Specimens Nos. 1 and 2 had the insulating medium applied on both sides of the stamping, and the remaining specimens on one side only.

(*b*) *Method of test.*

The methods used for determining the resistivity were similar in principle to those adopted in the other investigations on the thermal resistivity of dielectrics. Two flat specimens of the material under test were arranged one on each side of an electrically-heated plate of the same area, and the whole was then clamped between two cold plates maintained at a constant temperature by water circulation. A measurement of the energy input into the hot plate and of the temperature-difference between the hot and cold plates, subject to a small correction for the lateral escape of heat, serves to give the thermal resistivity.

The details of the apparatus are shown in Fig. 23. The hot plate consisted of a flat heating coil insulated with mica and clamped between brass discs. The stampings, in two sets of fifteen, were arranged one set on each side of the hot plate, and were held between two water-cooled boxes, which in turn were clamped between heavy iron plates. The pressure was applied by means of springs previously calibrated, and shown in Fig. 23. These were compressed by nuts bearing on the top plate and working on rods which were anchored to the heavy base, and allowed of pressures up to 200 lb. per square inch on the test specimens, which were 3 in. in diameter. The thickness of the specimens was found to vary only slightly with pressure, the maximum change being of the order of 3 per cent.

The following procedure was adopted for the test on each specimen:—The resistivity was measured at a series of increasing pressures for a temperature-difference of about 20 deg. C. When the maximum load had been reached the resistivity was measured for a temperature-difference of 60 deg. C., as well as 20 deg. C. Reverting to a temperature-difference of 20 deg. C. the resistivity was then determined for a series of decreasing pressures. Measurements were thus made for a temperature-difference of about 20 deg. C.—corresponding to a mean temperature of the specimen of 25 deg. C.—for a cycle of increasing and decreasing pressures, and, in addition, at the maximum pressure, the effect of increasing the temperature-difference to 60 deg. C.—corresponding to a mean temperature of the specimen of 45 deg. C.—was determined. An indication was thus obtained of the effect of pressure and temperature on the thermal resistivity.

(c) Results of tests.

Before referring to the results, the factors which account for the thermal resistance of a composite material of the type under experiment will be considered.

The greater part of the thickness of the pile of stampings (about 90 per cent) is accounted for by the sheet metal. This portion has so low a resistance that, in spite of its great thickness, it contributes very little to the thermal resistance of the aggregate. By far the greater portion of the resistance is due to the high resistivity of the material composing the insulation and to the discontinuities between the superposed surfaces of the pile.

As the thermal resistivity K of the steel from which the punchings are made is of the order of 3, and the tests showed that the thermal resistivity K of a pile of fifteen insulated stampings was of the order of 120, the resistance of the steel only accounts for from 2 per cent to 3 per cent of the total. It is thus seen that as far as the resistivity of the aggregate, transverse to laminations, is concerned, the resistivity of the metal composing the sheets is practically immaterial. On the other hand, the thickness of the sheet metal, composing some 90 per cent of the aggregate, affects the numerical values of the transmission of heat when expressed in units of "resistivity," since this refers to a unit thickness of the material. Now the thickness of the metal sheet with which the present investigation is concerned has varied from specimen to specimen, so that it is clear that a better comparison of the relative resistances of the several coatings on the stampings would be obtained by using a unit which expresses the heat-conducting power irrespective of the arbitrary thickness of the metal. It would be preferable to express such power in terms of the thickness of the insulating coating. This thickness is, however, so small as to be difficult to measure accurately, and, moreover, it is affected to an uncertain extent by rust and other surface irregularities, and by burred edges of the specimens. Hence, in the following the "thermal resistance per stamping" has been considered.

In addition to expressing the results in terms of the "thermal resistance per stamping" the thermal resistivity K has also been calculated, the latter, of course, referring to a pile of stampings 1 cm in thickness. (See Tables 23 and 24.)

The measurement of thickness made on the stampings is recorded in Table 25.

The "total" thickness per stamping was obtained from measurement of the thickness of the pile of 15 stampings when under the maximum load. To get the

TABLE 23.

Comparative Results of Thermal Resistivity Tests on Insulated Steel Stampings.
Pressure, 160 lb. per Square Inch. Temperature, 25° C.

Specimen		Thermal resistance per stamping	Thermal resistivity K for 1 cm of stampings
No.	Insulation		
1	Core plate japan	5·0	105
2	Core plate varnish	6·7	140
3	Insuline	7·7	170
4	Paper	6·0	140
5	Paper	7·1	150
6	Paper	6·5	150
7	Paper	9·2	170

"metal" thickness, specimens of the stampings were lightly rubbed with emery paper to remove insulation, rust, etc., and measurements were made on single specimens with a micrometer. The "remainder" obtained by difference from the other two values represents the combined thickness of the insulating medium, of the rust and scale, etc. The average value of the "remainder" for all the specimens was 0·006 cm per stamping, and the estimated accuracy of the measure was ± 0·001 cm. Table 25 records the results obtained.

TABLE 24.

Results of Thermal Resistivity Tests on Insulated Steel Stampings.

Specimen (Number and insulation).	Pressure, lb. per sq. in.	Approximate temperature-difference, deg. C.	Thermal resistivity *K* for 1 cm of stampings
No. 1, core plate japan ..	2	20	347
	35	20	180
	77	20	135
	127	20	112
	168	20	100
	168	60	75
	127	20	75
	81	20	76
	39	20	85
	9	20	119
No. 2, core plate varnish	2	20	333
	50	20	174
	89	20	156
	125	20	145
	173	20	140
	173	60	108
	110	20	114
	67	20	117
	36	20	120
	2	20	151
	139	20	113
No. 3, insuline	2	20	348
	45	20	257
	85	20	229
	150	20	167
	190	20	162
	190	60	157
	150	20	157
	105	20	159
	62	20	166
	8	20	200
No. 4, paper	7	20	252
	50	20	194
	93	20	162
	135	20	144
	170	20	139
	205	20	135
No. 4, paper	205	60	129
	152	20	129
	103	20	135
	63	20	150
	5	20	188
No. 5, paper	2	20	406
	50	20	243
	94	20	211
	135	20	176
	162	20	144
	162	60	143
	123	20	144
	80	20	154
	42	20	159
	10	20	202
No. 6, paper	3	20	251
	57	20	199
	105	20	163
	154	20	147
	205	20	132
	205	60	128
	121	20	128
	77	20	129
	34	20	138
	3	20	170
No. 7, paper	2	20	380
	50	20	217
	91	20	192
	140	20	189
	193	20	169
	193	60	161
	142	20	161
	88	20	170
	36	20	196
	4	20	249

In Figs. 24 and 25 the "thermal resistance per stamping" has been plotted for the complete range of the tests.

Referring first to the effect of an increase of temperature on the transmission of heat, this was investigated, as has already been explained, by increasing the mean temperature of the specimen from 25° C. to 45° C. when under the maximum load. It will be observed from Fig. 24 that the result in the case of specimens Nos. 1 and 2 has been a pronounced decrease in the resistance per stamping amounting to some 30 per cent. The curves further show that the decrease is permanent since it was not appreciably affected by again lowering the mean temperature to 25° C., as was done in the subsequent observations. The phenomenon suggests that possibly the insulating media, which were " core plate japan " and "core plate varnish " respectively, softened under the combined effect of pressure and heat. In the case of the last-mentioned coating the stampings were found to have adhered slightly at the end of the experiments. The other specimens, Nos. 3 to 7, appeared to show also a small permanent decrease in resistance per stamping on raising the mean temperature to 45° C., but the decrease never exceeded 5 per cent in these cases.

TABLE 25.

Results of Thickness Measurements of Insulated Steel Stampings.

Number	Thickness per stamping (cm)		
	Total	Metal	Remainder
1	0·048	0·041	0·007
2	0·047	0·041	0·006
3	0·045	0·040	0·005
4	0·043	0·037	0·006
5	0·047	0·041	0·006
6	0·045	0·040	0·005
7	0·052	0·046	0·006

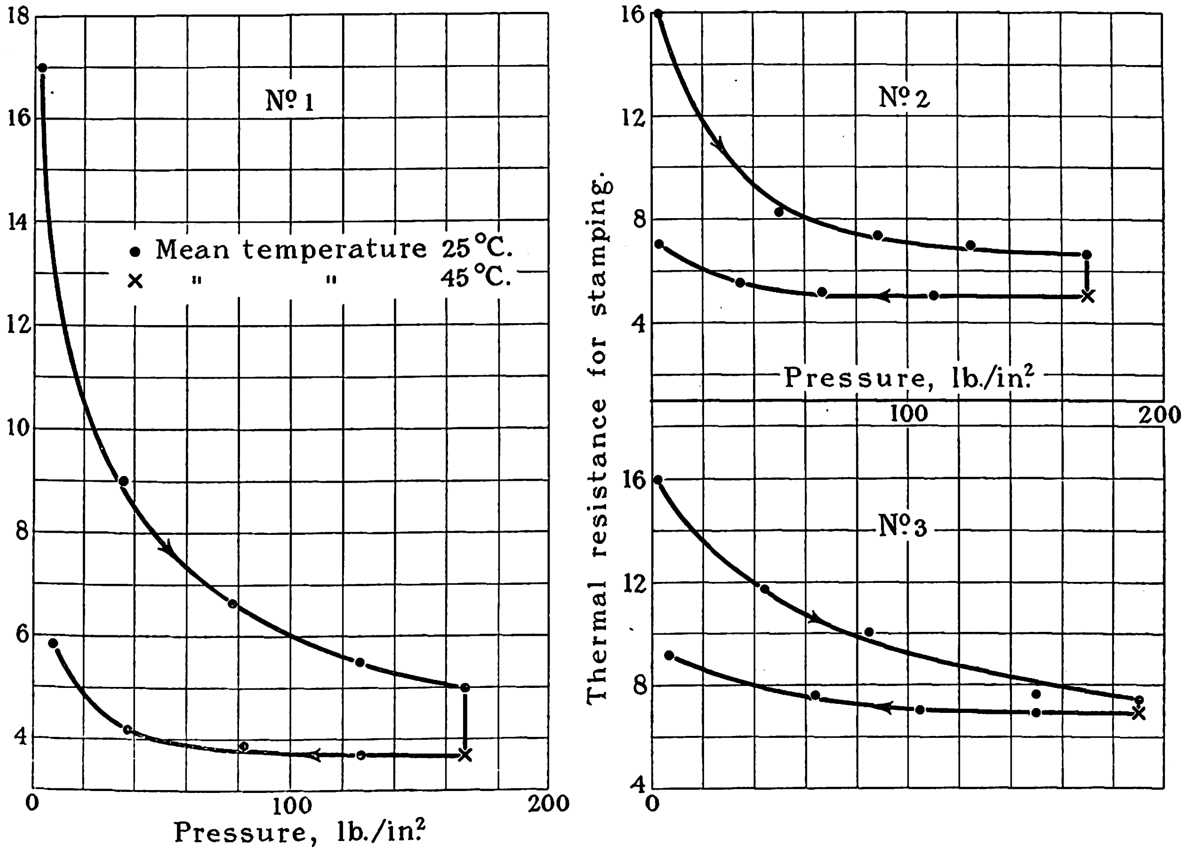

FIG. 24.—Curves showing the variation of the thermal resistivity of sheet-steel stampings under pressure.

As already stated, the effect of pressure was studied by taking each specimen through a complete cycle of increasing and decreasing pressures. Except in the case of No. 5, where irregular values were obtained, the curves for increasing pressure indicate a tendency to a minimum value for the thermal resistance. On decreasing the pressure the curves obtained for the several specimens departed considerably in shape from those for increasing pressure. If allowance is made for the permanent change due to heating when at the maximum pressure, the curve for decreasing pressure would give considerably the lower value for the resistance per stamping at any particular pressure. The scope of the investigation did not extend to a study of the effect of again increasing the pressures after the first cycle of increasing and decreasing pressures. A single experiment was, however, made with specimen No. 2 and the value, found for a final increase of pressure after completing the cycle referred to, fell on the curve previously obtained for decreasing pressure.

The fact that the relation between thermal resistance and pressure should depend on the maximum pressure to which the pile of stampings had been subjected is probably to be expected in aggregates of laminated materials.

As for the comparative values of the thermal resistance of the several stampings, the figures given in Table 23 refer to a pressure of 160 lb. per square inch, as taken from the curves for increasing pressures and for a mean temperature of 25° C. The pressure chosen for obtaining the comparative values was the highest pressure to which all the specimens were subjected.

The detailed results of the tests made are recorded in Table 24.

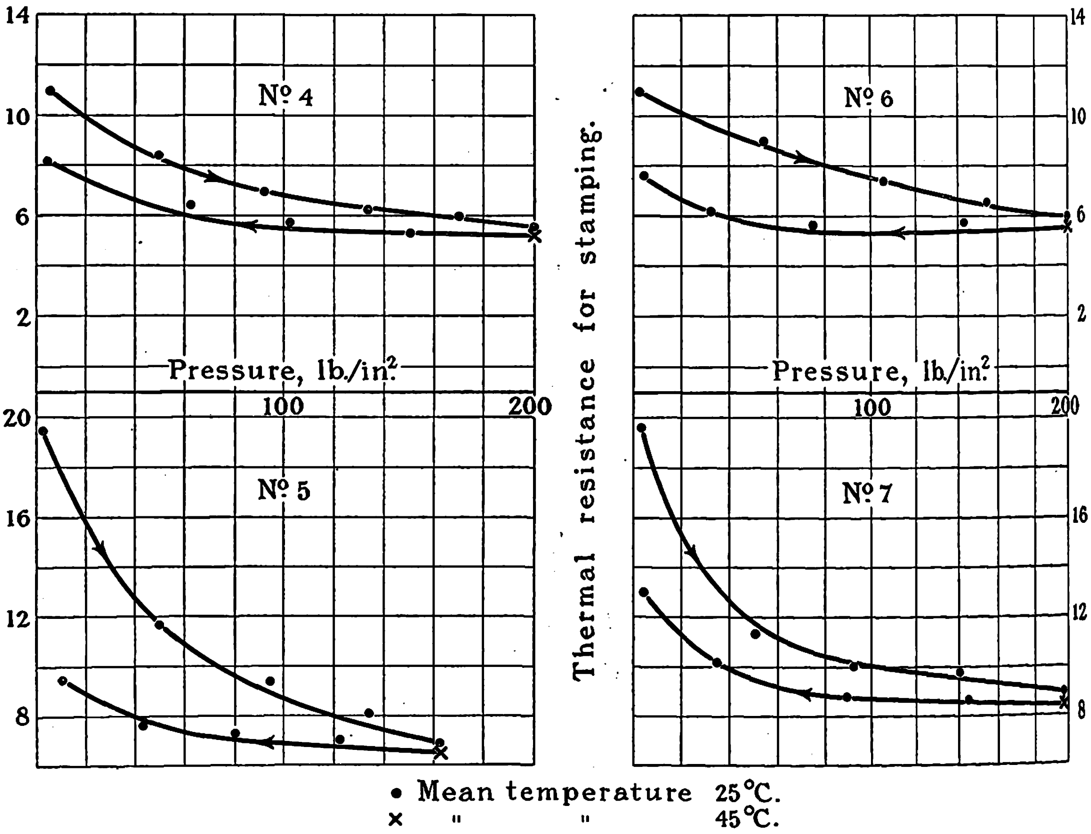

Fig. 25.—Curves showing the variation of the thermal resistivity of sheet-steel stampings under pressure.

It will be observed that a considerable range of values is found for the thermal resistivity at a pressure of 160 lb. per sq. in., that for core plate japan being the lowest. The figures apply to a mean temperature of 25° C. For a higher mean temperature, say 45° C., the values for both core plate japan and varnish would apparently be considerably lower than for the remaining specimens, owing to the large change shown by the two first mentioned under the combined effects of temperature and pressure, to which reference has already been made. As to the resistivities of the insulating coatings, if these are taken to be about one-tenth of the total thickness, the values will range from about 1 200 to 800. It may be remarked that these figures are slightly below the range of values found for the resistivity of paper by other observers.

It is of interest to compare the values obtained in the present investigation with that of Ott.* The latter investigator used two specimens of stampings, consisting of sheet iron 0·5 mm thick and paper 0·05 mm thick, the surface of the metal in one case being stated to be smooth and in the other granular. The resistivities found in these two cases, for a pressure of 50 lb. per square inch (3·4 kg per cm²), were 97 and 186, which values are within the range of those found in the present investigation.

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* See Bibliography.

(*d*) *Summary of results.*

The transmission of heat through sheet-steel stampings has been investigated for specimens coated with the following insulating media, viz. core plate japan and varnish, insuline and paper (several specimens). The main results obtained are summarized below:—

(i) In all cases the sheet metal accounted for only a very small fraction of the total thermal resistance transverse to the laminations.

(ii) The thermal resistance K per stamping ranges from 8 to 16, i.e. 160–320 for a 0·02-in. stamping piled to 1 cm.

(iii) The specimens coated with japan and varnish showed permanent decrease of resistance of the order of 30 per cent on raising the mean temperature from 25° C. to 45° C. when under the maximum pressure, and under these conditions the transmissions of the two specimens named were considerably higher than those of the remaining specimens, which gave only small changes when subjected to the combined effect of heat and pressure.

(iv) Experiments with a cycle of pressure, first increasing and then decreasing, showed that the latter part of the cycle gave the higher values for the heat transmission at any particular pressure.

Part IV.

A Study of the Thermal Resistivity of Air Spaces: Results of Tests Carried out by the Research Laboratories of the Metropolitan-Vickers Electrical Co., Ltd., and Kindly Placed at the Disposal of the Association by Mr. A. P. M. Fleming, C.B.E.

(*a*) *General.*

In considering the paths of heat flow in electrical machinery and apparatus, it is necessary to make an allowance for the presence of air spaces, intended or otherwise. In many cases air spaces are located in such a way that appreciable air flow cannot take place through them, so that heat has to be transmitted through a layer of still air. Examples of unintended air spaces are those due to the imperfect fit of a field coil on a pole or a stator conductor wrapping in a slot. In such cases, only the possible magnitude of the thermal resistance due to the air spaces can be estimated and not the actual magnitude, since all that is known is that the air spaces are not likely to exceed a certain value in thickness. However, taking the maximum thickness that is likely to occur, one can calculate the thermal resistance and see whether it is important compared with the total resistance of the heat path under consideration. The uncertainty in the total resistance due to the presence or absence of the air space can then be estimated and sufficient margin allowed for keeping the temperature-drop within the required limits.

Many cases occur where the thickness of an air space is definitely known. In such cases the thermal resistance can be estimated with fair accuracy if suitable data are available. The tests described in this report were carried out with the object of providing such data. The accuracy claimed for these results is not high, and probably does not exceed 5 per cent, but it is quite sufficient for engineering purposes. By various refinements in the method and apparatus, a considerably higher degree of accuracy could be attained. This would be appropriate to an exhaustive investigation of the subject, but in view of the fact that the subject is not of primary importance to designers, the expense of an exhaustive investigation can hardly be justified.

The tests herein referred to were carried out with a thermal resistivity apparatus which had been developed for measuring the resistivity of refractories and electrical insulating materials.

(*b*) *General arrangement of the apparatus.*

The general set-up of the apparatus is shown diagrammatically in Fig. 26. Two specimens A and B of the same dimensions are used. Between the two specimens is placed a square central electrode C surrounded by a guard ring electrode D, the guard ring being separated from the central electrode by a small air space. Both these electrodes contain heaters made up of nichrome ribbon wound on flat asbestos slate formers. On the other sides of the two specimens are placed the heavy electrodes E and F which also contain heaters.

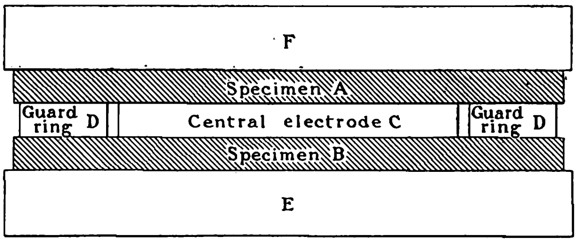

Fig. 26.—Diagram of apparatus used for the study of the thermal resistivity of air spaces.

By adjusting the currents in the various heaters the temperatures of the guard ring and central electrodes are made equal, whilst the temperatures of the electrodes E and F can be adjusted to give any desired temperature-drop across the specimens. When steady temperature conditions are obtained the input to the central heater gives a measure of the quantity of heat being transmitted across the specimens, and from a knowledge of the steady temperatures and the dimensions of the electrodes and specimens the thermal resistivity of the specimen can be deduced. Temperatures are measured by means of platinum-rhodium thermo-couples suitably placed.

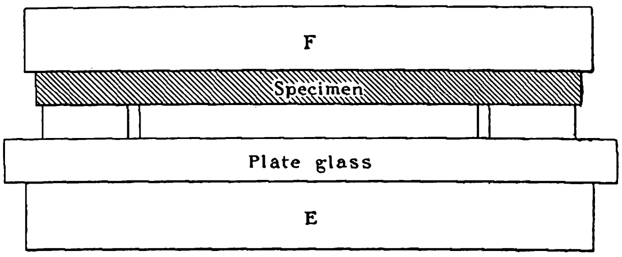

Fig. 27.—Alternative arrangement of apparatus shown in Fig. 26.

In certain tests where it may be desirable to obtain measurements on only one specimen, an alternative arrangement of the electrodes can be used, as shown in Fig. 27. Here the bottom specimen is replaced by a high-resistance material such as a sheet of plate glass, and the temperatures of the central guard ring and bottom electrode E are all adjusted to the same value. Under steady temperature conditions the input to the central heater is now all dissipated through the one specimen to the top electrode F.

(*c*) *Considerations of design.*

In designing the electrodes many points required special attention. The more important of these are outlined below.

The electrodes required to be made of sufficiently massive dimensions to ensure temperature equalization over the whole surface. For this purpose it would have been best to make them of copper, but a preliminary trial showed that copper scaled very badly at a temperature of 500° C. when in the presence of asbestos insulation. Brass was found to behave much more satisfactorily, and was therefore used.

The thermal resistance of the air path between central and guard ring electrodes was required to be as large as possible to prevent a slight want of balance in temperature between the two electrodes causing an appreciable flow of heat from the one to the other. For this reason the air gap was made $\frac{1}{8}$ in. wide, and the thickness of the electrodes kept down to a minimum.

The same apparatus was required to cover measurements in thermal resistivity K, expressed in the number of degrees C. drop in temperature per cm of material to cause a heat flow of 1 watt per cm^2, from 50 to 4 000. Moreover, the temperature-drop across the specimen was required to be kept low owing to the known large variation in resistivity with temperature of most materials. It was necessary, therefore, to make the electrodes of such a size that the watt input even for very high values of K would be easily measurable and not appreciably affected by other experimental errors, but at the same time without increasing the thermal capacity of the electrodes to such an extent as to make the time-constant of the apparatus large, and thus making the time required to obtain steady conditions in any test unreasonably long.

Leads to the central electrode heater had to be arranged so that conduction effects along them would be negligible compared with the total input. This was chiefly obviated by the fact that these leads had to pass through the guard ring, which is at the same temperature as the central electrode during a test. The whole of the heaters and leads had to be made suitable for withstanding prolonged temperatures of well over 500° C. Mica was used to insulate the heaters from the electrodes, and porcelain tubes to insulate the lead-in wires. The final arrangement and design of the electrodes is shown in detail in Figs. 28 to 31 inclusive.

With regard to temperature measurement, thermocouples were, of course, used. It was considered advisable for temperatures as high as 500° C. to use couples of platinum and platinum-rhodium.

Accordingly, couples were made up from wire of about 0·01 in. diameter supplied by Messrs. Johnson, Matthey and Co., of Hatton Garden, London. For the measurement of temperature balance between the central electrode and guard ring, one couple was placed on each of these electrodes. The two wires of the couple were secured separately on to the metal of the electrode by means of grub screws, as shown in Figs. 29 and 30, the couple wires being insulated from the electrode by thin silica tubing. Provision was also made on the outer electrodes for temperature measurement by similar couples also secured by grub screws near the surface of the electrode. The thermal e.m.f.'s set up in the couples were measured on a Tinsley thermo-couple type potentiometer, capable of reading to one microvolt. Thus any contact resistances between the couple wires and the electrode were made of no account.

The temperature-drop across the specimen was, in certain cases, taken as the temperature-difference between the central and outer electrodes. In other cases, thermo-couples were buried in the specimens at known depths.

(*d*) *Considerations of accuracy.*

(i) *Temperature measurement.*

A calibration of thermal e.m.f. against temperature-rise was supplied with the thermo-couple wire by the makers. As a check on this, however, one of the couples was calibrated at the National Physical Laboratory. Very good agreement existed between the two calibrations, and the actual temperature measurements at 500° C. were correct to ± 1 deg. C., whilst the balance of temperature between guard ring and central heater could be obtained to less than $\frac{1}{4}$ deg. C. Assuming balance to be obtained to this accuracy, and taking K for the air space between the guard ring and central heater as 1 000, this lack of balance would cause a flow of heat from the one electrode to the other of 0·07 watt, on a minimum input of about 5 watts. Conditions are usually much better than this, so it can be said that the error due to lack of temperature balance between guard ring and central electrodes is always less than 1 per cent.

(ii) *Measurement of thickness.*

These measurements were usually correct to 2 per cent. In the tests on resistivity of air spaces the electrodes were spaced by very small spacers of silica or sheet glass, the thickness of which was measured by micrometer. The thickness of the gap was also checked by means of feelers, an accuracy of 1 per cent being obtained except for the very small gaps.

(iii) *Measurement of power input.*

This was measured by ammeter and voltmeter to an accuracy of $\frac{1}{2}$ per cent.

(iv) *Overall accuracy.*

Reviewing the possible causes of error as outlined above in the tests on air spaces the overall accuracy is thought to be of the order of ± 5 per cent.

(*e*) *Method of testing.*

The thermal resistivity of a gas can be directly determined from a knowledge of the viscosity and specific

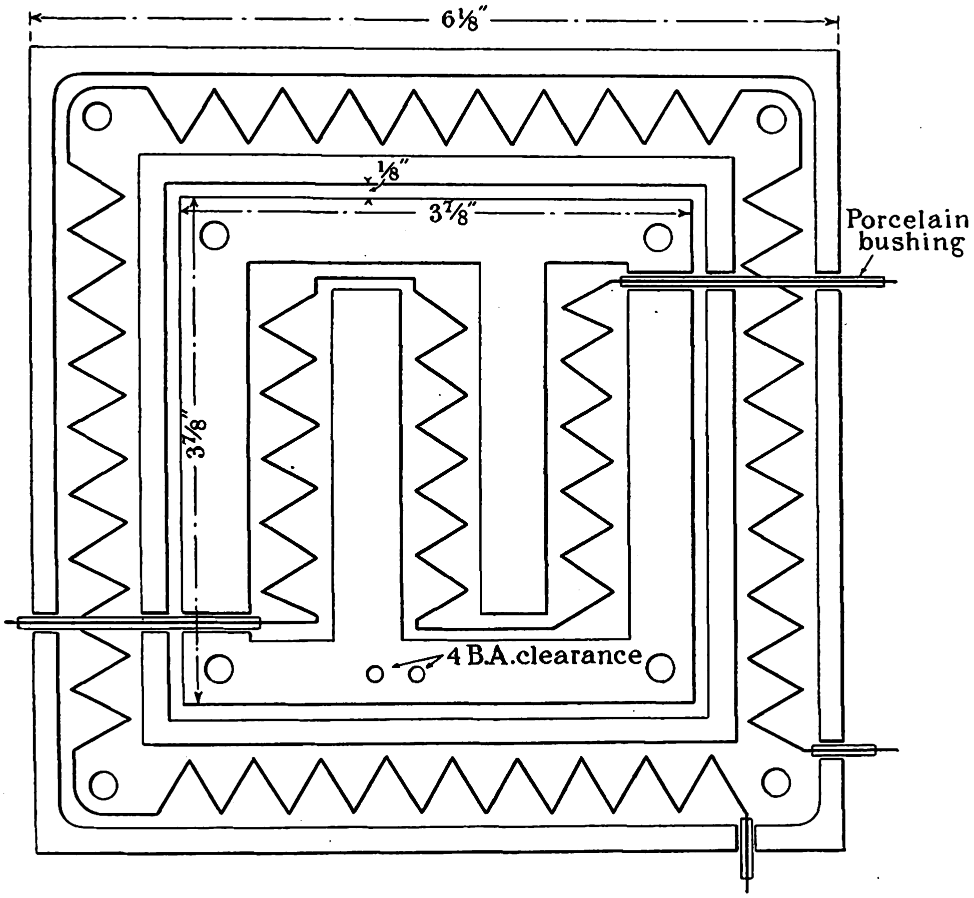
6⅛″
⅛″
3⅞″
3⅞″
Porcelain bushing
4 B.A. clearance

FIG. 28.—Plan of heating coils.

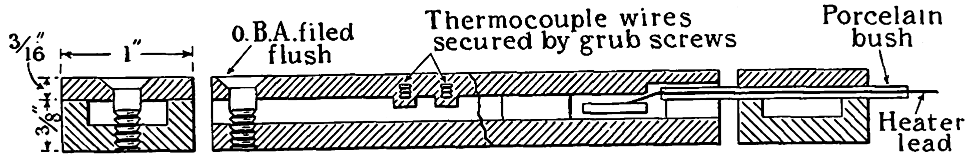
3/16″
1″
⅜″
O.B.A. filed flush
Thermocouple wires secured by grub screws
Porcelain bush
Heater lead

FIG. 29.—Method of securing thermo-couple and lead-in to heater-coil.

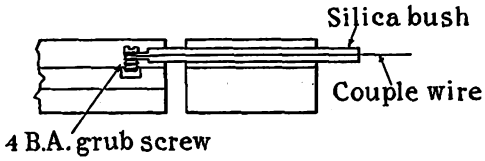
Silica bush
Couple wire
4 B.A. grub screw

FIG. 30.—Showing lead-in to thermo-junction.

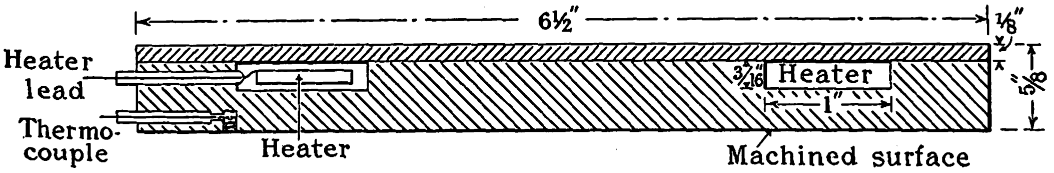
6½″
⅛″
⅝″
Heater lead
Thermo-couple
Heater
3/16″
Heater
1″
Machined surface

FIG. 31.—Cross-section of outer heater elements E and F.

heat at constant volume of the gas, but in practice this theoretical value is of little use, owing to the fact that transmission of heat even through thin films of gas takes place not only by conduction, but by convection, and possibly radiation also.

The apparatus was set up as shown in Fig. 27 with a sheet of ½-in. plate glass interposed between the bottom electrode and the central and guard ring electrodes. Before commencing the tests the surfaces of all the electrodes were re-machined flat and smooth, and the guard ring and central heater machined to the same thickness. The air space between guard ring and central heater was filled with Kieselguhr Diatomite powder to prevent the formation of air eddy currents, while still preserving a high thermal resistance between the two. The top electrode was packed off the guard ring by small spacers of glass or silica to give the required air-space between the central and top electrodes.

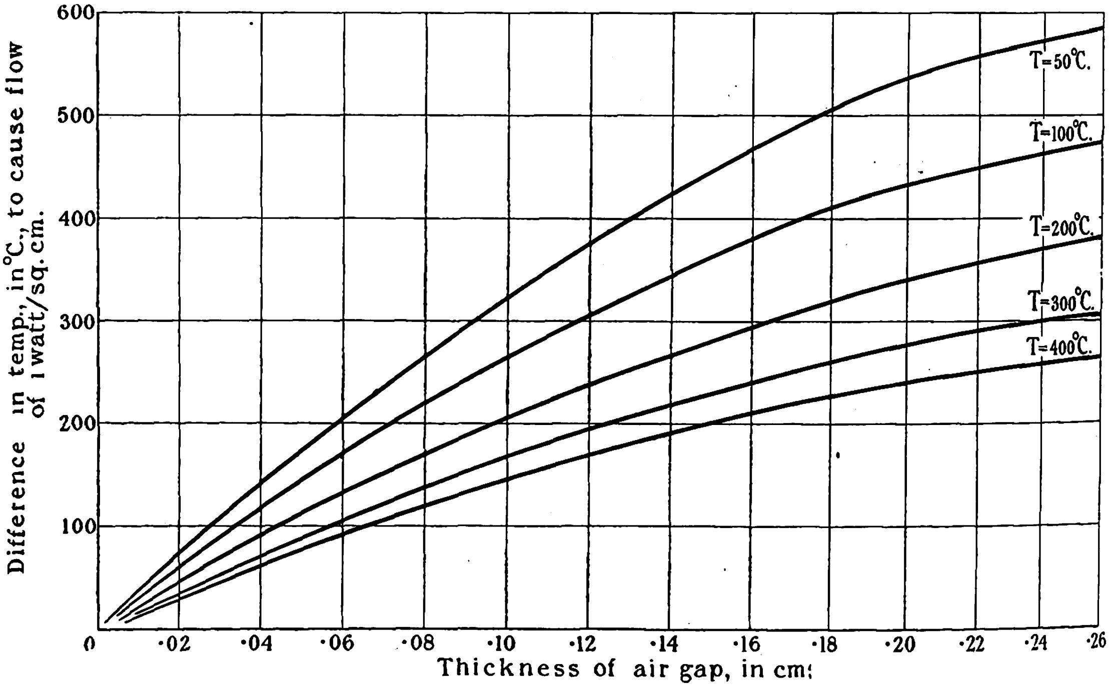

FIG. 32.—Thermal resistivity of air gaps at various temperatures and spacings, excluding effect of black radiation.

Tests were then made of the resistivity of the air space for various mean temperatures of the air space up to 400° C., the temperature-drop across the air space being taken as the temperature-difference of the central and top electrodes.

Curves were obtained of resistivity against mean temperature for gaps varying in width from 0·5 mm to 2·5 mm. These values of resistivity included the effects of:—

(i) Pure conduction across the air space.
(ii) Convection eddies set up in the air space.
(iii) Radiation loss across the air space.

It was not intended to separate the conduction and convection effects, but it was considered worth while to separate these losses from the radiation loss. To do this necessitated a knowledge of the emissivity coefficient of the surfaces of the electrodes as used in the tests. To obtain this coefficient, therefore, the following test was made:—

With the top electrode removed and the central electrode surface untouched, a curve of heat dissipation from this latter surface in watts per cm² against temperature-rise of the surface was obtained. This surface was then painted dull black, and a similar curve again obtained. The radiation loss in this latter case was then calculated from the radiation law:—

$$\text{Watts per cm}^2 = 5\cdot72 \times 10^{-12}(T_1^4 - T_2^4)$$

where T_1 and T_2 are the absolute temperatures of the surfaces and surroundings respectively. In this way the radiation was separated from the convection. (The effect of the thermal resistance of the coating of paint was considered and found to be negligible.)

Returning now to the first curve, the losses were split up into convection and radiation. Hence the value of the emissivity coefficient for the surface was obtained from the ratio of the radiation loss in the two cases. It was found to be 0·476.

The radiation across the air space in watts per cm² per deg. C. difference of temperature of the electrodes at mean temperatures of 50° C., 100° C., 200° C., 300° C., and 400° C. was then calculated, being $(0\cdot476)^2 \times$ the full or black radiation for the same conditions—calculated from the formula above. It was thus possible to convert the original test curves of resistivity against air-gap width into a set of curves showing the required difference in temperature in degrees C. to cause a flow of 1 watt per cm² across varying widths of air gap at different mean temperatures, when radiation is entirely absent. These curves are plotted in Fig. 32. Again, a similar set of curves was easily calculated on the assumption of black radiation across the air space in addition to conduction and convection, and these curves are given in Fig. 33.

(*f*) *Discussion of results.*

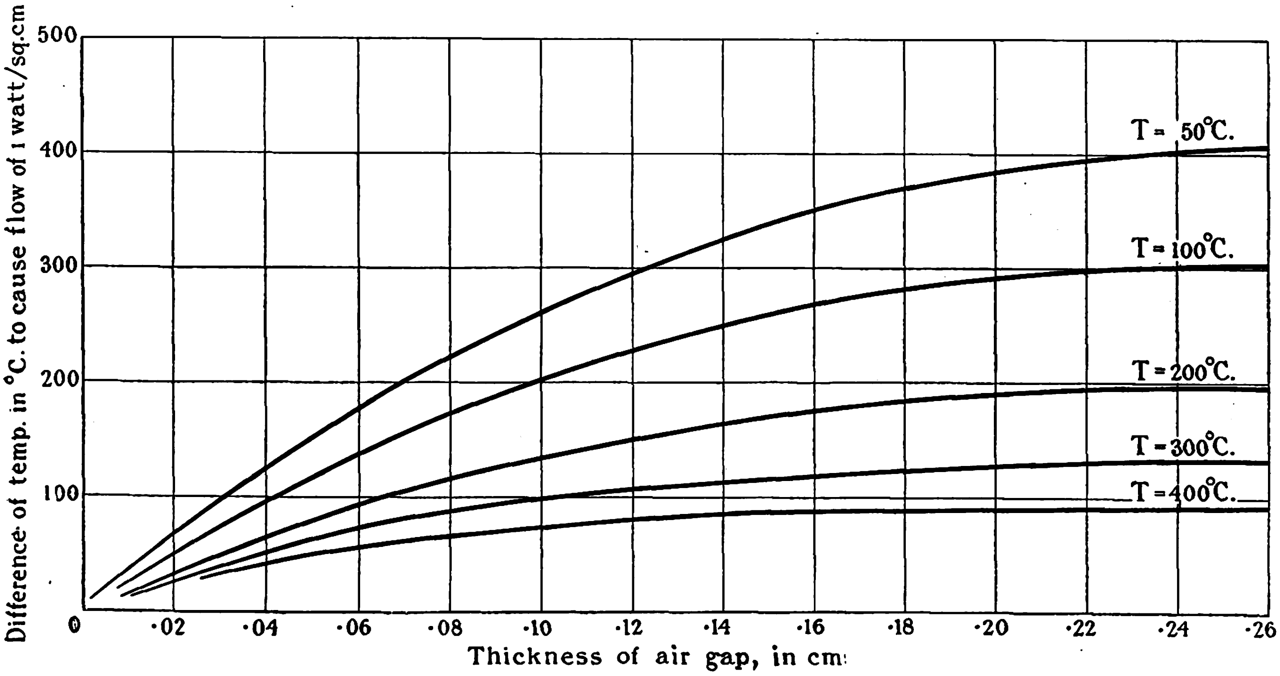

FIG. 33.—Thermal resistivity of air-gaps at various temperatures and spacings, including effect of black radiation.

Referring to Fig. 32 (no radiation) it will be seen that for a given mean temperature the thermal resistance does not increase in proportion to the thickness of the air space. The reason is that with very small thicknesses heat transmission takes place by conduction only, but as the thickness is increased the air has greater freedom of motion, and convection becomes of increasing importance, supplementing the transmission by conduction. It will be seen that the resistance for a given thickness varies considerably with mean temperature.

With regard to radiation, the surfaces generally occurring in electrical machinery and apparatus all have high radiation coefficients. Thus, dull painted surfaces of almost any colour and varnished surfaces have radiation coefficients very nearly equal to unity, while dull or rusty iron surfaces may be over 0·75. For practical purposes the curves which include the effect of full radiation should therefore be used.

The results given in this report may be checked with other published data as follows:—

Professor Miles Walker in his book "Specification and Design of Dynamo Electric Machinery," page 223, gives a curve from which the thermal resistance of air spaces of different thicknesses may be obtained. The mean temperature at which the measurements were made is not stated. A comparison of results is given below, the Metropolitan-Vickers' results including the effect of full radiation.

Thermal Resistance, deg. C. for 1 *watt per cm*^{2}.

	Walker	M.V.Co.
Mean temperature	Not stated	50° C.
Resistance for 0·1 cm ..	220	260
Resistance for 0·2 cm ..	350	382

A more accurate check may be obtained as follows:—

If the curves excluding radiation be taken and the slope for small thicknesses found, the thermal resistivity of air can be calculated. The values in watts and centimetres for different mean temperatures are given below:—

Mean temperature, ° C.	Thermal resistivity K
50	3 800
100	3 100
200	2 300
300	1 820
400	1 580

Now if the conductivities be plotted against mean temperature the points will be found to lie on a straight line, with the exception of the 400 degree point, which is probably in error. Ignoring this point and producing the line to zero mean temperature we obtain a conductivity of $2 \cdot 09 \times 10^{-4}$ at 0° C. The conductivity of air at 0° C. and in C.G.S. units is given on page 52 of Kaye and Laby's "Constants" as $5 \cdot 22 \times 10^{-5}$. Converting this into the units employed above by multiplying by

4·184 gives the value $2\cdot18 \times 10^{-4}$, thus showing an agreement to within about 4 per cent.

ACKNOWLEDGMENTS.

For the main series of tests the E.R.A. is indebted to Dr. G. W. C. Kaye, Dr. Ezer Griffiths, F.R.S., and Mr. F. H. Schofield, B.Sc., of the National Physical Laboratory.

For assistance in preparing the test specimens the Association is indebted to Mr. B. G. Churcher (Metropolitan-Vickers Electrical Co., Ltd.), Mr. A. D. Sloan (English Electric Co., Ltd.), and Mr. H. Warren (British Thomson-Houston Co., Ltd.).

For the investigation on the thermal resistivity of air spaces, and for many valuable suggestions during the progress of the researches, the Association wishes to acknowledge its indebtedness to Mr. B. G. Churcher.

APPENDIX I.

ESTIMATION OF THE THERMAL CONDUCTIVITY OF THE INSULATION ON A RECTANGULAR BAR.

The peculiar shape of the cross-section of insulating material wound on a rectangular bar is such that its thermal conductivity does not admit of exact mathematical treatment.

Two cases are illustrated. Fig. 34 shows the cross-section of an insulated bar; the heat flows straight through the flat sides, but the stream lines are disturbed at the corners. The disturbance does not extend far from the corner, and may be examined by investigating one half of one corner, as between the lines A and B in Fig. 34.

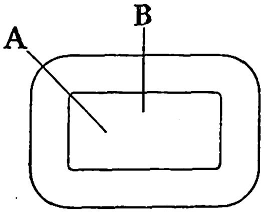

FIG. 34.—Section of bar, showing part A B.

Two cases are so examined in Figs. 35 and 36, in which isothermals are shown surrounding the bar and heat flow radiating from it.

These diagrams are got by trial and error on the principle that only one set of curves is possible, satisfying the following conditions:—

(i) The lines of heat flow must everywhere be at right angles to the isothermals.

(ii) The figures formed by intersection must (if taken small enough) be rectangles having the same ratio of length to breadth. (They may conveniently be made squares.)

The assumption is made of homogeneous conductivity, and that the inner and outer surfaces of the insulation are isothermals.

The conductivity of unit cube is taken as unit conductivity giving unit heat-flow for unit temperature-difference. Taking unit length of the bar, we get—

$$\text{Conductivity} = \frac{p + at}{t}$$

where p = peripheral length, t = thickness, and a = a correction factor for corner effect.

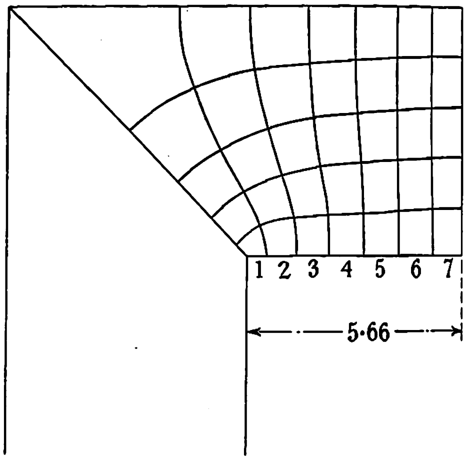

FIG. 35.—Graphical diagram of isothermals and lines of heat flow for square corners.

Case 1 (*Fig.* 35).

Let all corners be square. Taking the unit as 1 cm (the diagram shows $\frac{1}{2}$-cm squares), then $t = 5$. Assume temperature-difference as shown = 5, i.e. 1° per unit of t. Now where the peripheral length in the whole of the disturbed area ending at a corner is 5·66 cm, the figure shows that the corner effect allows 7 units of heat to flow; that is an excess of 1·34 on one side of one corner, or an excess of $1\cdot34 \times 8 = 10\cdot72$, taken on the two sides of the four corners. This is equivalent to an addition of 10·72 cm to the periphery for a thickness

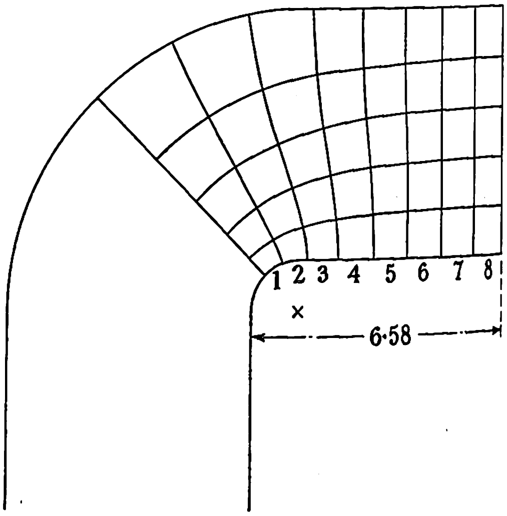

FIG. 36.—Graphical diagram of isothermals and lines of heat flow for rounded corners.

of 5 cm, and is proportional to the thickness; hence the correction factor is $10\cdot72/5 = 2\cdot14$, or:—

$$\text{Conductivity} = \frac{p}{t} + 2\cdot14$$

Case 2 (*Fig.* 36).

Let the corners be rounded to a radius $= t/5$, and let the thickness of the insulation be uniform all over.

Now where the peripheral length in the whole of the disturbed area ending at a corner is 6·58, measured flush with the square end, the figure shows that the corner effect allows 8 units to flow; this is an excess of 1·42 on one side of the corner, or 11·36 on the four corners, hence the correction factor = 2·27, or:—

$$\text{Conductivity} = \frac{p}{t} + 2\cdot27$$

General.

Comparing Cases 1 and 2, it will be seen that the loss of periphery due to rounding-off the inside corner has been more than compensated for by the rounding-off of the outside corner. A radius on the corner $= t/5$ is more than is generally employed; hence the correction factor is of the order of 2·2 on an average.

On scaling the q squares it is thought that the cumulative error is probably not more than about $\frac{1}{2}$ mm, which taken on a difference of 1·34 to 1·42 corresponds to ± 0·08 on 2·14 to 2·27.

On a bar of any length l, substituting A the surface area for the peripheral length, and taking the conductivity as k for 1 cm cube, we get for Case 1:—

$$\text{Conductivity} = k\left(\frac{A}{t} + (2\cdot14 \pm 0\cdot08)l\right)$$

For Case 2, if the bar measures $b \times c$ centimetres in cross-section, we have:—

$$\text{Conductivity} = k\left(\frac{2(b+c)}{t} + (2\cdot27 \pm 0\cdot08)l\right)$$

and for all present purposes we may take:—

$$\text{Conductivity} = k\left(\frac{2(b+c)}{t} + 2\cdot2l\right)$$

NOTE.—Since writing the above our attention has been drawn to a mathematical treatment of this subject published in Jeans's "Electricity and Magnetism," 4th ed., pp. 277–9. This reference gives 2·23 as the added length in terms of the thickness when the sides of the coil are appreciably long compared with its thickness.

The method employed in Appendix I has, however, been reproduced as it gives a general solution applicable where there is no rigid mathematical solution.

APPENDIX II

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Published information on the subject of the thermal resistivity of insulating materials is both scarce and scattered. For the results of other investigations reference may be made to the following:—

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PHENOMENA CONNECTED WITH THE COLLECTION OF CURRENT FROM COMMUTATORS AND SLIP-RINGS.*

By H. G. Taylor, M.Sc. (Eng.), Graduate.

(*Paper first received* 21*st January, and in final form* 18*th March*, 1930.)

Summary.

One of the troubles experienced in the collection of current is that of "copper picking." A description is given of an experimental investigation of this phenomenon, and this is followed by a critical survey of existing data, leading to an explanation to account for this deposition of metal, and an investigation into the mechanism of the passage of current from the slip-ring or commutator to the brush.

The variation of contact voltage-drop with speed, brush pressure and current is shown. Peripheral speeds higher than previously have been used and an investigation has been made at very low current densities.

In order to show the variation of contact voltage-drop, oscillograms have been taken which show its fluctuating nature. These oscillograms show the effect of increased speed and brush pressure, and the change in nature of the contact as the latter is reduced. Intermittent contact is shown to account for rising voltage-drop with speed, but a speed is attained at which an air film is drawn between the brush and the ring.

Introduction.

The author was led to make this investigation largely as a result of a paper presented to the Institution in 1919 on "Carbon Brushes." † This paper revealed a great diversity of opinion, and showed that considerable information was still required on fundamental questions of current collection, and it was in an attempt to elucidate these points and to extend the range of knowledge that this work was undertaken.

The problem of voltage-drop between contacts having relative motion has engaged the attention of a number of experimenters, but it is believed that this is the first time that results showing the variation of contact-drop at speeds greater than 10 000 ft. per minute have been published. The inherent difficulties of an investigation of this nature have been frequently expressed. The chief difficulty is that of reproducing conditions. The contact-drop is to a considerable extent dependent on the state of the surface of the ring and whilst rotation takes place this is continually changing due to oxidation, abrasion and the deposition of moisture and dirt. It is therefore practically impossible to obtain the same contact-drop on any one day as was obtained on the previous day with the same conditions of speed, current and brush pressure.

Recommendations for the ideal test apparatus for determining voltage losses due to contact were made by H. R. Edgecomb and W. A. Dick in a paper presented to the American I.E.E. in 1913,* and as far as possible these have been followed in the construction of the apparatus used by the author.

The problem of copper picking has always been a source of trouble to the engineer, and the phenomenon has never been satisfactorily explained. Because of this, a considerable portion of the paper is devoted to a critical review of existing opinions on the subject and to an analysis of the results of an experimental investigation of the phenomenon.

The Apparatus.

The apparatus used for the above tests consisted essentially of a pair of phosphor-bronze slip-rings $12\frac{5}{8}$ in. dia. and each $\frac{5}{8}$ in. wide mounted on a shaft and direct-coupled to a 6 000-r.p.m. motor. The brush gear was mounted quite separate from the bedplate, so as to eliminate transmitted vibration, and the brushes used were the Morgan Crucible Co.'s type HM.6. The brushes were $\frac{1}{2}$ in. × $\frac{7}{8}$ in. × $1\frac{1}{2}$ in. and they rested side by side on a hard-wood support. The $\frac{1}{2}$ in. × $\frac{7}{8}$ in.-face was in contact with the ring—the longer dimension being vertical. The brushes were maintained in contact with the rings by pivoted arms. At the top of each arm the desired force was applied by a string, to the other end of which was attached a weight.

Copper Picking.

The surface of the rings was prepared by grinding and by the use of glass paper and very fine emery paper. After the first run it was found that on one brush small flakes of phosphor bronze were deposited. These pieces of metal were removed and on reversing the current the phenomenon was found to occur on the other brush—in each case at the brush where the current flowed away from the rings (henceforth referred to as the negative brush). This phenomenon is similar to that which occasionally occurs with copper commutators and is referred to as "copper picking." It appears that with a commutator these flakes may be formed in very large numbers, and, in addition to those which adhere to the brushes, many may alight on the surrounding bedplate. The general opinion seems to be that these flakes leave the commutator in their fully formed state, and some unfortunately adhere to the brushes and thereby cause a great reduction in contact-drop and scoring of the commutator. The author's opinion is, however, that every flake is formed on the brush by the aggregation of small particles, and is then swept off the brush face, and a fresh one formed. This certainly has been the case with phosphor-bronze slip-rings. The many flakes which alighted on the surrounding parts were identical in form with those picked from the brush face. The chips or flakes were discoloured purple and blue with oxide, and this, together with the small curled projections visible under the microscope (see Fig. 13), serves to indicate that intense heating takes place in their formation. The flakes are long and narrow and appear to grow mainly in the direction of motion of the ring. Several may fuse together at one end and give a resultant flake of forked appearance (see Fig. 14).

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* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† P. Hunter-Brown: "Carbon Brushes: considered in relation to the Design and Operation of Electrical Machinery," *Journal I.E.E.*, 1919, vol. 57, p. 193.

* See Bibliography, (37).

It is generally understood that copper picking may be reduced or cured by improving the mechanical conditions and reducing vibration. Everything possible along these lines was done, but without complete success. The rings were tested for concentricity with a dial indicator reading to 0·001 in., but not the slightest movement of the needle was apparent.

In general, copper picking was restricted to the negative brush, but on several occasions it took place also on the positive, and on one occasion it took place on both brushes at once with no current flowing. This occurred after the machine had been "running-in" the brushes at 4 000 ft. per minute for 3 hours. The flakes in this case were about 0·6 in. long by 0·1 in. wide. Several methods of preparing the surfaces of the rings were tried and the best result was obtained from burnishing with a chain burnisher. It is possible to obtain a deposit of metal on the carbon when there is no relative motion, but this only takes place with a current of the order of 200 to 300 amperes per square inch. In this case the deposit appears to be copper and not phosphor bronze, and is in the form of very many minute specks—entirely different from the deposit when running.

It has been suggested [*] that copper picking may be due to any of the following three causes.

(1) Mechanical breaking-up of the copper crystals during the process of drawing the bar through the die, or a change in structure due to alternate heating and cooling in service.

(2) Electrolytic copper contains a certain amount of hydrogen. The presence of hydrogen may affect the structure of the metal or its behaviour when current is passed from it to the carbon.

(3) Electrolytic copper sometimes contains small traces of sodium and this may possibly affect the structure or the electrical wear.

None of these theories will hold for the particular case under consideration. The fact that the phenomenon occurs with phosphor bronze as well as with electrolytic copper and with castings as well as with drawn copper, and that the deposits were actually phosphor bronze and not an electrolytic separation of any one metal, certainly controverts these theories.

The various descriptions of copper picking show that the phenomenon with a commutator is rather different from that occurring with slip-rings. With a commutator more flakes are produced, they are smaller, and they do not adhere so firmly to the brush. This difference is accounted for by the essential difference between the surfaces of the commutator and slip-ring. The smooth surface of the slip-ring has much less tendency to remove the flakes from the brush face than has the surface of the commutator with its alternate copper bars and mica. There being less tendency to remove the flakes they become larger, adhere more firmly to the brush, and are produced in fewer numbers.

However smooth the surface of the brush and ring may be, contact is actually only possible at three points, and with the ring in motion these points are rapidly changing in position. Experimental justification is given for this by Stine,[*] and Baily and Cleghorne.[†] Stine's paper gives a curve connecting contact-drop with the current per brush. The one curve was obtained by plotting values obtained by using three different sizes of brush, thus indicating that, as regards contact-drop for one particular current, the size of the brush had no effect. The same total pressure was used in each case and the result can only be explained by assuming that the actual area of intimate contact between the brush and the ring is the same for each brush. A set of curves is also shown connecting contact-drop with total brush pressure at fixed nominal current densities for three sizes of brush. Three separate, similar, curves are obtained one above the other, the greatest voltage-drop taking place with the largest brush, and the least voltage-drop taking place with the smallest. This is due to the fact that the actual area of contact is the same in each case. The nominal current density being the same for each type of brush, the largest brush carries the greatest current and therefore, owing to the actual contact area being no greater than that with the smallest brush, the actual current density and consequently the voltage-drop are highest. Hence the contact-drop increases with the size of the brush for a fixed nominal current density and constant total brush pressure.

Further justification for the three-point contact theory may be deduced from the work of Baily and Cleghorne. From their experiments they obtain a formula for voltage-drop in terms of current and brush pressure. It is for a particular type of brush and its application is necessarily limited to the range over which the experiments were conducted. It is given as

$$E = \frac{i^{0\cdot28}}{1 + 0\cdot22\sqrt{P}}$$

where P = brush pressure in ounces per unit area, and i = current in amperes per unit area.

If now the area of the brush be reduced to $1/n$th of its value, the current density will be ni and the pressure intensity Pn, and the voltage-drop will be changed to

$$E_1 = E\frac{(in)^{0\cdot28}}{i^{0\cdot28}} \cdot \frac{1 + 0\cdot22\sqrt{P}}{1 + 0\cdot22\sqrt{Pn}}$$

Within large limits the ratio of E_1 to E differs very little from unity. For example, take $P = 2$ lb. per sq. in. and $n = 5$, i.e. compare two brushes one having five times the nominal contact area of the other; then

$$E_1 = E(5\cdot0)^{0\cdot28} \cdot \frac{1 + 0\cdot22\sqrt{32}}{1 + 0\cdot22\sqrt{5 \times 32}}$$

whence $E_1 = 0\cdot93E$.

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[*] See Bibliography, (11), p. 299.

[*] See Bibliography, (16).

[†] *Ibid.*, (22).

Hence reducing the brush to 1/5th of its size has the effect of reducing the contact-drop only 7 per cent. It is thus clearly evident that the contact-drop is practically independent of the nominal area of the brush. If conduction were taking place simultaneously over the whole of the brush surface this would be inconceivable, hence we are forced to the conclusion that conduction takes place at small points of contact, the number and area of which bear no relation to the size of the brush.

In optical work it is difficult to grind two surfaces together so that the maximum distance between them nowhere exceeds $0 \cdot 5\mu$, but Rother has shown * that with a contact-drop of $1 \cdot 5$ volts a gap of only $0 \cdot 07\mu$ may be considered as an insulator between two metal surfaces, which further confirms the view that current conduction does not take place over the whole surface of the brush.

Assuming, then, the three-point contact theory to be true, three important facts follow:—

(1) Owing to rapid changing of points of contact very minute sparking must be taking place continuously.

(2) The current density at the points of contact must be very high.

(3) The pressure intensity at the points of contact must be very high.

Arising out of (1) and (2) we have the corollary that the points of contact must be instantaneously at a very high temperature. The result of this is that volatilization of the carbon takes place and the atmosphere around the point of contact is conducive to the maintenance of current flow through the medium of an arc. This has been fully confirmed by a recent paper by J. Neukirchen † which describes in some detail the mechanism of current transfer, and gives reasons for the variations of contact resistance which induce sparking.

It has been shown ‡ that the curves connecting brush contact resistance with current density closely resemble those connecting potential-drop and current in an arc of constant length, and experiments have been made which support the theory that elementary arcs are formed at and around the points of contact. With the formation of the arc, metal is carried from the ring and deposited on the carbon, just as metal is deposited from the (positive) metal electrode on to the work in the well-known metallic arc welding process.

This is the explanation of what is sometimes known as the "electrical wear" of a commutator or slip-ring. The process is taking place continuously, and it is a well-known fact that the wear under the negative brush (speaking in a motor sense) is much greater than that under the positive. Given suitable conditions, the speck of metal formed on the brush face adheres and forms the nucleus of a metal deposit of considerable size. High speeds encourage copper picking, and in accordance with the above explanation this is to be expected because (1) an increase of speed means that more work is done against friction at the points of contact, so increasing the maximum temperature, and (2) vibration increases with speed and more violent sparking takes place. The effect of increased brush pressure is also to raise the temperature and so make the conditions more suitable for copper picking. At high speeds the difficulties of current collection are considerable because a high brush pressure must be used to assist in maintaining intimate contact and so prevent copper picking, but at the same time this high brush pressure increases the temperature at the points of contact and so assists copper picking.

The deciding factor as to whether the deposit shall adhere to the brush face is probably the temperature of the point of contact, as deposition appears to be increased by all those factors which tend to raise the temperature. If the speck of metal sticks firmly to the brush, it will constitute a point of contact by virtue of its being at first higher than the remainder of the brush; scoring of the ring, accompanied by intense heating, then occurs, and metal is scraped off the ring and fuses to that already on the brush. The trouble becomes rapidly cumulative as, in addition to the heat produced by friction, the whole of the current will now be passing through the metal-to-metal surface, and a solid flake or scale of phosphor bronze is the result.

It should be noted that the position of the points of contact between the brush and the ring is normally rapidly changing, and it is this fact which distributes the heat uniformly over the brush face and so prevents pitting. When, however, a flake commences to form, this changing of position of the points of contact ceases to take place, with the result that intense local heating occurs. With regard to the case of deposition on the positive brush, and to the case where deposition occurred without the flow of current, it can only be suggested that the first particle of phosphor bronze became deposited on the brush by some abnormal means. It may have been released from some minute blow-holes on the surface of the rings; a microscopically thin and small flake formed by polishing may have been detached from the surface of the ring; or, finally, the ring may have been scored by a particle of abrasive matter in the brush. Once the first particle has been deposited and has adhered to the brush face the flake may, quite conceivably, be formed independently of the flow of current. In view of the considerable wear which takes place at negative slip-rings it appears that a very large amount of material which never adheres to the brush face is removed from the ring.

CONTACT-DROP.

The variation of contact-drop with peripheral speed, current density and brush pressure has been previously investigated by a number of experimenters and the opinion has not infrequently been expressed that it is difficult to reproduce values of contact-drop. The drop may vary with (1) composition and physical characteristics of brush; (2) composition of rotating part; (3) fit of brush in holder; (4) brush pressure; (5) peripheral speed of rotating part; (6) temperature; (7) humidity; (8) current density; and (9) condition of surface of rotating part. In this work (1), (2), (3) and (7) have been maintained constant. The variation with temperature was found to be small, but nevertheless the temperature was kept practically constant over each particular test. Of the remaining items, viz. (4), (5),

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* See Bibliography, (31).

† *Ibid.*, (35).

‡ *Ibid.*, (24).

(8) and (9), (9) was beyond control but its effect was only considerable when running under severe conditions, i.e. at very high speeds; of (4), (5) and (8), two always were retained constant whilst the third was varied.

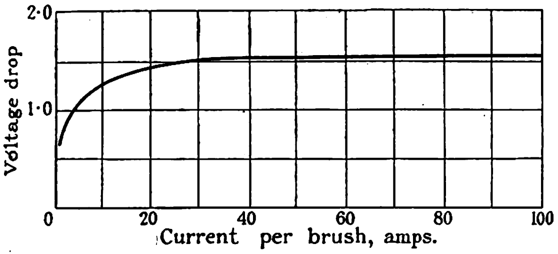

FIG. 1.—Voltage-drop and current. Brush pressure = 2 lb. per sq. in.; speed = 6 560 ft. per minute; positive brush.

The variation of contact-drop with current is well known for normal values of current, and a typical curve is shown in Fig. 1. In view of previous statements when referring to copper picking it will be apparent why the curves are plotted on a basis of current per brush and not per square inch, although on account of the custom of referring to the latter it may be stated that the area of the brush used throughout the experiments was 7/16 sq. in.

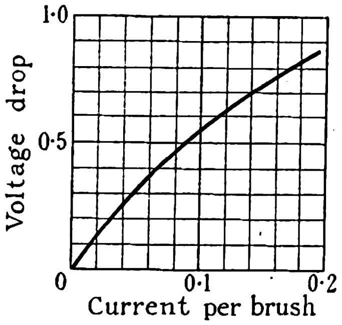

FIG. 2.—Negative brush, ring stationary. Brush pressure = 1½ lb. per sq. in.

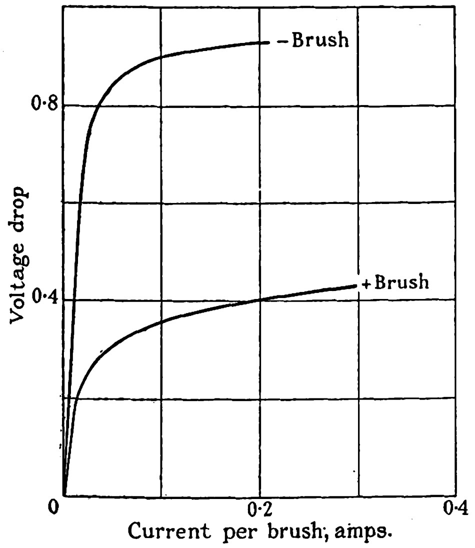

FIG. 3.—Variation of voltage-drop with small values of current.

Speed = 8 000 ft. per minute; brush pressure = 2 lb. per sq. in.

The author has been unable to discover that the variation of contact-drop with very low values of current has ever been thoroughly investigated, and diversity of opinion was shown in the discussion of a paper on “ Carbon Brushes in Relation to Electrical Machinery.” *

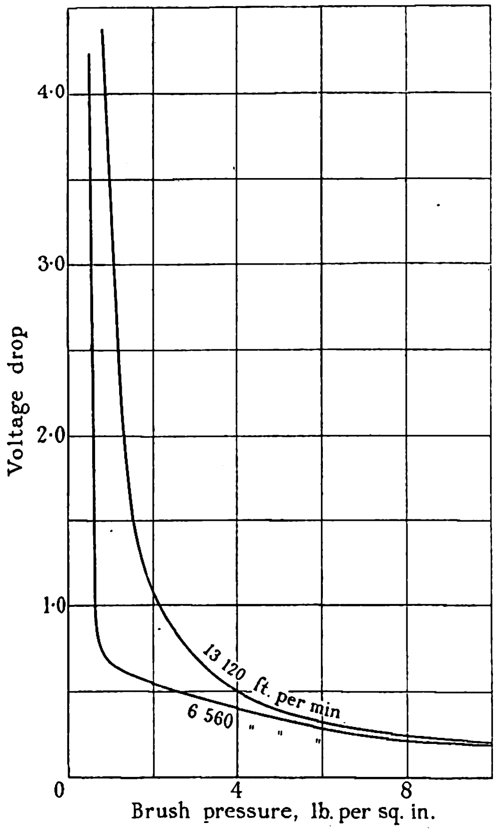

FIG. 4.—Brush pressure and voltage-drop. Current = 20 amperes per brush; negative brush.

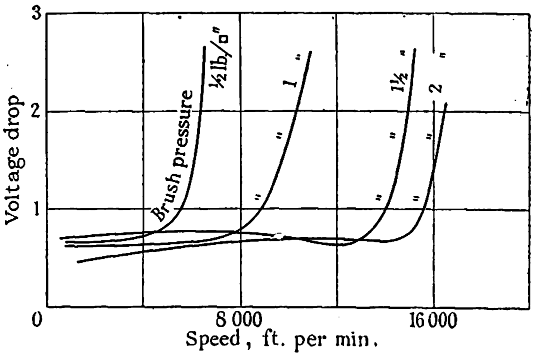

FIG. 5.—Voltage-drop and speed curves. Current = 10 amperes per sq. in. (4·375 amps. per brush); positive brush.

It was said both that there was a minimum voltage below which no appreciable current would flow, and also that the voltage-drop curves passed through zero. This has led the author to investigate this problem closely, both for a stationary and moving contact.

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* See Bibliography, (8).

The results are shown in Figs. 2 and 3. Fig. 2 shows that for a stationary contact the voltage-drop curve definitely passes through zero and rises steadily and almost proportionally to the current up to about 0·2 ampere. Fig. 3, however, shows a very different result. Here we have a marked difference between the positive and negative brushes. With the negative brush it would be true to say that there is a voltage below which no appreciable current will flow, but this is not the case with the positive brush. If the ordinates of the two curves were added together to give a curve of combined drop, the voltage would rise very steeply up to 0·02 or 0·03 ampere per brush and the curve would be of such a shape as to justify the statement that there is a voltage below which no appreciable current will flow. Fig. 2 shows not the slightest indication of this minimum voltage. The effect is noticeable at all speeds and corresponds to the sudden increase in voltage-drop immediately rotation commences. This is easily demonstrated by turning the moving contact by hand whilst watching the voltmeter. It is rather doubtful whether this sudden rise is entirely due to relative motion, as the voltage commences to increase on the application of a tangential force to the ring before motion takes place.

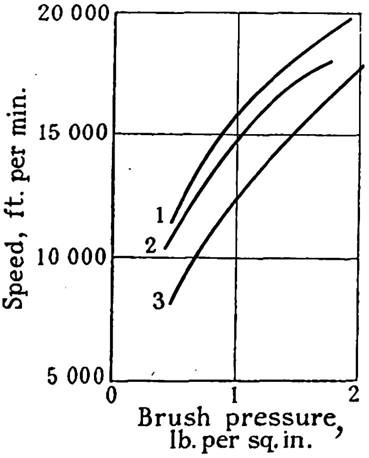

FIG. 6.—Instability curves.

Curve 1.—160 amperes per sq. in., 70 amperes per brush.
Curve 2.—40 amperes per sq. in., 17·5 amperes per brush.
Curve 3.—20 amperes per sq. in., 8·75 amperes per brush.
Positive brush.

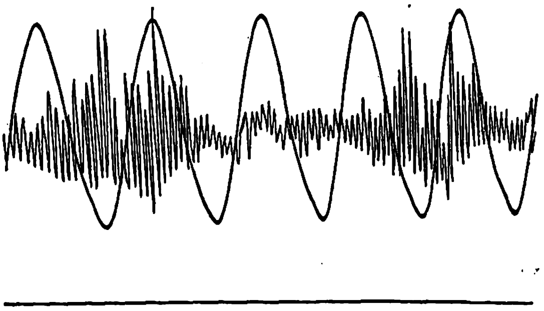

FIG. 7.—Speed = 3 300 ft. per minute; brush pressure = 2 lb. per sq. in.

Typical curves connecting voltage-drop and brush pressure are shown in Fig. 4. The voltage-drop is very high with low pressures and tends to a definite minimum at high pressures. These curves show the necessity of a high brush pressure to maintain low voltage-drop at high peripheral speeds.

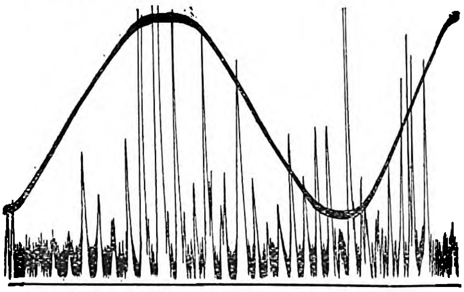

FIG. 8.—Speed = 9 900 ft. per minute; brush pressure = 2·5 lb. per sq. in.

Fig. 5 shows the change of voltage-drop with speed at various brush pressures. Up to a point the voltage-drop is practically constant, the general tendency being to rise slightly to a maximum and then fall somewhat before the final rise. This effect has been more marked in other results not shown here. The exceptional rise at high speeds is due to almost entire failure of contact of the brush and ring, caused by a high-speed intermittent contact and the formation of an air film between the brush and the ring. The fact that the speed at which the voltage commences to rise rapidly increases with brush pressure, led to an investigation resulting in the instability curves shown in Fig. 6. These were determined by fixing the brush pressure and then gradually increasing the speed until the voltage-drop showed a decided increase and a tendency to instability.

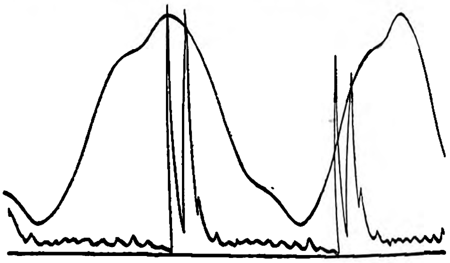

FIG. 9.—Speed = 9 900 ft. per minute; brush pressure = 4 lb. per sq. in.

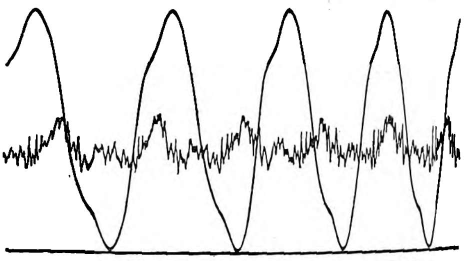

FIG. 10.—Speed = 12 100 ft. per minute; brush pressure = 4 lb. per sq. in.; rubber pad used.

It was found that an unstable voltage at a particular brush pressure and speed could be rendered stable by increasing the current. This is illustrated by the three curves taken at different current densities. As stated above, the instability is due to intermittent contact and it seems reasonable to suggest that the stabilization of the voltage-drop by an increase of current is due to the more vicious sparking retaining a low-resistance path between the brush and the ring for a greater portion of a revolution than is possible with the degree of sparking obtained with the lower current.

It has been observed that the coefficient of friction between a ring and a brush may decrease as the speed increases, and at the same time the contact-drop may increase. Two theories have been suggested to account for this.* The first suggests that an air film is drawn in between the brush and ring, and the second that an intermittent contact entirely accounts for the phenomenon. The originator of the second theory expressed the opinion that oscillograph records of the contact-drop at various speeds would tell us very much more clearly what is actually happening when current is being collected.

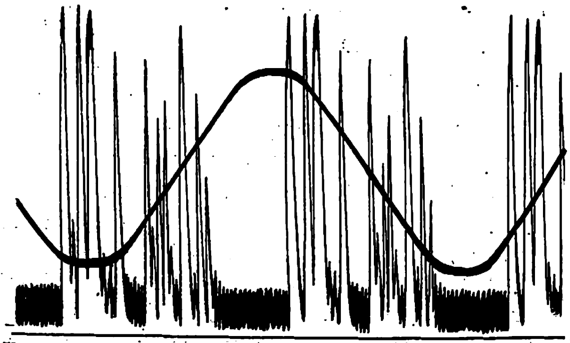

FIG. 11.—Speed = 9 900 ft. per minute; brush pressure = 1 lb. per sq. in.; rubber pad used.

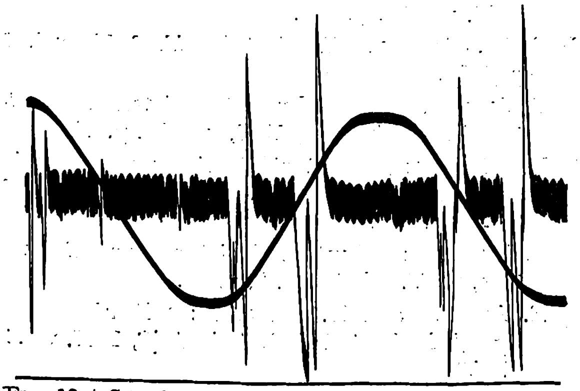

FIG. 12.—Speed = 9 900 ft. per minute; brush pressure = 1 lb. per sq. in.; rubber pad used.

Acting on this recommendation the author has taken oscillograph records and some of these are reproduced in Figs. 7 to 12. The oscillograms reveal the fact that the contact-drop is very unsteady and that the fluctuation increases with speed and decreases somewhat with increase of brush pressure.

Figs. 7 and 8 show the effect of speed on the fluctuation of voltage-drop. Each oscillogram was taken with a current of 23 amperes per brush. In Fig. 7 the brush pressure was 2 lb. per sq. in. and the speed 3 300 ft. per minute, and in Fig. 8 the pressure was 2·5 lb. per sq. in. and the speed 9 900 ft. per minute. In the former case the voltage-drop as recorded by a voltmeter was 0·9 volt and in the latter 1·6. In all the oscillograms a 50-cycle timing wave is shown. Figs. 9 and 10 illustrate the effect of increasing the flexibility of the connection between the brush and the arms applying the pressure. The current and brush pressure were in each case the same, and Fig. 9 shows a very bad case of intermittent contact giving a contact-drop (by meter) of 0·96 volt. This was entirely cured by inserting a small rubber pad behind the brush—Fig. 10 illustrates the result—the speed having been increased from 9 900 to 12 000 ft. per minute. The mean contact-drop was reduced to 0·55 volt.

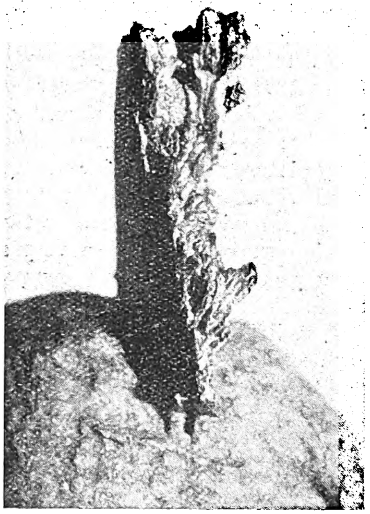

FIG 13.—Phosphor-bronze chip, 20 times full size. The dark plane on the left was flush with the surface of the brush. The chip is erected in plasticine to facilitate photographing.

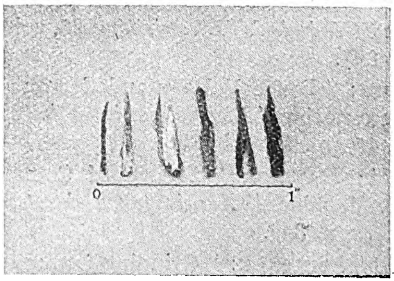

FIG. 14.—Phosphor-bronze chips removed from surface of brushes.

The change in character of the contact-drop fluctuation as it approaches instability is interesting and affords insight into the nature of the contact. Figs. 7 and 10 indicate the stable condition, and Figs. 8 and 9 show incipient instability. The last stage before complete instability is shown in Fig. 11—an oscillogram taken at 9 900 ft. per minute and 1 lb. per sq. in. brush pressure, the mean voltage-drop being 2·7 volts. There is no doubt about the intermittent nature of the contact. Fig. 12 depicts the unstable state—an air film has been produced between the brush and the ring, and contact only occurs once or twice per revolution. This phase developed from that shown in Fig. 11 with no perceptible change of speed, but resulted in the current falling from 23 to 2 amperes and the contact-drop increasing from 2·7 to something over 15 volts. In this state cyclical variation does not seem to take place as it was impossible to synchronize the oscillograph motor so that a steady picture might be viewed on the screen.

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* See Bibliography (8), pp. 195 and 204.

The high peak values of voltage-drop are undoubtedly due to the brush breaking contact with the ring, or at any rate reducing the pressure to a very small value; but it is equally certain that the low points on the oscillograph record indicate good contact between brush and ring, and therefore we have an increased mean voltage-drop due to an intermittent contact. Nevertheless, if the speed is increased sufficiently or the brush pressure sufficiently reduced then an air film is established, as shown by Fig. 12, and the voltage-drop increases very considerably. This, however, must be considered to be an abnormal condition, and one under which only a small current will pass and very violent sparking takes place; no real contact can be considered to exist. The theory of intermittent contact is therefore the correct one and accounts for the rise in contact-drop and the reduction in coefficient of friction with increase of speed.

The author desires to acknowledge, with thanks, assistance rendered by Prof. C. L. Fortescue, O.B.E., M.A., and Mr. J. W. Sims of the City and Guilds (Engineering) College.

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DISCUSSION ON

"AN INVESTIGATION OF EARTHING RESISTANCES." *

Messrs. P. D. Morgan and **H. G. Taylor** (*communicated*): *Electrical Endosmose.*—On page 737 the author states that "when the direct current flowed continuously . . . it was noted that the soil near the *positive* electrode was getting wetter and that near the negative electrode drier." Again, on page 738 it is stated that in another similar test the percentage of moisture was 7·1 per cent adjacent to the negative electrode and 16·5 per cent at the positive. On the other hand, on page 738, column 2, in the description of Fig. 5 it is stated that the moisture collected at the *negative* electrode, which appears to contradict the former statements if all the effects are to be ascribed to electrical endosmose. Fig. 4 shows a very large increase of resistance of the sample of soil after the passage of a small current for 50 hours. Part of this effect appears to be due to diminution of the total amount of moisture in the soil and part due to moisture movement. By using the figures given in Table 1 for change in resistivity of sandy loam with moisture content, and the stated values of the percentage moisture in the three sections after the test, it is estimated that the increase in resistance due to movement and evaporation of the moisture is less than 300 ohms, i.e. about 25 per cent. The actual increase in resistance recorded by the author, however, was about 320 per cent. A curve relating the percentage moisture to the distance from positive electrode, when extrapolated back to zero, indicates that the layer of soil touching the electrode is only sufficiently dry to have a resistance of twice its initial value. It seems clear, therefore, that the major part of the increase of resistance is due to some phenomenon such as the formation of gas films around the soil particles and on the surface of the electrodes. This is an important piece of evidence in connection with the comprehensive research which the E.R.A. is now carrying out on the problem of earthing in relation to power systems. The author's results suggest that an increase of resistance is to be expected with an earth electrode from which a current is steadily flowing to the soil, owing to electrolysis and to gradual moving away of the moisture. The figures given by the author for an earth plate (page 745) are 10 to 20 per cent, but some explanation is needed to account for these low results. Further work might well be done to find out whether, under any practical conditions, an increase of resistance takes place which is comparable with the 4 : 1 increase obtained by the author when using a tube containing soil. On the other hand the results show that, where a current is steadily flowing to an earth electrode from the soil, moisture moves in the same direction, and so tends to counteract the effect of the gas evolved from the electrolysis of the water. Whether sufficient water can be moved by this means to keep an electrode permanently moist, and keep its resistance low despite the gas evolved, is an interesting speculation which might repay investigation. The tramway system negative busbar earth plate is an example of a case where the current is always flowing towards the electrode. These results also indicate the errors which may occur from the use of direct current for measuring the resistance of earth electrodes. In connection with the author's second electrical endosmose experiment, it would have been interesting if, after obtaining a head of water of 9 ft. and a minimum current of about 36 mA, he had reversed the direction of flow of current and noted how its value changed as the head of water diminished. The result might have modified his view that "the phenomenon was one of mechanical back-pressure affecting electrical resistance in the same way as an electrical back-voltage." For the analogy to hold it would be necessary for the current to jump to a value in excess of that with which the experiment commenced, and then gradually fall to the initial value as the head of water diminished to zero. This seems hardly likely to take place.

Electrode Resistance Measurements and Comparison with Theoretical Values.—The author has been a little unfortunate in the piece of land he used for his tests on earth electrodes, and this renders difficult any comparison between the practical results and the expectations from theory. An example of this difficulty is seen in comparing the curves of Fig. 16 with the results shown in the second and third parts of Table 7. Both the tables and the curves refer to the variation in resistance with separation of 6 ft. by 1-inch pipes connected in series and parallel. If the values given are plotted it is found that the first three points fall on a curve similar to the theoretical curve (the difference in position of the two curves is of little account and coincidence would occur by selecting a slightly higher value of resistivity). The fourth point, however, upsets the curve entirely and this suggests that the resistance of electrode No. 5 is much higher than that of Nos. 1 to 4. This is confirmed by the fact that the resistance of No. 1 and No. 5 in parallel and 12 ft. apart, is greater than that of No. 1 and No. 2 in parallel and only 1 ft. apart. Unfortunately, the author does not give the separate resistances of electrodes Nos. 1 to 5. The value of experiments to determine the change of resistance with spacing is considerably diminished if the electrodes are not all of approximately the same resistance. In the case of the plate electrodes the theoretical values agree well with those obtained in the author's tests and it seems that, at least for these tests, the resistivity has been chosen correctly. From this it appears that in the case under consideration the average resistivity around a plate buried 6 ft. below the surface is about 10 000 ohms per cm^3. The decrease in resistivity with depth, referred to by the author on page 742, would therefore account for a value of 10 000 ohms per cm^3 being too low for driven pipes. Again, with the strip electrodes the curves plotted from theoretical and test values agree well in shape except for the fact that the theoretical value of 29 ohms given for the resistance between strips 16 ft. apart does not fit the curve well; 32 ohms seems more nearly the value. The large disparity in actual value is again accounted for by the fact that the resistivity of the soil is highest near the surface. The strips were buried at a depth of 1 ft. The author has given a large number of theoretical resistance curves, but the value of these is liable to be diminished on account of the large difference between the calculations and measurements for his own tests. We have shown above that there is probably a rational explanation for this difference and it seems that the results would have been more valuable, and greater dependence would have been placed on the theoretical curves, if the author had taken account of the variation of resistivity with depth.

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* Paper by Mr. P. J. HIGGS (see page 736).

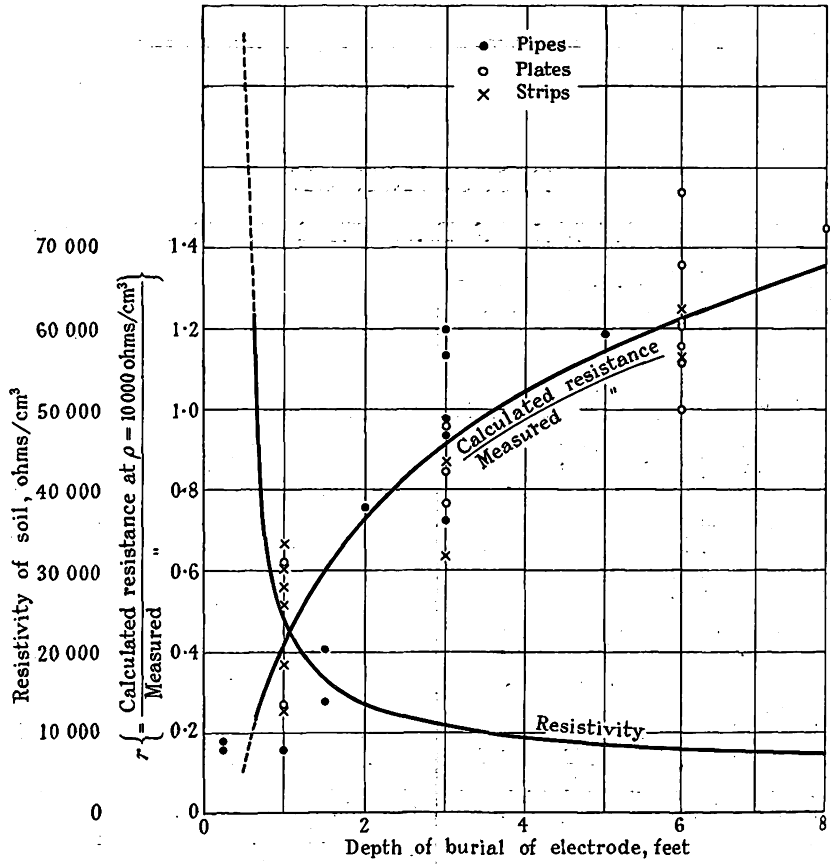

FIG. A.—Variation of resistivity and ratio of calculated to measured value of resistance with depth of electrode.

Variation of Resistivity and its Effect on Theoretical Values of Electrode Resistance.—We have calculated the ratio of the theoretical value of resistance to the mean measured value and find that for driven pipes this varies from 0·16 to 1·20, for plates from 0·27 to 1·54, and for strips from 0·26 to 1·25. In each case we have considered only the simple types of electrodes and have neglected the measurements for electrodes in series and parallel. These large variations are clearly due to changes in resistivity and it seems probable that these changes are in a large measure due to the varying depth of burial of the electrodes. We have therefore plotted a diagram (Fig. A) showing how the ratio varies with the depth, and, using the method of averages, have plotted the best curve to fit the points. (For the driven pipes we have assumed the depth to be half the length of the pipe.) It can be seen quite clearly that the ratio increases with the depth. It will also be noticed that the local variation of resistivity diminishes as the depth increases (see Table A). Fig. B shows how the ratio of the maximum to the minimum resistivity varies with depth.

TABLE A.

Depth	Maximum value of r	Minimum value of r	Ratio $\frac{\text{Max.}}{\text{Min.}}$
ft.			
1	0·67	0·16	4·18
3	1·2	0·64	1·88
6	1·535	1·0	1·535

On the assumption that the method of calculation used by the author gives a correct result, and since the resistance is proportional to the resistivity, we may say:—

$$\frac{\text{Calculated resistance of electrode (at } \rho = 10\,000 \text{ ohms/cm}^3)}{\text{Mean measured resistance}} = \frac{10\,000}{\rho}$$

Where ρ = actual average resistivity,

or $r = 10\,000/\rho$ . . . . (1)

$$\text{From (1)} \quad \frac{\text{Maximum value of } r}{\text{Minimum value of } r} = \frac{10\,000/\rho_{min.}}{10\,000/\rho_{max.}} = \frac{\rho_{max.}}{\rho_{min.}}$$

Therefore the last column in Table A and also in Table B is a measure of the variation of resistivity. From (1) the resistivity may be calculated for various values of r and hence, from Fig. A, for various values of the depth. This gives the curve relating resistivity to depth shown in Fig. A. It should be understood that these values of resistivity are based on mean values of resistance taken over a period of one year and that they are the mean values for the soil extending to at least 1 ft. on either side of a plate or strip. For a pipe, they refer to the mean value over the whole of its length. It would be interesting if the author could make direct measurements of resistivity at various depths to confirm this curve. The use of the values of resistivity obtained from the curve will bring the average value of the ratio of the theoretical to the measured value of resistance to unity.

TABLE B.

Type of electrode	Resistance		$\frac{\text{Calculated value}}{\text{Measured value}} = r$	$\frac{\text{Maximum value of } r}{\text{Minimum value of } r}$
	Measured	Calculated		
	ohms	ohms		
Pipes	39	46	1·20	7·5
	940	152	0·16	
Plates	13·1	20	1·54	5·7
	141	38	0·27	
Strips	24	30	1·25	4·8
	155	40	0·26	

Table B is obtained from the author's results and shows that by grouping them according to the type of electrode the ratio of the maximum value of r to the minimum varies from 4·8 to 7·5, and, if the type of electrode is disregarded, the figure is 9·7. If, however, the results are grouped as shown in Table A, according to depth of burial of the electrodes, and irrespective of their type, the figure is reduced to less than 4·2 in all cases. These figures represent the ratio of the maximum to the minimum resistivity. The resistivity varies both with locality and depth. Account has been taken of the latter factor, thus leaving only a locality variation, which, as stated, has a maximum value of 4·2 at 1 ft. depth and a much lower value at greater depths. It is clear, therefore, that the quality of the ground used by the author for his tests is not quite as bad as he inferred.

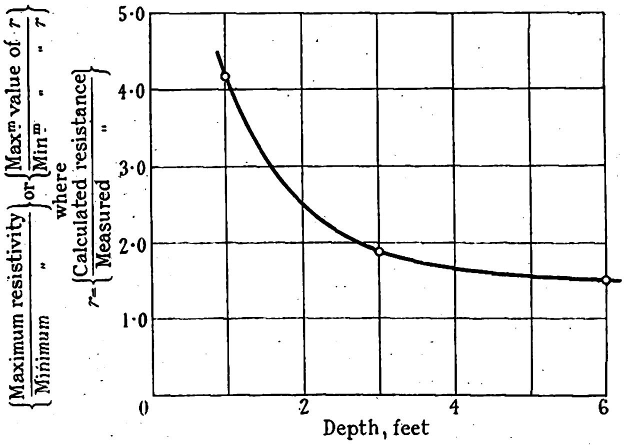

FIG. B.—Degree of variation of resistivity of soil at various depths.

Corrosion of Electrodes.—The author states on page 745 that the corrosion of an electrode may increase its resistance. This is contrary to the view of the Bureau of Standards,* who state that as a result of their tests, and also from the fact that rust layers formed in soil are permeable to water and are of no higher resistance than most soils, they have concluded that rust is of no effect in increasing the resistance of earth connections.

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* "Ground Connections for Electrical Systems," Bureau of Standards Technological Paper No. 108, p. 9.

Mr. G. F. Tagg (*communicated*): A considerable portion of the paper is devoted to tests carried out on samples of soil dug out of the ground, such tests being carried out in the laboratory. These tests do give a considerable amount of useful information as to the variations in the resistance of soil with temperature and moisture content, and also investigate the effect of electrical endosmose. The resistivity so obtained cannot, however, be taken as an indication of the resistivity of the soil before it was disturbed. From tests which have been carried out to investigate this point, it is quite evident that disturbing the soil by taking it up alters the resistivity very appreciably. This, of course, is most likely due to the difference in packing. The measurements of the various types of earth connections were carried out either by the three-point method or by measuring the resistance of two electrodes in series, the resistance of one being known. In the case of the electrodes with which the author had to deal, the values of the resistances were approximately of the same order, and thus the three-point method doubtless gave satisfactory results. It is not, however, a method of measurement which would be recommended in practice, as it can only be safely employed if there are three earth connections available, the resistances of which are of the same order of magnitude. If it is necessary to employ temporary earths such as pipes driven 2 or 3 ft. in the ground, the method should not be used as the resistances of such pipes may be 50 or 100 times that of the earth plate being measured, and cases have been known where observational errors of quite a small magnitude, say 2 per cent, have produced as a final result a negative resistance for the earth plate. Such methods as the alternating-current fall-of-potential method or one of its modifications are much more satisfactory for general testing. In calculating the values of the resistances of the earth connections, the author has assumed a figure for the resistivity of earth of 10 000 ohms per cm cube, but there is no indication as to the reason for this assumption. It is surely evident, as in fact the author mentions in one place, that the variation in the resistances of pipes of the same dimensions is a definite indication that the resistivity of the soil is different in various localities. For pipes of the same size different resistances can only be accounted for theoretically by different resistivity of the soil, as is evident from the formula $R = \rho/(2\pi C)$. It would have been more satisfactory if the resistivity of the soil in the immediate neighbourhood of each electrode has been measured by the four-electrode method. A number of tests in the immediate vicinity of each electrode would doubtless have given a good average value for the resistivity of the soil immediately surrounding that electrode. This would have enabled the resistance of each electrode to have been calculated with a possibly closer degree of accuracy. There is another reason, however, for discrepancies in the resistances, particularly in the case of pipes driven in the ground. It is a very difficult matter to drive a pipe into the ground in a perfectly uniform manner, and in all probability the soil will be more tightly packed in some places than others, and in fact there may even be places where the soil is making no contact whatever with the metal of the pipe. If tests are made immediately the pipe has been driven or within a short time afterwards, the resistance obtained is certain to be higher than the calculated value. In calculating the values of the resistances of the various types of earth plates, the author has gone to considerable trouble in developing formulæ. It is to be noted, however, that these are all based on the formula for a driven pipe which is again based on an assumption which is not strictly true. A rather more simple formula which has been quite extensively employed in connection with driven pipes can be developed by assuming that the pipe, together with its image above the surface of the earth, forms an ellipsoid of revolution. Then if

l = depth in centimetres to which the pipe is driven into the earth,
d = the diameter in centimetres of the pipe,
ρ = the resistivity of the surrounding soil in ohms per centimetre cube,

the resistance R may be written

$$R = \frac{\rho}{2\pi l} \times \log_e \frac{4l}{d}$$

This formula is perhaps more easily handled than the one given by the author.

Mr. P. J. Higgs (*in reply*): I thank Messrs. Morgan and Taylor for indicating the need for two minor corrections. In the description of the endosmose experiments on pages 737–8, the words "positive" and "negative" regarding the electrodes should be transposed; the meaning is shown by the wording that "the effect . . . was one of movement of moisture in the direction of the current flow." In Table 9 the calculated resistance of the strips in series and 16 ft. apart should be 32 ohms instead of 29 ohms. It seems probable that the major part of the increase of resistance shown by Fig. 4 is due to an effect of gas films, as suggested. It is possible, however, that the layer of soil touching the positive electrode may have become very dry due to the combined effects of endosmose and of the heating at the high-resistance contact.

Account was not taken of the variation of resistivity with depth in the calculations in order that the results may be of general instead of local significance, for the variation would be appreciably different in different localities and would itself vary with the seasonal changes in any particular locality. A piece of land having normally a resistivity that decreased with depth may, for example, have the conditions actually reversed during a period of rain following a drought. It seems, therefore, that to have localized the theoretical calculations would have made the results possibly confusing or misleading in a wider sense. Local variations in soil resistivity should certainly be taken into account in practice as they are known to occur.

If the variation of resistivity with depth had been taken into account in the theory, the resistance measurements and the theoretical values would have more nearly corresponded. The measurements show, however—if the theory be assumed correct—a local variation in soil resistivity of over 100 per cent of a mean value at a depth of 1 ft. and of nearly 50 per cent at 6 ft., which percentages would probably have been greater if the measurements had been a single set of readings instead of the average of 7 sets covering one year. These percentages are the limits of accuracy to which the resistivity for the calculations could be taken, and they appear to be much too large for any useful purpose to be served in attempting to correlate the measurements with the theory.

The piece of land used for the tests was considered unsuitable mainly in so far as its surface layer had been disturbed for purposes of cultivation, this being the probable reason for the high locality variation in soil resistivity at shallow depths. The unsuitability was recognized at the outset but the land was the only plot available for the purpose. If it had not been previously cultivated, however, it seems reasonable to suppose that it would have still had the variations of the greater depths. To attempt a comparison, that would be more or less satisfactory, of theoretical values with any such resistance measurements would appear, therefore, to be in any case a very intricate undertaking.

The individual resistances of electrodes Nos. 1 to 5, averaged over the year, were 56, 43, 49, 44 and 92 ohms respectively. Such values, together with the particulars of the variation of resistivity with depth, would have extended the paper, which was purposely curtailed for publication. The suggestions made for further investigation may well be carried out with advantage.

It would have been of interest if Mr. Tagg had briefly described the tests that were carried out to investigate the effect of digging soil out of the ground on the soil resistivity, giving typical results. The methods used in this investigation for testing the electrodes were simple and reliable.

The subject of the correlation of the theory with the measurements has been discussed above, the remarks that follow being additional. The measurements were made to give typical values of earthing resistance and seasonal change, there being a paucity of published information of the kind with reference to this country. The theory was developed (in an Appendix) to indicate the relative inherent qualities for earthing purposes of the different types of electrodes that are commonly used —qualities that are quite independent of the vagaries of soil resistivity. This part of earthing technique seems to be of prime general importance and not to have previously been treated so fully. To indicate the inherent qualities it was necessary to assume a soil of uniform resistivity, and 10 000 ohms per cm cube was arbitrarily taken because it was a convenient round number as well as a representative value for the soil of the land used. Because the results of the investigation indicate that the soil resistivity varied appreciably with short distances in depth and locality; because the resistivity of the soil within a few feet of an electrode practically determines its resistance; and because the four-electrode method deals primarily with soil over a region of very much longer distances in locality and of many feet in depth, it is difficult to see how the four-electrode method could have been of material assistance in the correlation in the manner suggested. Laboratory tests on miniature electrodes in a homogeneous medium, such as water, would probably be more satisfactory in this respect than field tests.

The investigation was made on many electrodes, including several driven pipes, and, over a period of 3 years from the time they had just been installed, the measurements gave little evidence of any original discrepancies in resistance due to imperfect contact. The two formulæ—that given in the Appendix and that in the discussion above—for calculating the resistances of pipes are both based on assumptions that are not strictly true, and for similar reasons, and they give results that are within a few per cent of error of each other and, presumably, of the correct result. They would appear, therefore, to be about equally suitable. The theory used in the Appendix is, however, continuously applicable to pipes, strips and plates, and to any known arrangement of them. Assumptions that are not strictly true but are made to simplify otherwise extremely difficult mathematics and that give results within a small percentage error, should hardly seem untoward in problems of this nature.

INSTITUTION NOTES.

Letter from Kelvin to the late Dr. Kapp.

On pages 798 and 799 of the June issue (No. 402) of the *Journal* a facsimile letter was published which purported to be an original letter from Kelvin to the late Dr. Kapp, setting out the theory of the excitation of the field magnets of a dynamo.

The authenticity of the handwriting having been called into question by Mr. R. H. N. Vaudrey, the matter was investigated, with the result that it has been definitely acertained that the letter published in the *Journal* was a copy made by another hand and that the original Kelvin letter is in the possession of Mrs. Kapp.

"The Organization of the Electrical Industry in Great Britain."

The Institution has published in pamphlet form a paper by Mr. P. Good with the above title. It consists of a very full account of the organizations which exist to-day in the various branches of electrical engineering in this country. The information contained in the paper was collected for the use of the British National Committee of the International Electrotechnical Commission, and it has been considered desirable to publish it in a more readily available form. Any member of the Institution wishing to receive a copy should apply to the Secretary.

List of Members.

A new List of Members, corrected to the 1st September, 1930, is in preparation and will be ready about the end of October. Any member wishing to receive a copy should apply to the Secretary.

The Benevolent Fund.

On the last page of the cover of this issue of the *Journal* will be found an appeal for subscriptions, donations and legacies to the Benevolent Fund.

Annual Tables of Constants and Numerical Data.

A special reprint has just been published of constants and data relating to the subjects of Electricity, Magnetism and Electrochemistry, being extracts from Volume VII (1925–1926) of the above Tables, in which all explanations are given in both English and French.

The reprint (136 pages) has been compiled by Dr. A. Buffat, Mr. G. Durand (École Supérieure d'Électricité), Prof. G. Foex (Strasbourg University), Prof. R. L. Fortrat (University of Grenoble), Dr. N. Marinesco, and Prof. N. Thon (Jerusalem University).

Members of the Institution can purchase copies at the following reduced prices:

Cloth-bound copies: 60 fr. (10s.) instead of 90 fr.,

Paper-bound copies: 54 fr. (9s.) instead of 80 fr.,

on applying to the Secretary to the Publishing Committee, Mr. C. Marie, 9 rue de Bagneux, Paris VI^{e}, from whom full particulars can be obtained.

Purchasers will also be entitled to receive free of charge, until the stocks are exhausted, the corresponding reprints from Volumes III to VI of the Tables.

Proceedings of the Wireless Section.

82nd Meeting of the Wireless Section, 5th March, 1930.

Captain C. E. Kennedy-Purvis, R.N., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 5th February, 1930, were taken as read and were confirmed and signed.

A paper by Mr. H. J. Lucas, Associate Member, entitled "Some Developments of the Piezo-Electric Crystal as a Frequency Standard" (see page 855), and a paper by Mr. J. E. P. Vigoureux, M.Sc., Graduate, entitled "The Valve-Maintained Quartz Oscillator" (see page 265), were read and discussed.

The meeting terminated at 7.30 p.m. with a vote of thanks to the authors, which was moved by the Chairman and carried with acclamation.

83rd Meeting of the Wireless Section, 2nd April, 1930.

Captain C. E. Kennedy-Purvis, R.N., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 5th March, 1930, were taken as read and were confirmed and signed.

A paper by Mr. R. H. Barfield, M.Sc.(Eng.), Associate Member, entitled "Recent Developments in Direction-Finding Apparatus" (see page 1052), was read and discussed.

The meeting terminated at 7.40 p.m. with a vote of thanks to the authors, which was moved by the Chairman and carried with acclamation.

84th Meeting of the Wireless Section, 7th May, 1930.

Captain C. E. Kennedy-Purvis, R.N., Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting of the Wireless Section held on the 2nd April, 1930, were taken as read and were confirmed and signed.

The Chairman announced that the following nominations had been made by the Wireless Section Committee to fill the vacancies which would occur on the Committee on the 30th September, 1930:—

Chairman: C. E. Rickard, O.B.E.

Members of Committee: G. W. N. Cobbold, B.A., B. E. G. Mittell, G. Shearing, B.Sc., and E. H. Shaughnessy, O.B.E.

In the event of a ballot for the new Committee being required, Messrs. E. W. Moss and F. Tandy were appointed scrutineers.

A paper by Messrs. P. P. Eckersley, Member, and N. Ashbridge, B.Sc., entitled "A Wireless Broadcasting Transmitting Station for Dual Programme Service" (see page 1149), was read and discussed.

The meeting terminated at 7.20 p.m. with a vote of thanks to the authors, which was moved by the Chairman and carried with acclamation.

DEVELOPMENTS IN MACHINE TELEGRAPH SYSTEMS AND METHODS OF OPERATION.

By H. H. HARRISON, Member.

[*Paper first received* 30*th December*, 1929, *and in final form* 22*nd January*, 1930; *read before* THE INSTITUTION 27*th March*, *before the* NORTH-EASTERN CENTRE 10*th March*, *and before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 17*th March*, 1930.]

SUMMARY.

The design and operation of machine telegraph systems has been very considerably affected in recent years by the production of high-speed communication links of the trans-oceanic order of length, and by new methods of operation on land lines enabling the line plant unit—the telephone pair—with its series loading and its repeater stations *en route* to be used for either the transmission of telegraph signals or speech, or both, simultaneously and independently.

The regenerative repeater, by enabling several sections of cable and land line to be interlinked, has given rise to methods of operation far-reaching in their effect both from the point of view of economy to the Administration and from that of reliability and speed to the user.

While the possibility of connecting two remotely situated medium-traffic offices over a single channel of a main-line high-speed multiplex system has been known for a number of years, this has not led to any considerable developments in that direction. Conditions are, however, arising in which medium traffic offices will use start-stop single-channel systems to an increasing extent, and this is being influenced by the large number of channels rendered available by the dual use of the land telephone cable. Wherever the telephone network extends, the telegraph network is ready to hand, and the single-channel system will, in course of time, replace the multiplex system for inland telegraphy.

The long-distance links with their regenerative repeaters require a precision in speed and phase control not necessary heretofore, and a study of this subject therefore forms a considerable portion of this paper.

The sending and receiving apparatus of the start-stop single-channel system are the inverse of each other, and the paper endeavours to establish a general underlying principle for the different variants described.

The last phase of machine telegraphy will certainly be that in which intercommunication between centres will be automatically effected and intermediate manual transmission avoided. This is possible by reason of the large number of channels available through the previously-mentioned dual use of the wire plant, and by the present-day standard of automatic switching technique.

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Motor speed control; classification of motors.

Governors. Baudot governor; D.M.O. governor; theory of Doignon governor; electro-mechanical governors; tuning-fork speed control; phonic-wheel motor; control of tuning forks; clock control of fork or reed rates of vibration; gang control of synchronous motors; inter-office speed control.

Phase control. Baudot's method; automatic phase-finding; action point; Picard's modification; Baudot epicyclic correction gear; Rothermel's corrector; Creed's correcting mechanism; Creed-Willson corrector; Wood's corrector; American corrector; Foll and Muirhead's corrector.

Methods of generation of correction impulses. Picard's correction from the signals; Western Electric method; Pernot's method.

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General principles of synchronizing schemes.

Speed and phase indicators. Fork speed adjustment; fork speed adjusted to speed of distant fork; Morkrum speed indicator.

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Construction of tuning forks. Carpentier's fork; Muirhead's fork.

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(3) The Translator or receiving mechanism.

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(5) Regenerative repeaters.

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(6) Methods of operation of line plant.

Composite working; sub-audio telegraphy on telephone pairs; 2-power multiplex operation; morse multiplex telegraphy by division of line time; transposition of land-line Morse Code; duplex operation of long cables; 2-way working on loaded cables; distortion correction on long cables; channel reversing; automatic direction control.

(7) Start-stop machine telegraph operation.

General; all-electric systems; tape control of transmission; automatic transmitter control; bell signalling; overlap at receiving end; overlap at transmitting end; interlinking of start-stop system with duplex-multiplex circuits; mechanical distributors.

(8) The future of machine telegraphy.

Bibliography.

INTRODUCTION.

Since the previous occasion on which the author had the privilege of reviewing the subject of machine telegraphy before the Institution,* the development both in apparatus and in methods of operation has been extraordinarily intensive.

As the matter was then left, divergent opinions were held as to the respective merits of the 5-unit and Morse Codes, while radio telegraphy was relatively inferior to the land line or cable branches.

To-day, the employment of the 5-unit Code has been extended to transatlantic cables, while radio telegraphy has reached a position in which it has to be acknowledged as a serious rival to the older, established, means of long-distance communication.

The rivalry between wire and radio telegraphy has stimulated workers in both fields, with the result that submarine cables exist having a far greater traffic-carrying capacity than was ever thought practicable before.

This results from the early theoretical work of Vaschy and Heaviside and the practical work of Pupin and his co-workers, backed by the courage of the able minds controlling cable enterprises.

In the field of radio telegraphy the beam system of Marconi is fulfilling all the possibilities predicted for it, and the present position can be summarized by saying that we are now in possession of many communication links of the order of several thousand miles in length characterized by reliability and operating speeds held, until quite recently, to be impossible over such distances.

The centres of the world can be and are being linked up to a remarkable extent, and rapid communication with points, however remotely situated, has now come to be regarded as a commonplace.

The new conditions have reacted both on the design of apparatus and the refinement of methods. Thus, the high speeds now possible on transoceanic links have demanded a perfection in methods of synchronizing such that, by comparison, older methods are crude and inadequate. As in the transmission of still pictures and in television, synchronism is a fundamental requirement, so in modern machine telegraphy, where the object is to obtain a perfect picture of the transmitted signals, it is equally important.

Although the old method of allowing a small phase difference to accumulate at one end of the line and then correcting the distributor there is satisfactory for the comparatively short land line of a few hundred miles in length with a negligible distortion effect on the signals, it is not admissible for the long transoceanic or transcontinental link.

It is becoming increasingly necessary to run the distributors at as nearly equal speeds as possible so as to eliminate signal distortion by phase difference and to correct both ways by the passage of working signals. This involves speed control of a high degree of precision, and the speed must be frequently compared with some standard and adjusted to within the narrow limits allowed. This is only possible by reference to a master time-keeper—a clock—at both ends of the line, and the frequency of reference is as high as once per second.

Telegraph links can be indefinitely extended to-day, due to modern adaptations of the regenerative repeater invented by Baudot.

The combination of the vibrating relay principle of Gulstad with the regenerative repeater represents a new development of far-reaching importance. The relay can be so controlled that its vibrations are absolutely synchronous with the distant transmitter, an adjustment difficult to obtain in the ordinary way. The regenerative principle removes defects in the signals which would exist if the relay repeated directly, while the relay interpolates signals which would not get through with the regenerator alone. The interpolator-regenerator thus represents a new device resulting from a combination of old ideas, and it not only permits the formation of indefinitely long links but also secures greatly increased speed of operation.

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* *Journal I.E.E.*, 1916, vol. 54, p. 309.

New methods of increasing the capacity of the line plant by the use of multiple frequencies and, more especially, the dual use of line plant for both telegraph and telephone purposes, will have an important effect on inland telegraph systems in the future; it represents a considerable part of the development which has been at once so rapid and so wonderful.

The object of this paper is to attempt to describe the various advances which have been made in machine telegraphs and their operation. A careful review of the different sections of the paper will force the student to the conclusion that of all the many contributors to the art of machine telegraphy, Baudot deserves the highest place. If he had left only the regenerative repeater behind him, the telegraph industry would have owed him a heavy debt, but he has been a source of inspiration to many of the inventors who succeeded him, and the designers of start-stop mechanisms in particular.

The author has to acknowledge information freely placed at his disposal by the late Mr. C. W. Schaefer, Electrician-in-Chief of the Eastern Telegraph Co., and by Messrs. K. L. Wood and Higgitt of the same company, relative to their regenerative system of cable operation. His thanks are also due to Mr. H. Kingsbury, European Plant Engineer of the Western Union Cable Co., to Mr. Sterling Morton of the Teletype Corporation of Chicago, the late Mr. C. F. Wilkins of Muirhead and Co., to Mr. J. V. Foll of the same company, and to Mr. A. Gibbs, Chief Telegraph Engineer of the New Zealand Post Office.

Section (1). SPEED AND PHASE CONTROL.

General.

The basis of all machine telegraph systems is synchronism.

The two aspects of this part of the subject are:

(*a*) Main-line synchronism, i.e. the synchronism between two revolving shafts at the opposite ends of a telegraph line, and

(*b*) Local synchronism. This is the synchronism required between distributor and printer units where the printer runs continuously and at the same speed as the distributor shaft, e.g. the Baudot and Rowland systems of machine telegraphy, while the same expression may also be applied to the Murray multiplex and its derivatives, in which the printing mechanism is released and completes the cycle of operation in the time of one revolution of the distributor brush arms.

It is to synchronism that we owe the possibility of the re-formation of distorted incoming signals and their retransmission—perfectly shaped with all errors removed. It is thus possible to link long land lines or cables together by means of repeaters, because signal-shaping errors are eliminated at each repeating point instead of being amplified and propagated.

Main-line Synchronism.—It is a comparatively simple matter so to adjust the angular velocities of the two rotating shafts at the end of a telegraph line that they are very close to one another, but a small, hardly measurable, difference of speed will give rise to a very appreciable difference of phase in a very short time. Practical synchronism therefore involves means by which the motors may be adjusted to a desired speed as closely as possible and held there. This is not in itself sufficient, and correcting means have to be added by which the cumulative phase difference is periodically destroyed.

In general, it is the practice to make one of the two shafts the standard, or time-keeping, shaft, and compare the speed of the other with it from time to time, making any necessary adjustments by means of some form of correction. The correction may be effected by varying the speed of the controlled shaft or adjusting its phase, or both.

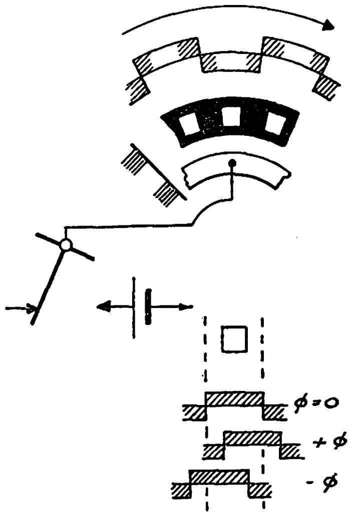

FIG. 1.—Influence of phase-swing on shortened segments.

It is usual to fix the speed of the controlled shaft at some definite fraction higher than that of the controlling master-clock shaft, and arrange for the gradually accumulating phase difference to determine a correcting influence before the phase error becomes large enough to mutilate the line signals.

For land-line working at speeds of 130 to 150 words per minute (5-unit code) phase differences of 1·25°, 0·9° and 0·75° per revolution have proved to be satisfactory. These correspond to speeds at the controlled end of 1·003, 1·0027 and 1·002 times those at the controlling ends.

Where great precision is required, it may be necessary to run at as nearly identical speeds as possible and then correct for phase deviation in either direction without appreciably affecting the speed. In addition, it is now being recognized that the integral effect of all phase corrections should be applied in such a direction as to vary the speed and make fewer phase corrections necessary. This refinement is not necessary on land lines of the length usually encountered, where there is ample margin; but on cable circuits, and more especially where two or more cables are interlinked, it is essential.

It is evident that, during running, the phase difference between the transmitted and received signals is continuously varying above and below the position of identical phase, and this phase swinging would cause overlapping of signals at the receiving end. Baudot recognized this and overcame the difficulty by shortening the receiving segments of his distributor, as shown in Fig. 1, thus retaining correct reception while allowing a phase error of $\pm \phi$.

It has been stated that the common feature of all synchronizing systems is the utilization of a slight deviation in phase to bring into operation forces preventing an indefinite increase in phase error. This is explained in a general way by Fig. 2. If the distributor brushes are running either fast or slow, these conditions can be represented by displacing the signal elements, as shown in the upper diagram. In addition to the signal-receiving segments, a set of correcting segments are provided, one pair for each signalling segment. The first of each pair, marked "F" in the diagram, are known as the "fast" segments, and the second, S, as the "slow." All the fast segments are multipled together, as are also the slow segments, and corrective forces are set up electrically in a variety of ways described later.

Motor Speed Control.

The first requisite of the motors employed is constancy of speed, the power required for the work to be done being usually insignificant.

There are three types of motor in use:

(1) Weight motors.
(2) Commercial-type electric motors.
(3) Synchronous motors with unwound iron armatures (phonic wheels).

Types (1) and (2) require some form of governor which will so adjust matters that a balance between the power applied to the motor and the power required to drive the distributor or other mechanism is maintained. The third type is driven by current impulses furnished from a vibrating reed or fork, the frequency of which is approximately constant over a fairly wide range of voltage variation and is only subject to slight creeping with variation of temperature.

The phonic-wheel motor is not capable of dealing with an appreciable load and hunts badly at about 0·01 h.p. For this reason it is sometimes combined with a d.c. motor, the speed of which is controlled by the same fork or reed as that driving the phonic motor itself. The constancy of operation of the one type is thus combined with the load capacity of the other, and two desirable features are thereby secured.

Such an arrangement is in use on the New York–Azores–Emden loaded cable.

Governors.

Baudot's Governor.—The centrifugal governor designed by Baudot is too well known to need description. Designed for Baudot apparatus and a standard speed of 180 r.p.m., it has given good service for nearly half a century.

D.M.O. Governor.—Recently (1925) a new type of governor which possesses remarkable properties has been developed for distributor speed control. Invented by two Portuguese telegraph engineers, Messrs. Mendonca and D'Oliveira, it has been constructed by the Ateliers L. Doignon of Paris, and is known as the D.M.O. governor. This governor is based on a principle the opposite to that which has hitherto been employed in nearly all printing-telegraph governors. The Baudot governor applies or withdraws an artificial load in accordance with the speed variation, so as to keep a balance between the load of the governed apparatus and the power supplied by the motor. In the D.M.O. governor, the power necessary to drive the apparatus at constant velocity is transmitted by the governor itself.

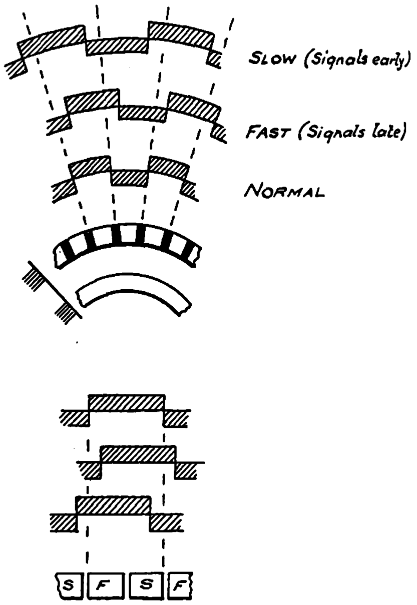

FIG. 2.—Generation of correction pulses from line signals.

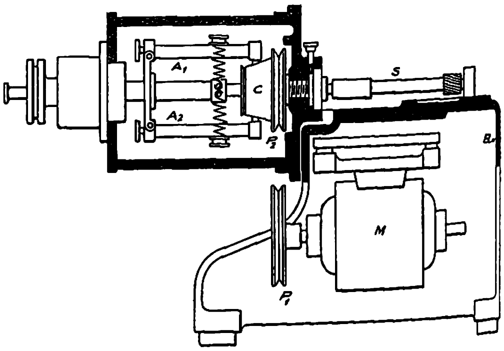

FIG. 3.—D.M.O. governor.

The construction of the governor, applied to drive a Baudot distributor by means of a commercial motor, is shown in Fig. 3. M is the motor carrying a pulley P_1, which drives shaft S through belt and pulley P_2, loose on shaft S. Pulley P_2 is coupled to shaft S through two arms A_1, A_2 pivoted at their left-hand ends to a cross-head solid with the shaft S. The right-hand ends carry friction pads which press with a certain force on the coned surface of P_2 by the agency of coiled springs.

As the motor M speeds up from zero speed, shaft S is carried round and follows the motor M, but when a certain critical speed is reached, slip is produced and S revolves at a constant speed regardless of that of the motor M.

The theory of the governor will be understood by reference to Fig. 4, which also represents an alternative method of construction.

Referring to Fig. 4, D_1 is a disc loose on the shaft S and carrying a pulley P driven by a belt from a motor (not shown). D_2 is a second disc rigidly connected to the shaft S and coupled to disc D_1 through friction pads "fp" mounted on the ends of two arms pivoted on D_2 which constitute the centrifugal masses of the governor. The two arms with their friction pads are kept up against the periphery of D_1 by a spiral spring, the tension of which counterbalances the centrifugal force of the masses "m." The friction coupling between D_1 and D_2 is proportional to the difference between the spring tension and the centrifugal force.

The power delivered

$$P_d = (T - m\omega_2^2 R)\mu R\omega_1 \quad . \quad . \quad . \quad (1)$$

where T = spring tension;

$m\omega_2^2 R$ = centrifugal force on the masses;
μ = coefficient of friction;
ω_1 = angular velocity of D_1;
ω_2 = angular velocity of D_2.

This power consists of two quantities:—

The useful power, $P_u = (T - m\omega_2^2 R)\mu R\omega_2 \quad . \quad . \quad (2)$
The power lost in heat, $P_l = (T - m\omega_2^2 R)\mu R(\omega_1 - \omega_2)$

Calling the resisting couple C, we have

$$\begin{aligned} P_u &= C\omega_2 \\ &= FR\omega_2 \quad . \quad . \quad . \quad . \quad . \quad (3) \end{aligned}$$

where F is the tangential resisting force.

Hence (2) can be written

$$P_u = (T - m\omega_2^2 R)\mu R\omega_2 = FR\omega_2$$

or

$$F = \mu(T - m\omega_2^2 R) \quad . \quad . \quad . \quad . \quad (4)$$

From the above it is seen that ω_2 is independent of ω_1. Also, from (4),

$$\omega_2 = \frac{T}{mR} - \frac{F}{\mu mR} \quad . \quad . \quad . \quad . \quad (5)$$

If the resisting couple is very small, ω^2 tends to approach $T/(mR)$. Obviously, to make ω depend as little as possible on F, F/μ must be small compared with T. This is done by using as large a spring tension as possible and a high coefficient of friction.

When these conditions are secured, then, as the critical velocity is reached, variations of ω_1 have no effect on ω_2, as shown by the curve in Fig. 4.

The speed of shaft S can be varied while running, by moving the governor arms A_1, A_2 (Fig. 3), backwards or forwards along the coned surface of the pulley. This increases or decreases T, and since matters are so adjusted that $\omega = \sqrt{T/(mr)}$ nearly, ω will vary as $\sqrt{T}$.

The results obtained with this governor are really remarkable. On the Lisbon–Oporto circuit *it* has maintained synchronism unfailingly, although the supply voltage to the motor at times varied between 30 and 40 per cent.

The French Government have reported its successful behaviour on the Paris–Lyons Baudot circuit and on the Paris–Lille sextuple Baudot circuit. Variations of voltage from 110 to 80 volts have not disturbed the distributor speeds. It has now been officially adopted by the French Administration.

Some 200 governors of this type have been fitted to the impulse sender mechanisms in the London automatic telephone system and have given satisfactory service.

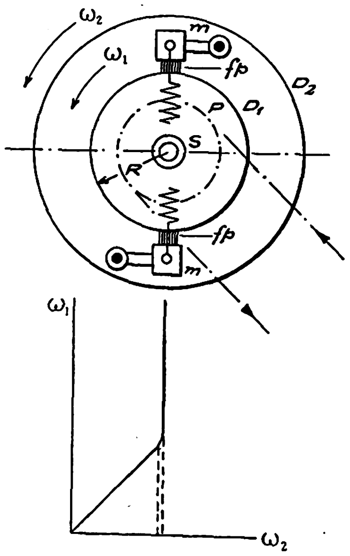

FIG. 4.—Theory of D.M.O. governor.

Governors, Electro-mechanical.—Fig. 5 shows an electrical method of speed control of a d.c. motor which depends upon a centrifugal governor. The motor shaft has mounted on it a disc D carrying a spring S loaded with a weight W. During the upper portion of a revolution of D, gravity acts against the centrifugal force of W, whilst gravity assists during the lower half of D's movement. S and W effect a short-circuit for half a revolution over the slip-rings SR on the resistance R_1, and the motor is accelerated and retarded periodically so that it runs at a certain mean speed.

In addition, the relay R is alternately operated and de-energized so that the pilot motor PM inserts and withdraws a vernier resistance R_2 in series with R_1. The weight W and spring S are so adjusted as to operate as described when the correct speed is attained. Any departure from normal speed varies the period of short-circuit, due to the weight-loaded spring S. If the motor tends to run fast the short-circuit is maintained when S is in the position shown in the diagram, centrifugal force overcoming gravity. If the motor runs slow the combined effect of gravity and centrifugal force is reduced and the period of short-circuiting is of less duration than when the speed is normal.

This method of speed control is due to the Lorenz Co. and is applied to high-frequency radio alternators. It is stated to give a regulation as close as 1 in 1 000.

Tuning-fork Control of Motor Speed.—The time-keeping properties of a tuning-fork may be utilized to keep the speed of a d.c. motor constant.

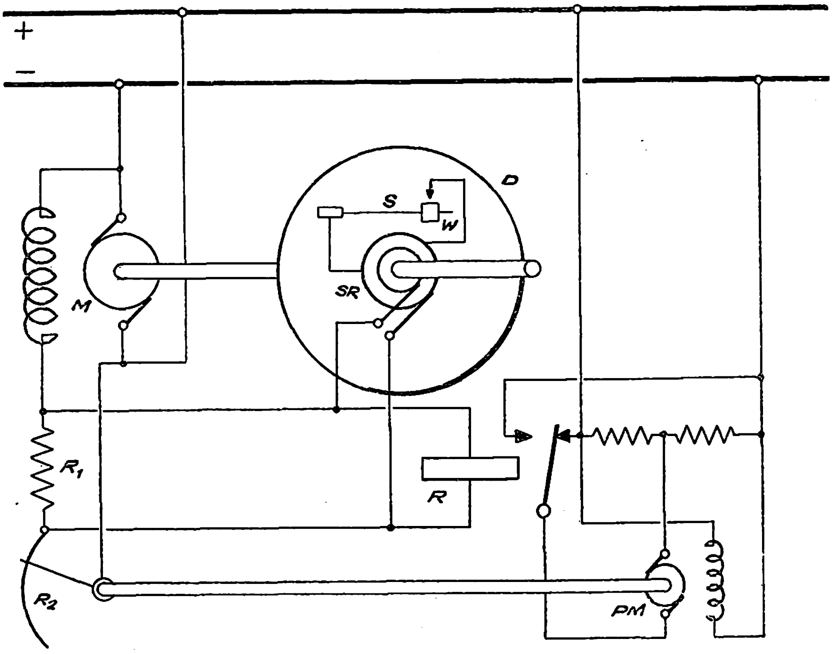

Fig. 5.—Electrical governor (Lorenz).

Fig. 6 illustrates an arrangement designed by the Morkrum Co. for speed control of a motor driven from d.c. supply mains. The fork induces alternating current in the secondary windings S of the transformer T. Two tappings are taken from the motor armature and led to slip-rings, by which they are connected through a lamp L to the secondary S of transformer T. If the motor runs at such a speed that the a.c. frequency generated is equal to the fork frequency, the fork will pull the motor into synchronism and it will operate practically as a synchronous motor. The motor speed is thus determined by the fork, and, since the fork frequency is very constant, the motor speed will remain constant also. The lamp L acts as a stabilizing load on the motor and also as a synchronism indicator. It burns steadily when the fork and motor are in phase and flickers when this phase relationship is disturbed. This arrangement, together with a phonic-wheel motor coupled to the same shaft and driven by the common fork, is the arrangement adopted on the Emden-New York cable previously referred to.

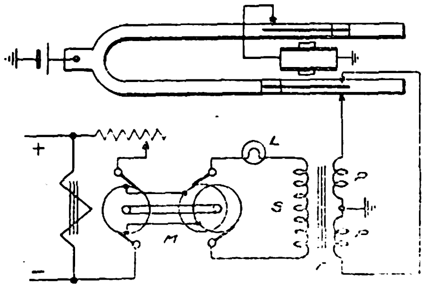

Fig. 6.—Morkrum fork control of d.c. motor.

Fig. 7 shows an arrangement due to Potts. The motor M is provided with a crown-wheel commutator C mounted on its shaft and provided with three brushes. The two outer brushes are joined to the pair of contacts controlled by one tine of the fork F. When the motor is running at the right speed, the number of contacts passed over by the central brush is the same as the number of half-vibrations of the fork in unit time. If the motor lags, the phase of commutator and fork contacts is upset and the resistance R is short-circuited, so that the current to the motor is increased.

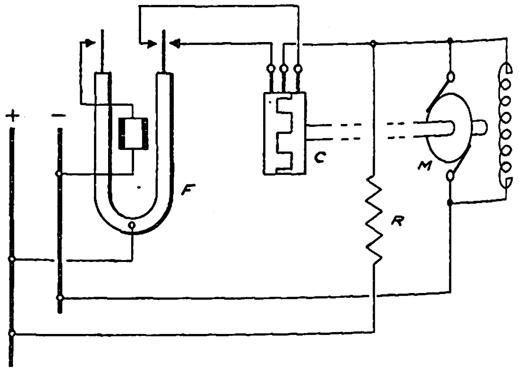

Fig. 7.—Potts's fork control of d.c. motor.

In the method shown in Fig. 8 a reed R drives a phonic-wheel motor PWM on the shaft of which is a disc D_1.

The d.c. motor is provided with a disc D_2. Each disc has a contact segment embracing a half-diameter. D_2 is set in advance of D_1 and, in the position shown, short-circuits a portion R_1 of the resistance $(R_1 + R_2)$.

Any variation of speed of DCM results in the period of short-circuiting being varied to retard or accelerate the motor.

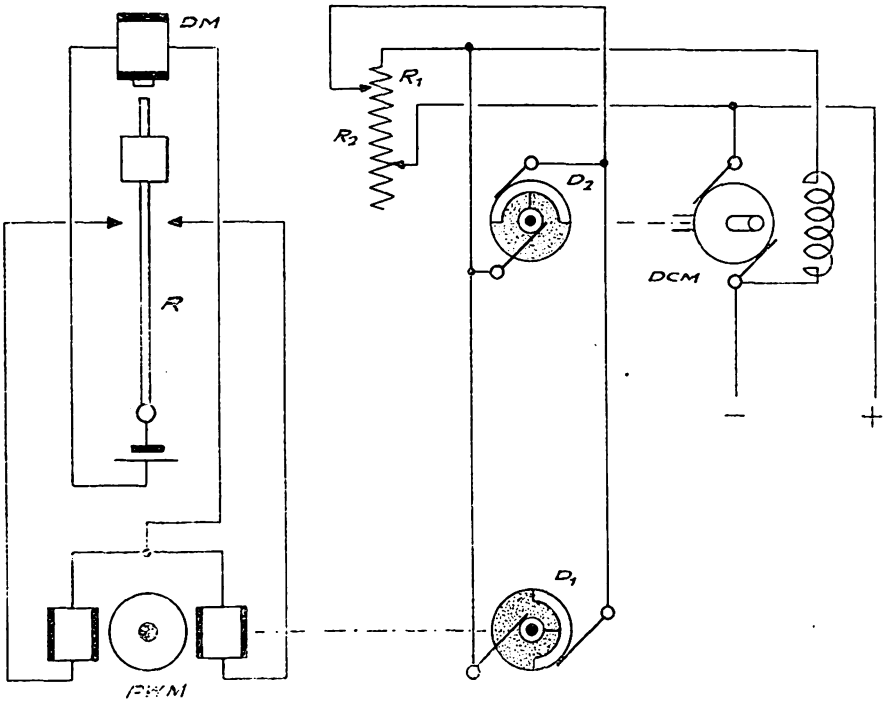

FIG. 8.—Phonic-wheel control of d.c. motor.

A method of accurately controlling the speed of d.c. motors, due to Mr. H. V. Higgitt of the Eastern Telegraph Co., is detailed in Fig. 9. Two multiple-segment commutators are swept over by brushes B_1, B_2 driven by the d.c. machine DCM and a phonic-wheel motor PWM, respectively. The brushes revolve at equal speeds through step-down and step-up gears. Normally, brush B_1 lags behind brush B_2, so that a certain number of resistance units are inserted in the field circuit of D.C.M. The phase angle between the brushes is determined by the voltage and the load on DCM. If this motor tends to lag, the phase difference increases and more resistance is inserted in the field. The reverse happens if it tends to accelerate. The speed is held at the desired point within the limits of the speed accuracy of the phonic-wheel motor. The motor DCM could be made to drive an alternator by which alternating current at a very constant frequency could be generated. Such an alternator could be of quite considerable power.

Phonic-Wheel Motor with Fork or Reed Control.—The phonic-wheel motor independently discovered by La Cour and Lord Rayleigh in 1865 is too well known to need description. Driven by a vibrating reed or tuning-fork it constitutes one of the best methods of furnishing the steady distributor speeds so essential to machine telegraphy. Although originally used by Delany and La Cour for morse multiplex systems, its energetic advocacy by Donald Murray has led to its adoption in England and America, and it has even penetrated to France, the home of the Baudot system.

The French telegraph engineer, Mercy, mentions its application to the Athens–Salonica quadruple circuit where the supply voltage varied between 180 and 240 volts. Salonica held Athens in synchronism in spite of the variable voltage, this being explained by the fact that a variation of 100 per cent in the energy supplied to the fork magnets caused, according to Mercy, a frequency variation of only 0·9 per cent. Mercy goes on to say that it does not require skilled attention and its maintenance is almost nil, and expresses the opinion that the phonic-wheel drive will render the Baudot system more practical and more robust and give more scope to its

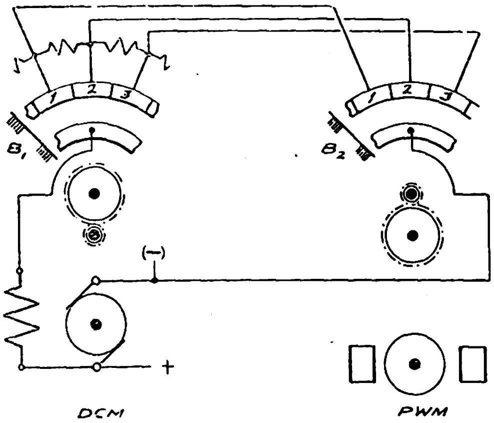

FIG. 9.—Higgitt's phonic-wheel control of d.c. motor

extension. This is in line with the experience of others.

As previously stated, the motor can be driven by either a reed or a fork, both of which possess identical properties and are equally satisfactory in use.

The explanation of the extremely satisfactory nature of the phonic-wheel fork-reed method of driving distributor brushes is simple. The motor is driven round tooth by tooth by receipt of current pulses fed to the driving magnets. So long as the rate of delivery of the pulses is constant, the motor revolutions are constant too.

The fork or reed can be constructed to have a natural frequency of vibration, which can be varied over a certain range by loading the tines with a weight or weights.

The rate of vibration of a fork or reed is subject to slight changes, due to the following external causes.

(1) Variation of current in driving magnet. If the driving current is reduced, the amplitude of vibration is reduced also and the rate of vibration is increased. The converse happens if the driving current is increased. The amplitude increases at the expense of the frequency.
(2) The adjustment of the driving contacts affects the degree of change in the rate of vibration. Variations in frequency are also caused by variations in contact pressure and chattering of the contacts, each of which effects changes in the driving force.
(3) Welding of motor-driving contacts and sparking at fork-driving contacts.
(4) Voltage variation.
(5) Temperature variation.
(6) Overload.

Under (1) it is to be noted that the rate of change of frequency is not the same when the fork-driving circuit is changed to decrease the frequency, as it is when it is changed to increase the frequency.

The effect of voltage variation is very slight, but temperature variation is more serious. The latter may be overcome by using Sinevar—a nickel-steel alloy with an almost negligible temperature-coefficient. Ordinary steel forks or reeds decrease their frequency by about 0·1 of 1 per cent per degree C. rise of temperature.

Control of Tuning forks.—The general method of driving a fork (wherever subsequently the term " fork " is used, " reed " is to be understood as being comprised also) is through a contact on one of the tines butting on a fixed contact suitably supported on the frame (Fig. 10*a*). The frequency of the fork is brought approximately to that desired by similar weights (not shown) on each tine, and a vernier adjustment is provided by the electromagnet SCM, the pole-pieces of which are opposite the tines when the fork is quiescent. The magnetic effect of SCM increases the stiffness of the tines of the fork and produces an increase in the rate of vibration. This increase can be regulated within sufficiently wide limits by adjusting the resistance R. The ammeter A is calibrated in terms of the fork frequency. The arrangement is due to the Western Electric Co. In Fig. 10(*b*) the same arrangement is proposed by Messrs. Muirhead and Co. as a means of driving the fork, the current pulses being furnished on both excursions of the fork tines to and fro, the tines being pulled into the normal position from either limit of motion. The advantage of this method of driving the fork lies in the fact that the fork is impulsed each time the tines move in and out, and it avoids the bias set up by the ordinary method where the tines are not vibrating in their normal position.

Small variations in frequency may be obtained by varying the gap between the tines and the driving magnet, which may also be slid along the tines, either above or below.

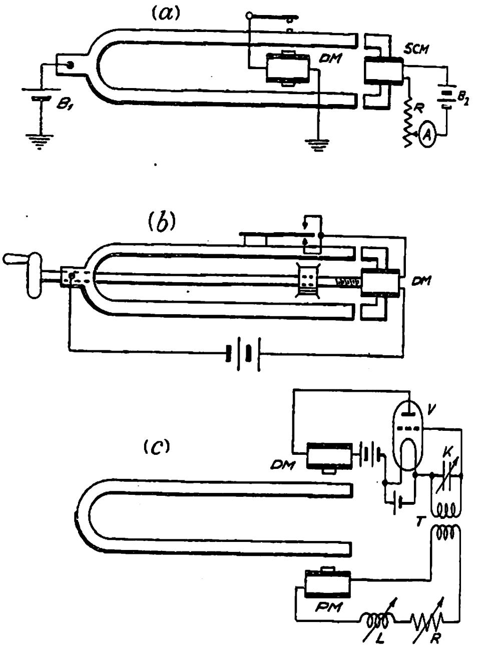

FIG. 10.—Three methods of tuning-fork control.

Fig. 10(*c*) shows a method of maintaining a fork in vibration by the use of a thermionic valve, and originates with the Western Electric Co. The operation of the arrangement is as follows: The fork is plucked to set it in vibration. An electromagnet PM with a polarized core acts as a generator and produces alternating current in the tuned circuit consisting of the transformer T, the secondary of which is also tuned. The voltage of this current is increased at the input terminals of the valve V, which, in turn, produces a considerable increase in the current through the driving magnet DM.

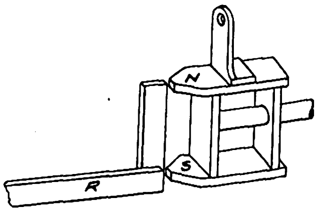

FIG. 11.—Higgitt's control of vibrating reed.

The phase relations between the current in PM and driving magnet DM are such that the generated current tends to maintain the vibration of the fork, which increases its amplitude until the energy dissipated becomes equal to the force supplied and the fork vibrates steadily at a given amplitude.

Fig. 11 shows Higgitt's method of controlling the frequency of a reed R of the Murray type. A small vertical steel piece is mounted on the free end of the reed and vibrates opposite the poles NS of two bar magnets mounted on a frame capable of oscillation. In the position shown the magnets act in the same way as the electromagnets of Fig. 10(*d*), and increase the stiffness of the reed. Its amplitude falls and the frequency rises. The control of the magnets may be reduced by rotating the whole system, thus weakening the effect on R and slowing it down.

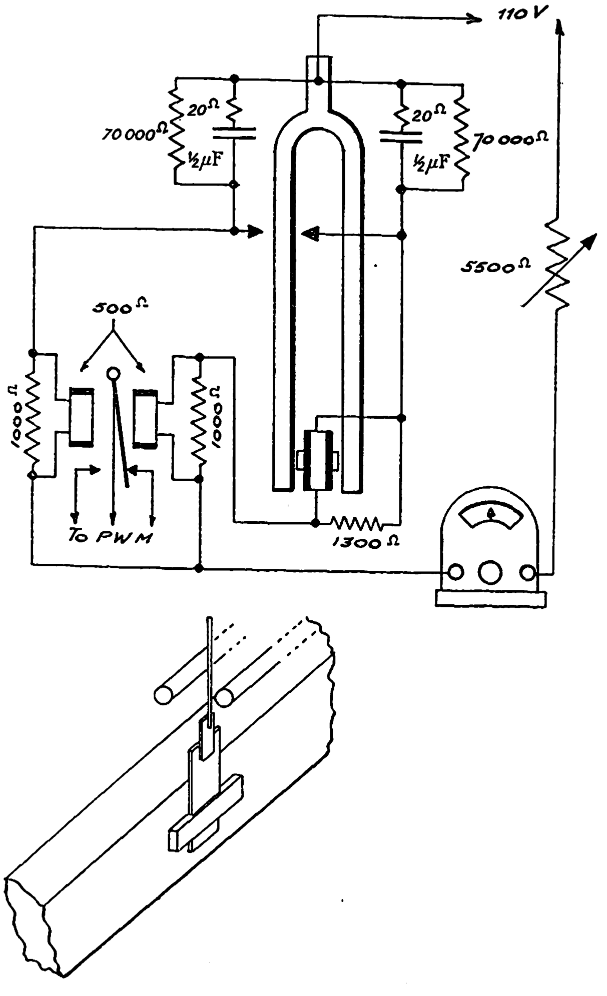

FIG. 12.—Muirhead's precision tuning-fork.

Fig. 12 represents a departure from practice by Messrs. Muirhead and Co. designed to give extreme constancy of frequency. Temperature variation has been met by the use of a non-temperature alloy for the tines. Frequency variation due to driving-contact spring control has been eliminated by dispensing with motor-driving contacts entirely and using the fork-driving contacts to control a relay which, in turn, controls one or more phonic-wheel motors. The type of contact employed is a 0·005 in. dia. platinum-iridium wire operating between two circular butts of the same material (see lower sketch of Fig. 12). The gap between the fixed butts is fixed, as variations of this gap affect the speed. The contacts are mounted on a carriage so as to be adjustable relatively to the moving-contact spring, which should be centrally between the fixed contacts when the fork is at rest. Sparking, even when scarcely evident, produces considerable variations in speed and this is eliminated by the spark-quenching circuits shown. The milliammeter is provided to keep the current to the fork-driving magnet constant. All causes of fork-frequency variation are eliminated as far as possible, and on a test lasting for several weeks the variation was found to be 0·0001 of 1 per cent with a maximum temperature difference of 26 deg. F. The advantages of this fork, as applied to synchronous telegraph working, are very considerable. When several regenerative repeaters are operated in series, there is phase variation due to distorted signals. By improving the constancy of speed at all points, the amount of correction necessary is considerably reduced. Four sets of tines are made, covering a frequency range of 400 to 4 000 cycles per minute.

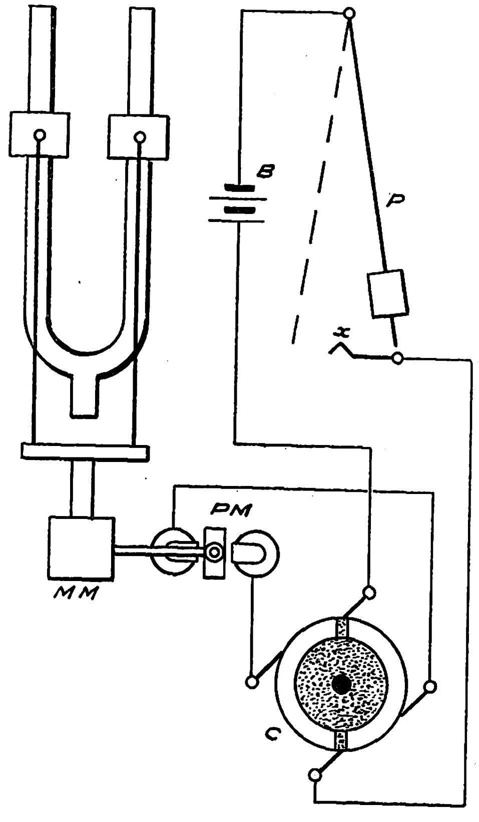

FIG. 13.—Brown's clock control of fork frequency.

Clock Control of Fork or Reed Rates of Vibration.—For a variety of reasons, dealt with later, motors of the phonic-wheel type when considered in connection with speed control of the type being discussed do not give an absolutely accurate control. S. G. Brown recognized this and brought out the arrangement of Fig. 13. Here the fork—driven by means not shown—has its frequency referred to a clock and its rate increased or reduced, depending upon the conditions indicated when the comparison is made. For this purpose the shaft of the phonic-wheel motor—not shown—carries a 2-part commutator C. The fork has two weights controlled by links so that they can be slid along the tines of the fork backwards or forwards, by the polarized relay PM and suitable mechanism MM. The operation of the arrangement is as follows: The relation between the to-and-fro swing of the pendulum and the revolution is such that if the speed of the motor is correct, i.e. it has made either one or an exact number of revolutions when the pendulum contact "x" is closed, the vertical brushes are standing as shown in the drawing and no circuit is closed for battery B. If the disc C is leading or lagging, the circuit is com-

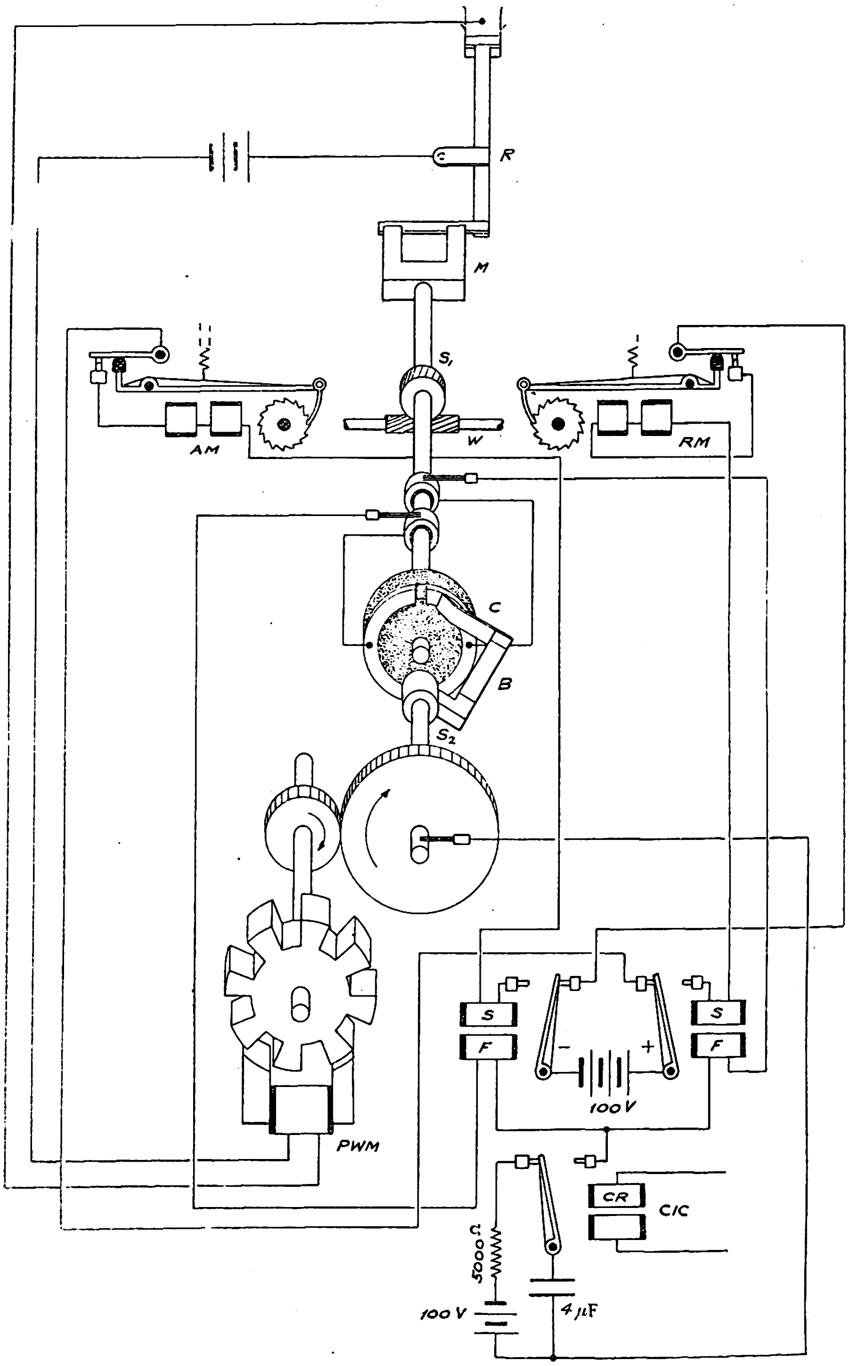

Fig. 14.—Eastern Telegraph Co.'s clock control of fork frequency.

pleted in one direction or the other through the polarized relay PM, and the weights are shifted to raise or lower the speed of the fork in accordance with the requirement which the position of C indicates. Since a good clock will keep accurate time to within a few seconds per day, the advantage of this method of fork-frequency control will readily be seen, and it furnishes means by which distributors in various offices remotely situated can be kept in very close synchronism with each other.

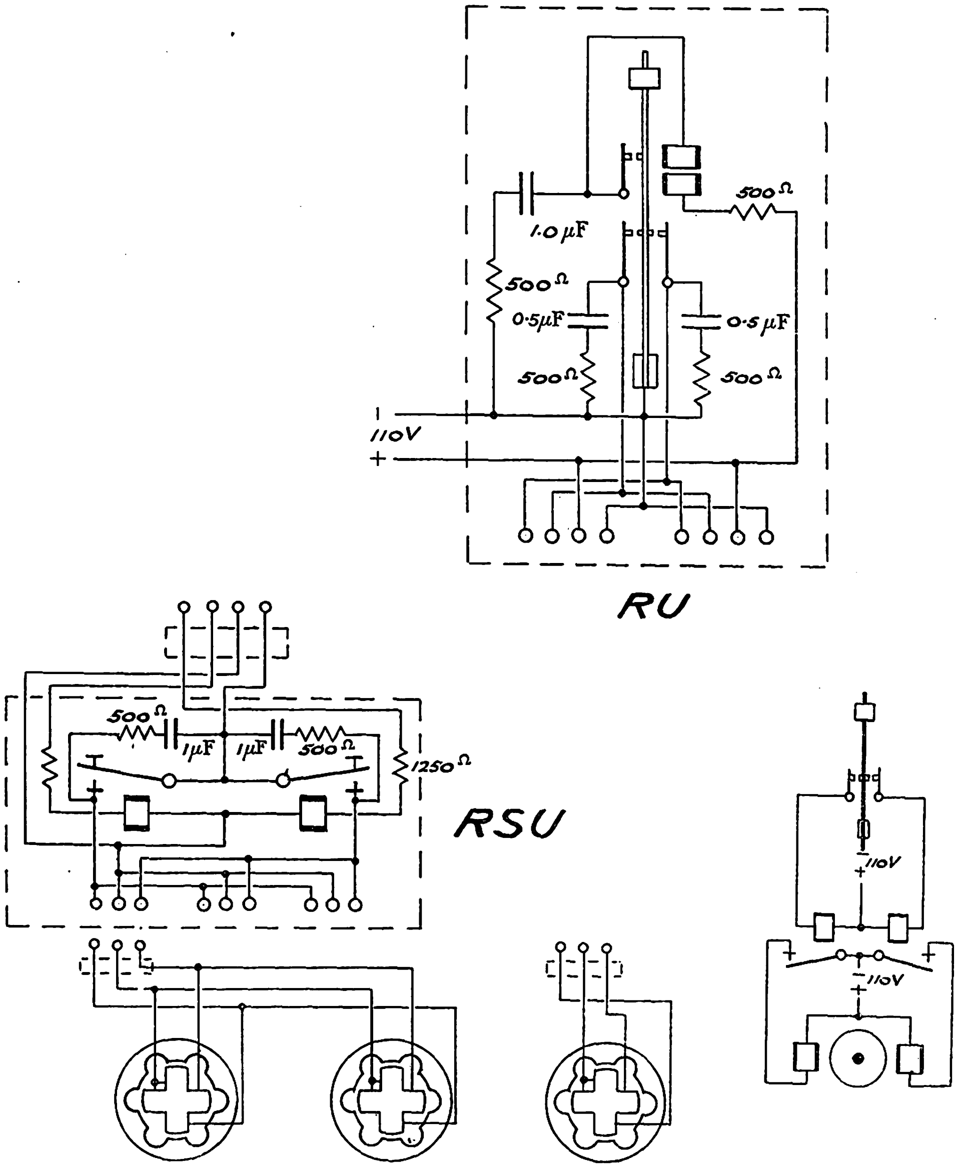

Fig. 15.—Eastern Telegraph Co.'s gang control of phonic-wheel motors.

The method of keeping the frequency of a reed or fork within narrow limits by periodic reference to a standard clock, as employed by the Eastern Telegraph Co. and invented by Higgitt, is detailed in Fig. 14. R is a reed, the driving contacts of which are not shown. M is a permanent magnet, the oscillation of which from time to time will, as previously explained, control the fork frequency at the desired value. The reed drives a phonic-wheel motor PWM which, through reduction gearing, rotates a brush B on shaft S_2 over a two-part commutator C. C is carried by a second shaft S_1 which carries the magnet M and is adapted to be rotated slightly in either direction by means of the worm gear W actuated by the two ratchet-and-pawl mechanisms shown. The brush B sweeps over the 2-part commutator C in 1 second and, if the reed frequency is correct will occupy a position midway between the two metallic segments on C at the end of each second of time. A Synchronome standard clock—not shown—sends out 1-second impulses over the clock impulsing circuit CIC in which there is included a correcting relay CR. In the normal, unoperated position of the armature of this relay, a 4-μF condenser is charged to 100 volts through a 5 000-ohm resistance. When the seconds impulse is received the armature of CR moves to its front contact and partly completes a circuit for the condenser to discharge through the flick magnets F of the two relays immediately above CR. If B has completed 1 revolution in 1 second, there is no path through which the condenser can discharge. If, however, the reed frequency is too high then B will be on the right-hand segment of C and the condenser will discharge through the flick magnet of the right-hand relay. The latter operates and closes a circuit from positive pole of 100-volt battery, its operated contact, stick or holding winding S, the magnet of the retarding mechanism, RM, contacts of armature of the latter, back contact of left-hand relay to negative pole of battery. RM operates over the circuit just traced, and its pawl moves its associated ratchet wheel and thereby the worm wheel W so that M is moved from the position shown to one where its control on the amplitude of R is reduced. The amplitude of R is increased and, therefore, its frequency is reduced. Subsequently, if R is running slowly M is moved back by the advance magnet AM. When either magnet operates fully it breaks down its own circuit and that of the stick circuit of its controlling relay. The two latter are interlocked through the back contacts of their armatures so that they cannot be operated at the same time if the correcting discharge current should divide between the two flick coils.

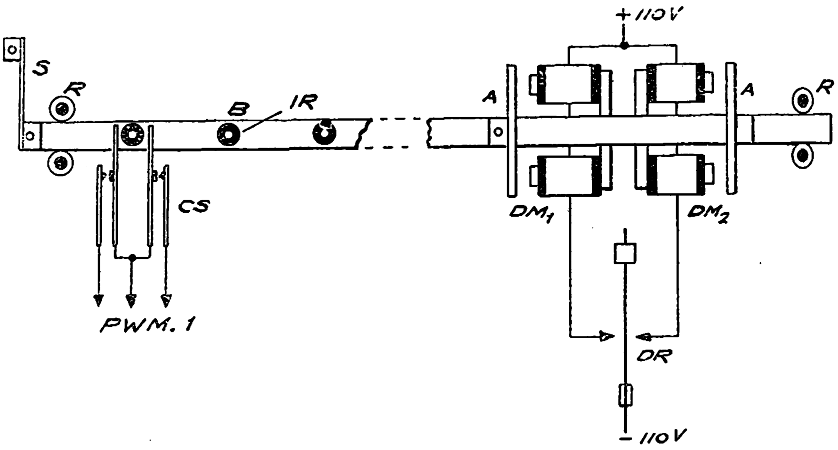

FIG. 16.—Method of gang control for phonic-wheel motors.

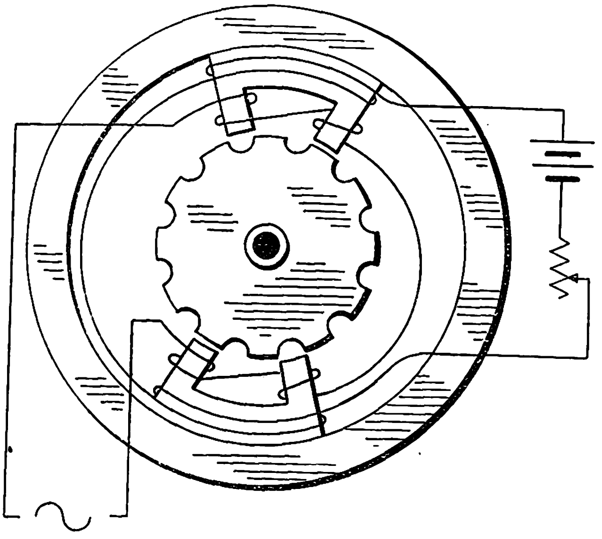

FIG. 17.—Polarized phonic-wheel motor

It will be seen that by the adoption of the clock control method just described it is possible to keep phonic-wheel motors at stations remote from each other running at speeds very closely identical, by means of the constant check on their driving reeds or forks. A standard clock such as the Synchronome will, if properly adjusted, keep correct time to within a second or so per day, and this gives some idea of the important step due to Higgitt's invention. The reed or fork has inherent time-keeping properties and on these is superposed a very accurate time control which takes account of slight frequency creeping due to any of the causes previously referred to.

Gang Driving of Synchronous Motors.—The speed control of a gang of phonic-wheel or other types of synchronous motors is divided into two broad aspects as follow:—

> The gang speed control of the motors in a single office.
>
> Interlinking gang-controlled motors in two or more offices.

The Eastern Telegraph Co. have done a considerable amount of work on the speed control of a gang of motors in one office, and Fig. 15 is an outline of their arrangements. RU is one of several reed units, the frequency of which is controlled by reference to a standard clock. Each reed unit is provided with connecting sockets by which it can control two reed sounder units RSU. Each of these units RSU has three parallel connecting sockets on the first of which it is customary to plug up two motors, and one on the second, leaving the third spare. The connections and operation of a phonic-wheel motor will be clear from the small sketch at the lower right-hand corner of the figure. By this arrangement one controlled reed can furnish driving pulses to 8 phonic-wheel motors. The author has seen this system in operation and is of the opinion that the arrangement is extremely efficient and reliable.

Another method of distributing constant-frequency pulses to a number of mechanisms is shown in Fig. 16. It consists of a bar B supported on rollers R and reciprocated by two sets of driving magnets DM_1 and DM_2, alternately energized by a vibrating reed DR. Along the bar and on both sides are placed, suitably spaced, insulating rollers IR adapted alternately to close pairs of contact springs CS which, in the diagram, are shown as controlling phonic-wheel motors.

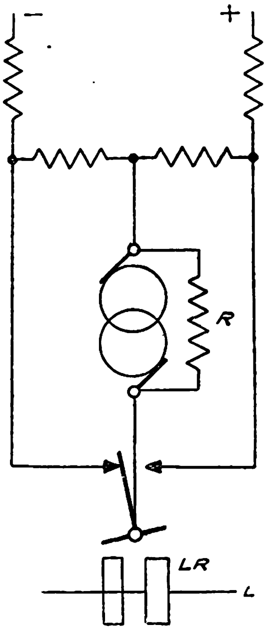

Fig. 18.—Inter-office control of synchronous motor.

By polarizing the driving magnets of a phonic-wheel motor as in Fig. 17, the motor can be run from a.c. supply mains. A better arrangement would be to use a closely governed motor-generator such as Higgitt's arrangement indicated in Fig. 9. In this way the phonic wheels of a large telegraph office could be controlled without employing either forks or reeds. This is in the direction of reduction of maintenance and operating costs, and is worth consideration. The polarized phonic-wheel motor for direct connection to supply mains was invented by Favarger in 1902. He used permanent magnets instead of the polarizing winding shown in the figure.

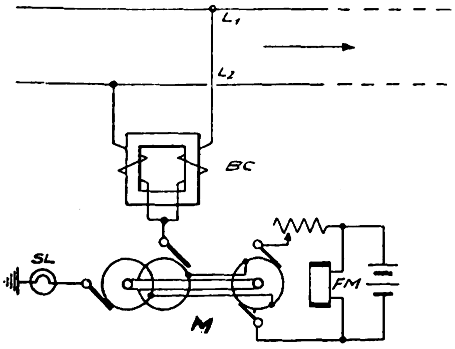

Fig. 19.—Synchronizing of motors over line wires.

It is clear from what has been said that the speed control of a number of synchronous motors in one office is not only possible but is quite practicable, and that its advantages require no emphasis.

Inter-Office Speed Control.—Inter-office speed control can be effected either by

> Transmission of impulses over a wire between the two offices or
>
> The clock supervision adopted by the Eastern Telegraph Co., previously alluded to.

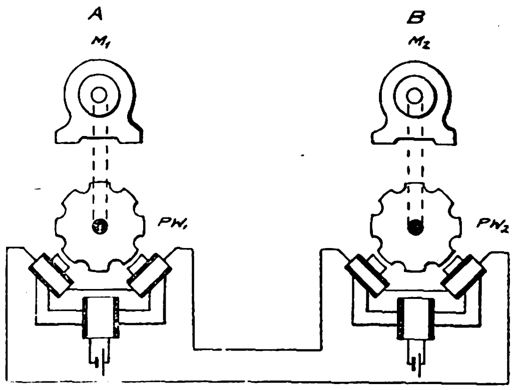

Fig. 20.—Synchronizing of motors over line wires.

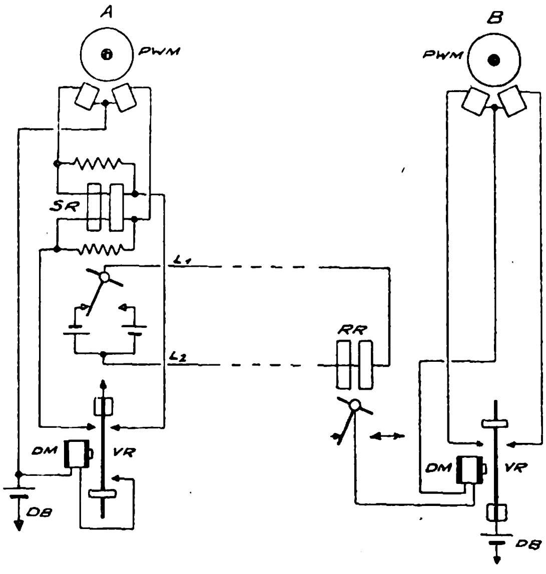

Fig. 21.—Remote control of phonic-wheel motor over line wires.

The simplest way to control a distant office by wire is to send out positive and negative pulses alternately from a master distributor at the one office over a line exclusively reserved for the purpose. At the distant end the oscillations of the relay tongue give rise to similar positive and negative currents in the armature of a synchronous motor, as will be understood by reference to Fig. 18. R is shunted around the motor to minimize sparking at the relay contacts. The motor of Fig. 17 could obviously be substituted for that shown. Fig. 19

is an arrangement described by Captain Poirson of the French Army. It was used in connection with a system of secret telephony which was effected on the two wires L_1, L_2. The motor armature of the motor M is tapped at two diametrical points and led to slip-rings. The alternating current passes over the two lines in parallel and is the synchronizing means by which a similar machine at the second station is controlled. The bridging coil acts as a choke to the telephone currents circulating round the circuit, while the lamp SL is a synchronizing indicator. This system has been successfully operated over a line, 615 km long, between Paris and Bordeaux. The frequency of the synchronizing current (only a few mA) was 50 cycles. It is stated that the system is eminently stable and will run into synchronism very rapidly.*

An arrangement of Siemens and Halske is illustrated in Fig. 20. Two motors M_1 and M_2 are directly coupled to phonic-wheel motors PW_1 and PW_2. By means of the polarized field magnet system the phonic wheels act as generators, and any departure from synchronism gives rise to synchronizing currents tending to pull the two systems into step.

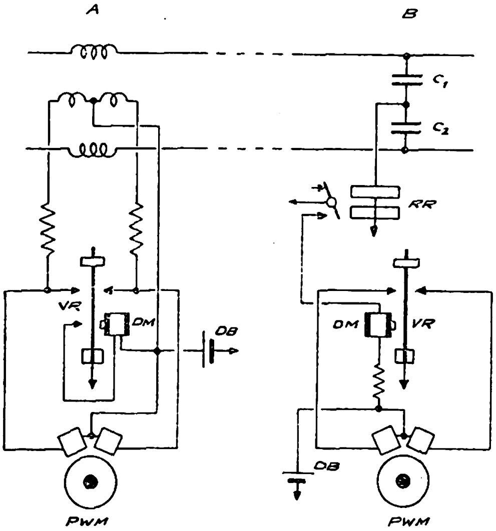

FIG. 22.—Remote control of phonic-wheel motors over line wires.

Fig. 21 represents a reed VR at a station A controlling a phonic-wheel motor there and also a relay SR by which alternating current is sent over the metallic circuit L_1 L_2. At the station B a receiving relay controlled by the reed at A drives the reed at B at exactly the same rate as the control reed. The two synchronous motors at A and B will thus be in step.

In the arrangement of Fig. 22, the driving pulses from the reed at station A are sent over the two lines in parallel. The arrangement scarcely needs description, but has the advantage over the previous one that the line circuit can also be used for signalling purposes. The two arrangements are described by Messrs. King and Barnes.†

The advantages of inter-office control and group driving are very considerable. Under certain circumstances synchronism can be maintained without the necessity for correction. Individual forks or reeds can be dispensed with and a great deal of adjustment saved, with decreased liability to faulty operation of the individual circuits.

Inter-office speed control may be accomplished by superposing the impulses on existing circuits, as has been shown, or the clock-control methods of the Eastern Telegraph Co. can be adopted.

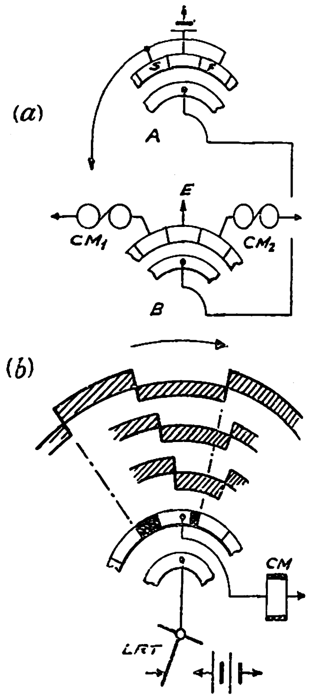

FIG. 23.—Method of effecting correction by special signals (Baudot).

On many land-line circuits the use of inter-office speed control will enable all correction arrangements to be abolished, provided that synchronous motors are used and all hunting is eliminated at the controlling end. With clock-control, correction from the signals will be necessary, although the frequency of correction will be very much reduced. The speed-difference between the two ends of the circuit tends to zero, phase-swinging becomes small in amount and the cycle of change is very slow. As a result there is less need to provide for shortened segments or land-line circuits and the number of segments may be increased, leading to higher speeds

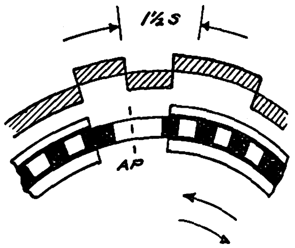

FIG. 24.—Position of receiving segments with respect to "action point."

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* See Bibliography.

† *Ibid.*, (26).

of transmission, or, alternatively, if the segments remain at the same number the operating margin will be increased.

Phase Control.

Phase control or correction may be effected:—

By special correcting impulses sent out from the controlling station, or

By correcting impulses generated from the letter signals sent out from the controlling station.

The first method is applicable only where the alphabet is an equal-letter one, such as the 5-unit. Wherever an unequal-letter alphabet, cable or land-line morse is employed it is not practicable to employ special correcting pulses, since these must occur at an invariable part of the signalling cycle and the letter signals are of variable length.

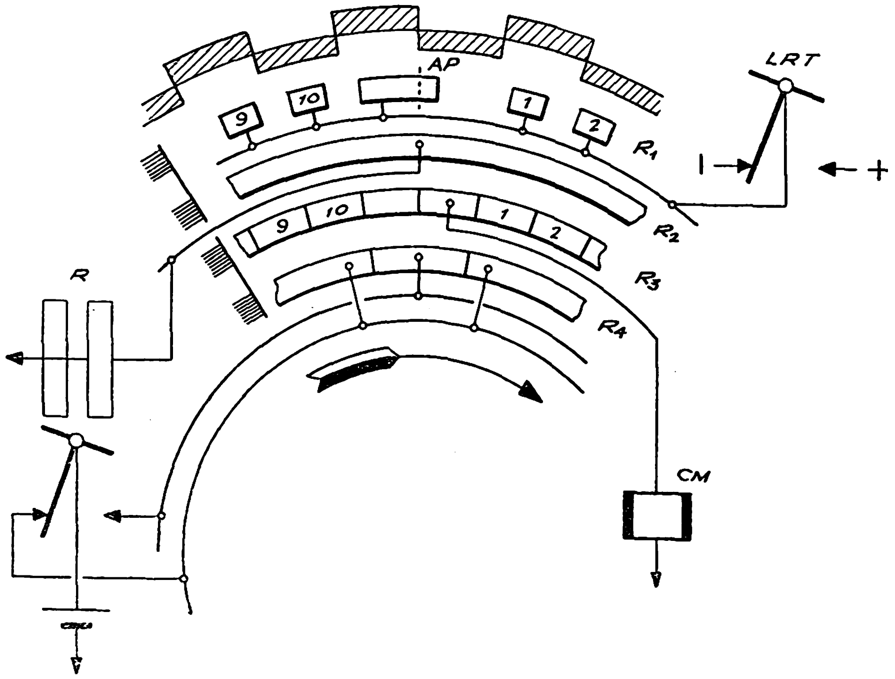


FIG. 25.—Picard's improvement on Baudot's correction.

Baudot's Method.—Fig. 23(*a*) shows an early method of Baudot. The part only of two distributors at stations A and B devoted to the maintenance of synchronism is depicted. Ignoring line lag, if exact synchronism exists the earthed battery at A connected to the segment intermediate between the two earthed segments S and F will send out a current pulse which, at B, is received on the earthed segment shown there. The current pulse from A exercises no corrective effect and, by assumption, this is not necessary. A is the time-keeping station and if B should, at the correcting period, be in advance of or lag behind A, the correcting pulse will be diverted to either of the correcting magnets CM_1 or CM_2, as the case may be.

Forward and backward correction is not now used on land lines, and the general practice, as previously explained, is to make the speed at station B slightly faster than at A and employ backward correction by means of one correcting magnet CM, as shown in Fig. 23(*b*).

Action Point.—As B creeps forward, indicated by the phase displacement of the received signals, the reversal from positive to negative takes place at a certain part of the correcting segment such that the time of contact is long enough for the local circuit closed by the line relay tongue LRT to operate the correcting magnet CM. As indicated in the diagram, this action point (*point de repère*) is reached after the third revolution. When correction takes place, the conditions shown in the first revolution (outer set of signals) are re-established and the cycle repeats. It is clear that, by moving the receiving correcting segment backwards or forwards, the number of revolutions between corrections will be reduced or increased. In practice matters are so arranged that the correction is effected about every 2 revolutions.

Automatic Phase-finding.—An advantage of employing special correcting signals, as described, is that in the event of disturbance to synchronism the distributor will " run in " automatically with the signalling channels in phase with those at the distant station. This cannot happen where more than one correcting point exists during a revolution, as the probability of " running in " at any one such point is equal and provision has to be made for " phasing," i.e. adjusting the channels to be in phase with the corresponding ones at the far end.

It has been usual to make the correcting segment movable and so adjust its position that corrections occur at the rate of about 1 per 2 revolutions. The receiving segments must then be so orientated that the middle point of these has a definite relationship to the action point. This is seen in Fig. 24, where the positive and negative correcting impulses are followed by a letter signal. Since, as previously explained, the shortened receiving segments should be placed in the middle of their signalling pulses, the middle point of the first of them must therefore be 1½ segments' length from the action point. In order that this may be done, the groups of 5 segments of each channel are mounted on slides, so that they may be rotated backwards or forwards to meet the above condition. This also necessitates the determination of the action point—a troublesome and time-taking operation.

The New Zealand Administration have abolished this procedure, and the correcting segment is fixed. The distributor runs-in automatically and the receiving segments are orientated until the receiver fails in both directions, the segments being fixed in the position midway between both extremes.

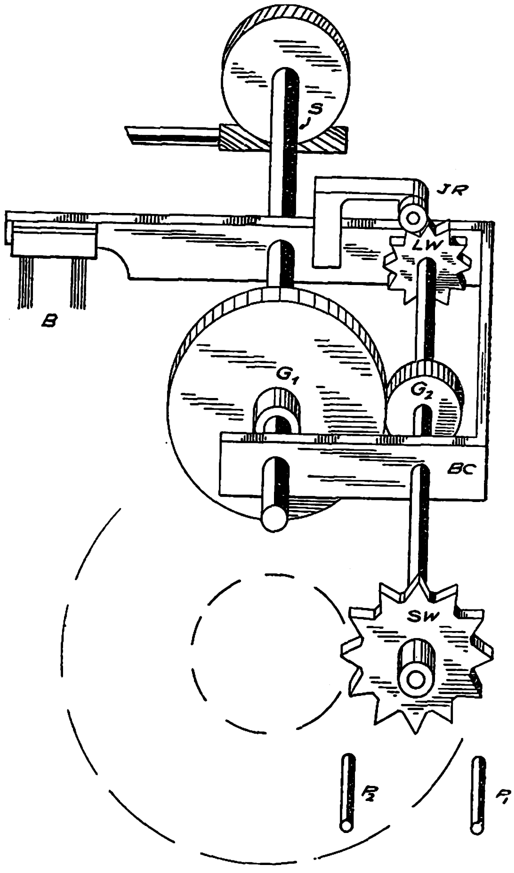


FIG. 26.—Baudot's epicyclic correcting gear.

Picard's Modification.—The arrangement of Fig. 23, in which the line relay actuates the correcting magnet directly, is not altogether satisfactory. The sensitiveness of the correcting magnet varies, being greater on frequent corrections than when these are relatively few in number. Consequently, the point at which correction is effected will vary, leading to under- or over-correction as the case may be. The correction of phase due to the correcting mechanism is constant in amount each time it is operated. When the correcting magnet is in an extra-sensitive condition, the mechanism may, be operated before the action point on the correcting segment is reached (over-correction). If, however, the correcting magnet is sluggish, the action point may have been passed over before the magnet operates, and the constant correction imparted by the mechanism is insufficient. In other words, the action point is subject to small variation, and although this causes little trouble on land lines where the margin is relatively large, it is a source of trouble on submarine cables. The

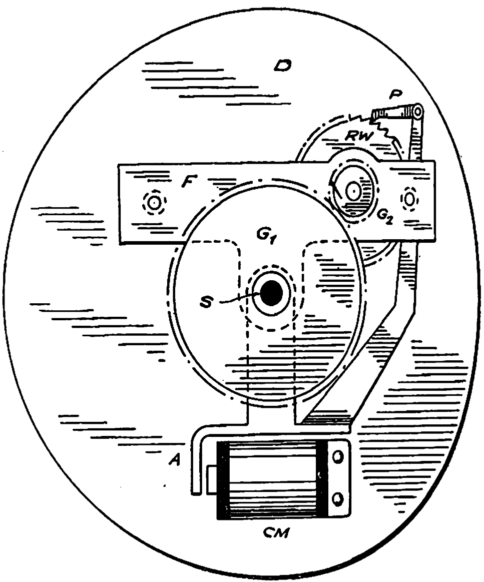


FIG. 27.—Rothermel's epicyclic correcting gear.

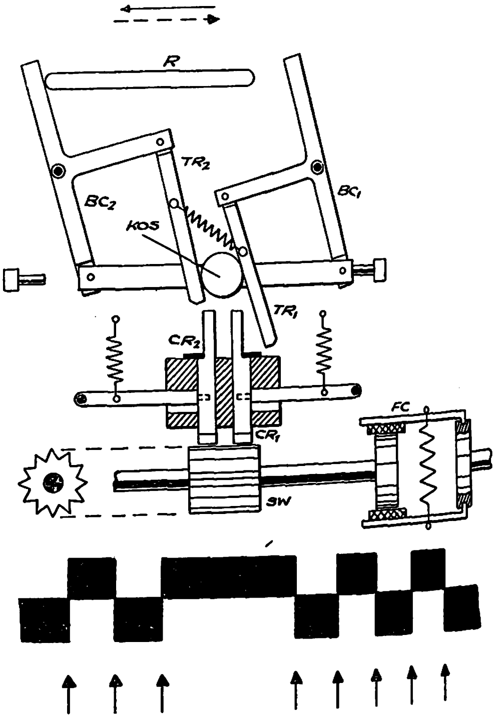


FIG. 28.—Creed's correction mechanism.

arrangement shown in Fig. 25 was introduced on the Algiers cables in 1910 by Picard. He interposed a relay between the correcting segment and the correcting magnet. As the relay has constant sensitiveness and little or no remanence, the action point remains constant. Furthermore, correction is always effected with impulses of constant duration, viz. the full length of the segment to which the correcting magnet is connected.

Correcting Mechanisms.—Fig. 26 is an early form of Baudot's epicyclic corrector. The brushes B are attached to a frame-like carrier BC free on the constantly driven shaft S, but locked to it by the epicyclic train consisting of the wheel LW held by the jockey roller JR_1 and the gears G_2 and G_1. On an extension of the shaft carrying wheels LW and G_2 is a star wheel SW. Two pins P_2 and P_1 can be thrust into the path of SW by means of two correcting magnets (not shown) and either unlock the train pushing BC and the brushes onwards in the direction of rotation, or momentarily uncouple them from shaft S. Thus the brush system can be retarded or advanced, according to which correcting magnet is operated. As previously stated, the general practice is now to run the controlled distributor slightly faster than the controller and adjust backwards when a certain phase difference has accumulated. One of the pins and its operating magnet is therefore suppressed. Correction can only be effected at one part of the revolution, and if it is to be effected from the signals the correction condition must be stored until the moment for operation is a suitable one.

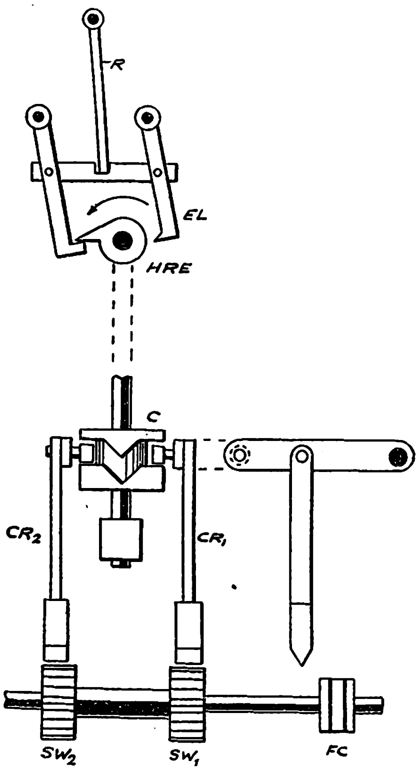


FIG. 29.—Creed-Willson correcting mechanism.

Under these conditions, it is not possible to allow for correction to be effected more than once or at most twice per revolution. Speed differences must therefore be small and the gear ratio G_1/G_2 high. This defect is overcome by Rothermel's construction, shown in Fig. 27. Here the gear train, locked at RW by means not shown, is controlled by a pawl P operated by a correcting magnet CM which is carried round with the mechanism, being mounted on the disc D, and the ends of its windings are carried to slip rings not shown. Correction can take place at any time during a revolution and more than once in the same revolution.

Fig. 28 is a diagrammatic representation of the well-known Creed correcting mechanism. It consists of two bell-cranks BC_1 and BC_2 pivoted at their mid-points to the machine frame. They are alternately rocked by a reciprocator R—controlled by the line signals—so as to move from right to left. The bell-cranks are pivoted at their lower end to a horizontal bar provided with a knock-off stud KOS. The horizontal portions of the bell-cranks are provided with trip rods TR_1 and TR_2. The motor is coupled to the main shaft of the mechanism through a friction clutch FS, and on the secondary shaft is a star wheel SW. Adjacent to SW are two corrector rods CR_1 and CR_2, which are thrust into the teeth of the star wheel each time the reciprocator R reverses its position by the trip rods under control of the bell-cranks. The corrective effects are transient as the knock-off stud KOS pushes the trip rods off the tops of the corrector rod at an early part of each cycle of operations. Correction is effected each time the line current changes sign, as shown in the lower part of the diagram. This mechanism corrects either backwards or forwards, as may be required at any instant, and it is only necessary to adjust and maintain the motor speed constant for practical synchronism to be maintained. Fig. 29 is the Creed-Willson corrector mechanism, which represents a considerable simplification. R is reciprocated by the

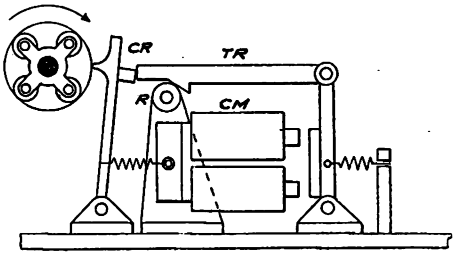


FIG. 30.—Wood's correcting mechanism.

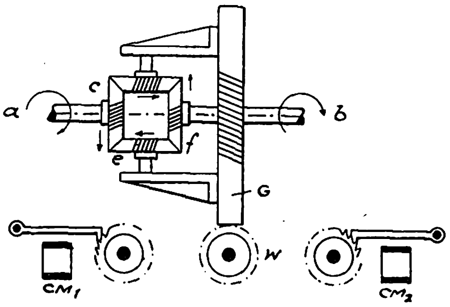


FIG. 31.—American epicyclic corrector.

line signals, and by means of the two escapement levers EL allows a shaft carrying the cam C to make a half-revolution each time R is reversed by the agency of EL and HRE. Cam C drives forward the corrector rods CR_1 and CR_2, which engage star wheels SW_1 and SW_2, thus effecting phase adjustment of a second shaft yieldingly driven by clutch FC.

Fig. 30 is Wood's corrector mechanism. The shaft is timed to make 1 revolution for 4 signal elements. The corrector rod CR is arranged to advance or retard the shaft according to requirements, the pointed tongue of corrector rod CR meeting the surface of the rollers to effect the phase adjustment. The trip rod TR has a cam surface on its under side which, as TR is pushed forward by the correcting magnet, raises it by means of the roller R and releases CR.

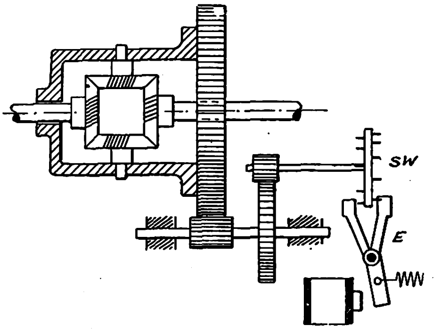
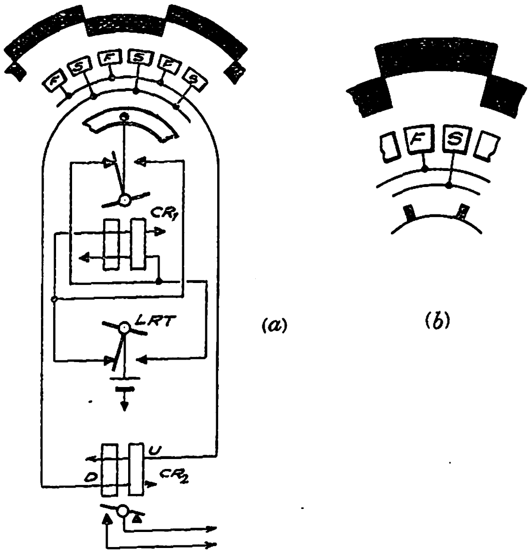


Fig. 32.—Foll and Muirhead's correcting gear.



(a) (b)

Fig. 33.—Generation of correction pulses from signals.

Fig. 31 is the mechanical corrector used on the New York–Emden loaded cable multiplex circuit. The driving shaft " a " is coupled to the driven shaft " b " by means of the differential gear. The gear is supported on the two shafts and by brackets carried on the large gear-wheel G. The latter is loose on " b " but is locked against rotation by the worm-wheel W. The shaft to which the worm-wheel is keyed can be rotated by either of two correcting magnets, CM_1 and CM_2, by which the shaft " b " is set back or advanced by a small amount each time a correcting magnet is operated.

Fig. 32 is an epicyclic corrector due to Messrs. Foll and Muirhead, in which the correcting magnet controls an escapement E by which the scape-wheel SW is intermittently released. No phase change between the two shafts takes place normally, the differential gear being locked by SW. The correcting magnet has only to do the work of releasing the train, the work necessary to vary the phase being thrown on the motor.

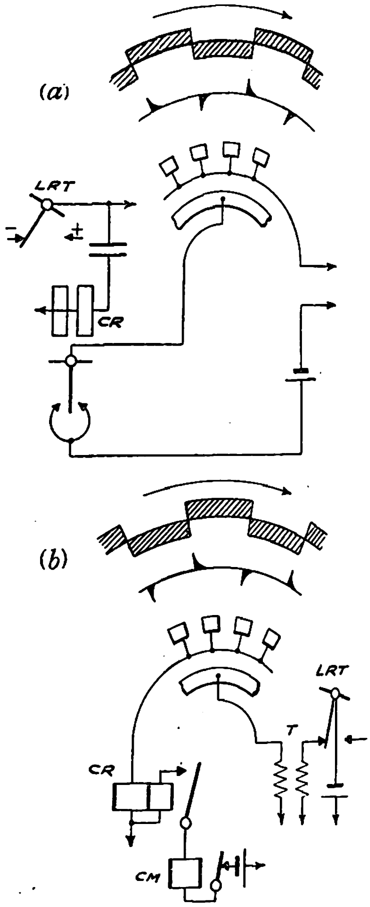


Fig. 34.—Generation of correction pulses from line signals.

Generation of Correction Impulses.

A variety of methods of generating correcting impulses are in existence and are employed in one form or another. A difference of phase is the primary requisite and it is becoming more and more the general practice to rely on the signals themselves to make the necessary change before the cumulative phase difference has reached the operating limit. In all systems of machine telegraphy, e.m.f. or current changes occur at certain definite times, which are separated by definite integral multiples of a time element—the elementary signal.

Fig. 33(a) is a typical example of the arrangements necessary for correction generation from the signals. With correct phase relationship, the changes in sign of the line current will occur exactly in the space between the slow and fast segments S and F. The line relay tongue LRT vibrates in accordance with the incoming signal and CR_1 vibrates similarly, but with a slight lag, under control of LRT. At the instant of change of current the line relay and relay CR_1 will have their armatures on opposite contacts, during which short interval a current can pass from earthed battery, left-hand contact, say, of LRT, right-hand contact of CR_1, solid ring of distributor, via the brushes (not shown) to either the slow or fast segment, depending upon the phase of the distributor brush with respect to these at the moment LRT has been reversed. The second correcting relay CR_2 will therefore be operated either to close the circuit of a correcting magnet or, if correction has been taking place and the phase difference has been annulled and carried slightly over in the other direction, so to operate CR_2 as to open the circuit to the correcting magnet. The circuit described for setting relay CR_2 is only momentarily established since CR_1 ultimately moves in obedience to the current from LRT, but once the correcting condition of CR_2 is set up it is not altered until the correction is effected and the phase difference changed in sign. The revolving brushes will therefore have a periodical phase difference which will alternately be above and below that of the controlling brushes at the other end of the line. Fig. 33(b) shows how the correction pulses fall if the phase is behind or in front at the corrected station. In this method of correction, the necessary conditions are set up regardless of whether the change in sign of the line signal is from positive to negative or the reverse. The corrected speed is arranged to be slightly faster than that at the correcting end of the line.

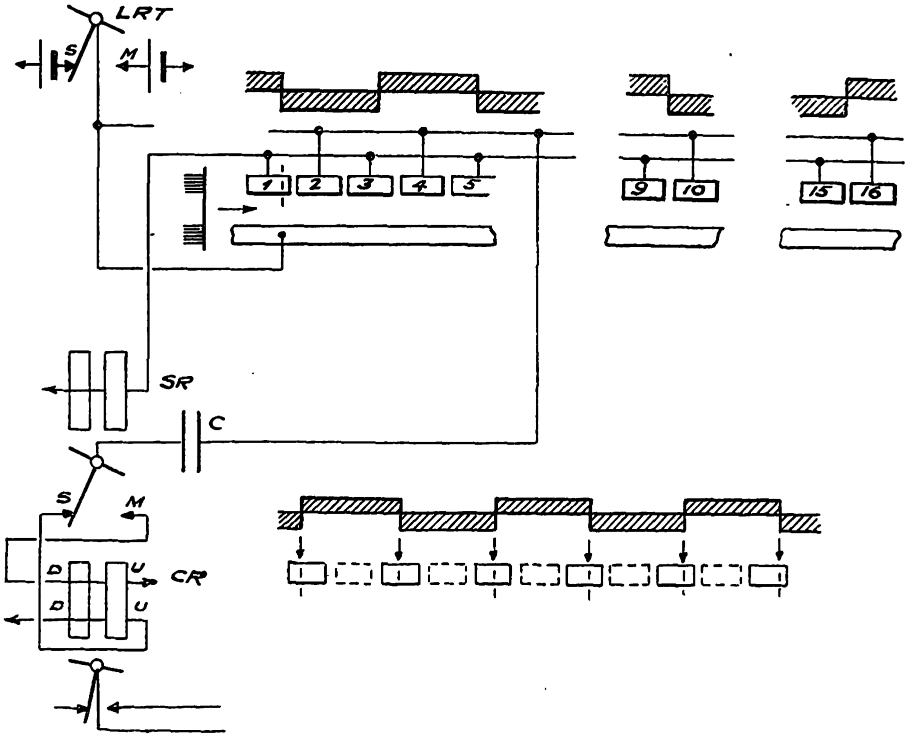


FIG. 35.—Picard's system of correction from signals.

Fig. 34(a) is a variation. The line relay tongue controls the receiver electromagnets (not shown), but, in addition, operates a relay CR through a condenser. The relay CR is of the central-zero type and is deflected to its right-hand or left-hand contact in accordance with the sign of the transient condenser current. Only "slow" segments are provided and the distributor is arranged to run slow with respect to that at the other terminal of the line. When a certain phase difference has accumulated, the condenser pulses occur when the correcting relay is on one of its contacts, while the correcting circuit from the tongue of CR is closed via the solid ring of the distributor and the right-hand extremity of any one of the correcting segments. The effect of correction is to speed up the distributor until, when the correcting pulses operate CR_1, the distributor brush is clear of the right-hand end of the correcting segments, and the corrector circuit is broken down. The distributor again falls behind until the correcting condition is again set up, and so on.

Fig. 34(b) differs from Fig. 34(a) in the generation of the transient correcting pulse and also by reason of the fact that only "fast" segments are provided. As the line relay tongue reverses, it makes and breaks the primary circuit of a transformer T. From the secondary of T, pulses pass via the distributor to a non-polarized correcting relay CR. This operates and locks itself up through a holding winding from earthed battery, interrupter springs on CM and armature of CR. By this arrangement the continued operation of CR is assured until the correcting magnet is fully actuated. The distributor in this case runs slightly fast.

Picard's Correction from the Signals.—Fig. 35 explains the correction method due to Picard, which may be said to be the basis of all modern methods. When synchronism exists, reversal of sign takes place when the brushes are very near the end of the odd-numbered correcting segments. The pulse of current is still long enough to operate the switching relay SR, which thus follows the motion of LRT. If the pulse is negative, relay SR spaces. This puts the lower winding of the correcting relay CR in connection with the condenser C, and when the brush passes over the succeeding even-numbered segment the condenser is negatively charged and the charging current puts the relay CR to spacing. Nothing is changed.

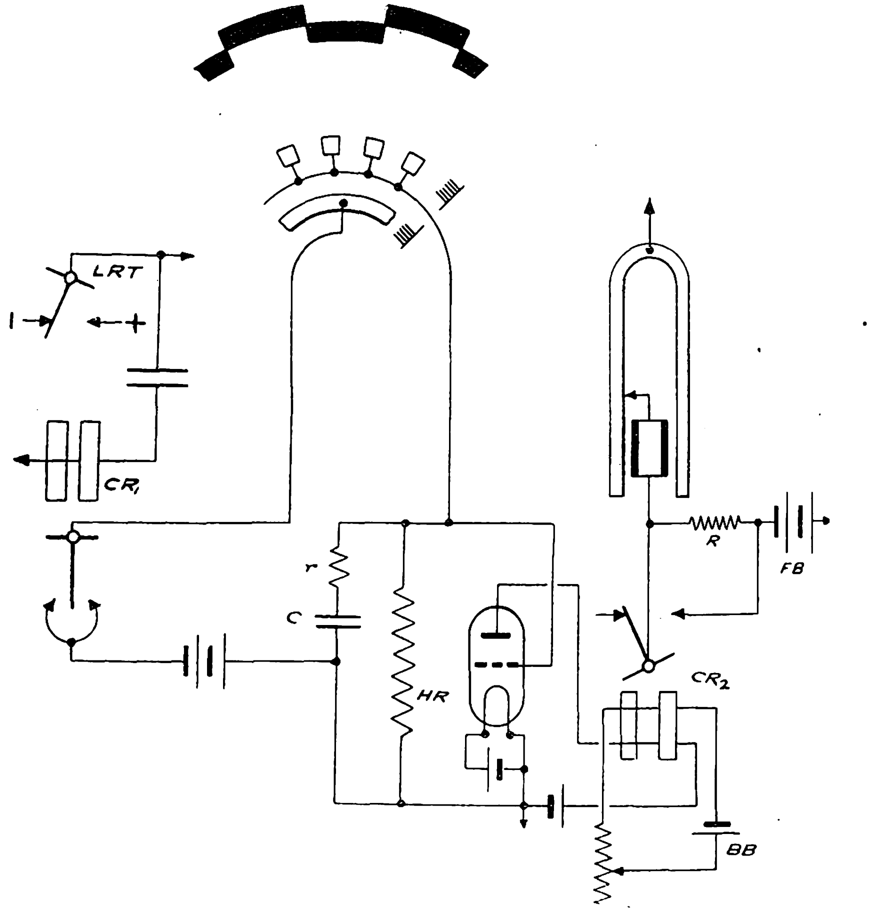


FIG. 36.—Western Electric Co.'s method of correction using a thermionic valve.

If a positive signal follows when the brush arrives at the end of the third contact, so that the pulse is still sufficient to operate SR, this marks but the correcting relay will still space because although the pulse is opposite in sign to the previous one it passes through the upper winding of CR in the opposite direction.

When the distributor, which is set to run slightly fast, has gained sufficiently, the moment of reversal will occur between the odd- and even-numbered segments or even on the commencement of the even-numbered one. Relay SR will no longer reverse with LRT but will remain where it was last placed. If the previous signal pulse was positive, the tongue of SR will be on its marking stop and the negative condenser-charging current will operate CR to the marking position, where it operates the correcting magnet (not shown).

In the Picard arrangement, the Baudot epicyclic corrector was employed. As this can be operated only at one part of a revolution, the correction is stored by CR until the brushes close, at a suitable moment, the circuit of the correcting magnet. The lower part of the diagram shows the creeping forward of the "action point" as the distributor gains in phase. At the right hand two opposite changes of sign are shown, from which it will be seen that the correction effect is generated in either case, provided the necessary phase difference has arisen.

The arrangement of Fig. 36, designed by the Western Electric Co., is applicable where extremely close synchronism is required. Correcting relay CR_1 is of the 3-position type, and, at each change of sign in the line current, is momentarily placed on one or other of its contacts. The negative pole of the battery connected to these contacts is applied via the solid ring and correcting segments of the distributor and to the high resistance HR and resistance "r" and capacity C in parallel. Condenser C is charged and negative potential is applied to the grid of the thermionic valve, causing a reduction in the plate current circulating round one winding of a second correcting relay CR_2. Current from the biasing battery BB is adjusted by a series resistance, so that with normal plate current relay CR_2 is maintained in its operative position, where it short-circuits the resistance R in series with the fork-driving battery FB, causing the fork to run slowly. When the current in the plate circuit is reduced by receipt of a correction pulse, as previously explained, the armature falls back to its unoperated position, shown in the diagram, due to the current in the output circuit of the valve being reduced by the application of a negative potential on the input circuit, and the biasing current from BB overcoming this. Resistance R is now in circuit with the fork-driving magnet and the reduced current results in the fork amplitude decreasing and the fork frequency rising, thus hurrying up the motor. The fork continues to run fast until the charge on condenser C has leaked off through resistance HR. This arrangement differs from other synchronizing systems in that the accuracy of correction is not dependent upon the time required for a current to reach an operating value in an electromagnet, but is determined solely by the time required to build up a charge on the condenser C. Thus a very small instant of time is required to register the correcting condition, and synchronism is held within extremely narrow limits.

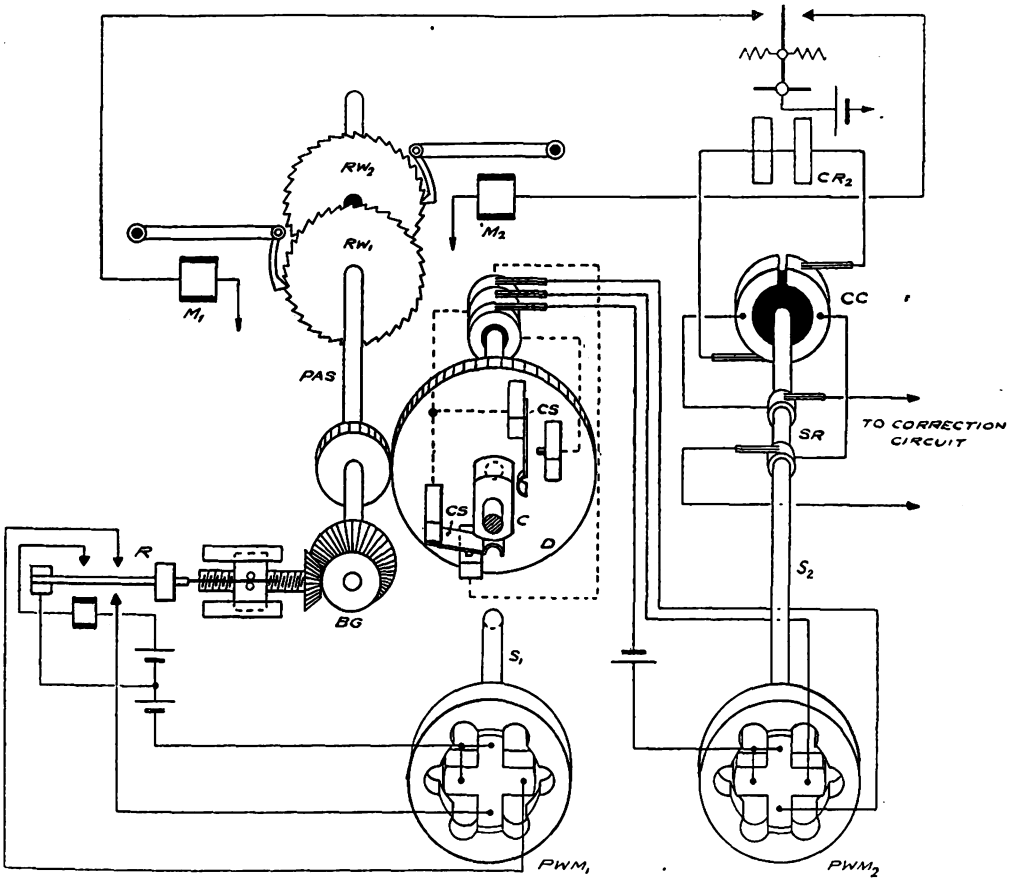


FIG. 37.—Pernot's speed and phase control of phonic-wheel motors.

Pernot's Method.—Fig. 37 represents a system of correction invented by F. E. Pernot, in which the integral of all phase corrections is applied in such a manner as to vary the speed and thus make fewer phase corrections necessary. It is designed to secure synchronism on a circuit operated by cable code morse.

R is a reed operating a phonic-wheel motor PWM_1. This motor rotates a cam C revolving in the path of two contact springs CS adapted alternately to deflect these against fixed contacts. The contacts and springs are fixed to a toothed disc D loose on shaft S_1, the springs being connected together and to a slip-ring on shaft S_1. The contacts are also connected to two other slip-rings, and the regular rotation of cam C furnishes driving pulses to a second phonic motor PWM_2. The vibrating end of reed R carries a spring which passes between two pins on a slide capable of to-and-fro motion. When the pins are near the end of the reed R the stiffness of the latter is increased and also the rate of vibration, and vice versa. Adjustment of the slide with the constraining pins to or from the reed constitutes a vernier adjustment, the weight on the reed furnishing the coarse adjustment to the approximately correct rate of vibration. The vernier adjustment is effected by means of shaft PAS and the bevel gear BG, which is operated in one direction or the other by means of the two ratchet wheels RW_1 and RW_2 having oppositely disposed teeth and actuated by electrically controlled pawl-and-ratchet mechanism. Two electromagnets M_1 and M_2 step the ratchet wheels on one tooth each time they receive a current pulse.

The shaft PAS not only varies the adjustment of the reed R, but, by means of a pinion meshing with the teeth on the periphery of the disc D, rotates this slightly.

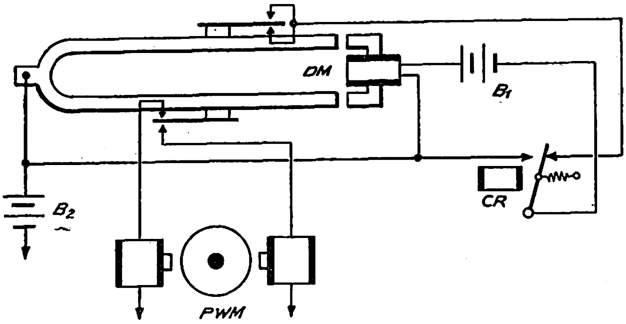


Fig. 38.—Muirhead's speed and phase control of a tuning fork by line signals.

The effect of this operation of D is that the relationship of the contact springs and contacts on D is altered with respect to the cam C, and the phase of the driving pulses furnished to the second phonic motor PWM_2 is altered thereby. The two motors make one rotation for a dot-and-space signal element, and motor PWM_2 drives the cam shaft of a receiving perforator or retransmitter of the regenerative type. By suitable means, transient correction impulses are generated at the beginning of each signal element or block signal coming over the line. These impulses are passed to the second correcting relay CR_2 via slip-rings SR, the two sectors of the correcting commutator CC and the two brushes resting on this and connected to the windings of CR_2. If the phase is exactly right, the circuit to CR_2 is not completed, since the two brushes of CC will rest on diametrically opposite insulated sections between the two segments, and no correction takes place. If PWM_2 leads or lags, CC acts as a reversing switch and CR_2 is actuated in the appropriate direction to operate M_1 and M_2 and vary the speed of reed R, while also effecting the phase adjustment previously described. As previously stated, if phase error persists in one direction the gradual minute adjustments to the rate of vibration of the reed effect a permanent change in speed, and the closeness with which the synchronism is maintained is far greater than in any of the systems previously described. Such refinement is not necessary for land lines, but on long cables and where two or more cables are interlinked it is essential; the additional distortion which would otherwise be introduced by relatively coarse phase errors makes such interlinking impossible.

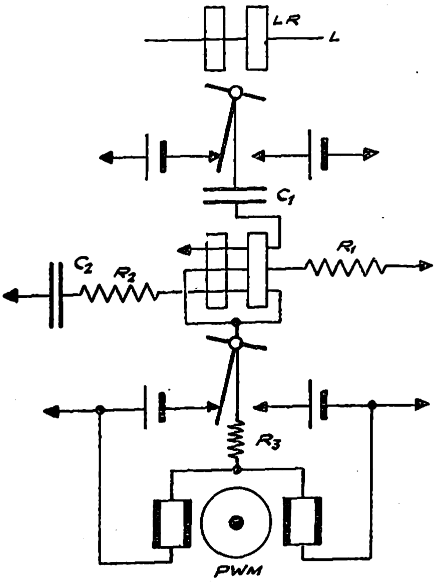


Fig. 39.—Bille's control of phonic-wheel motor by Gulstad relay.

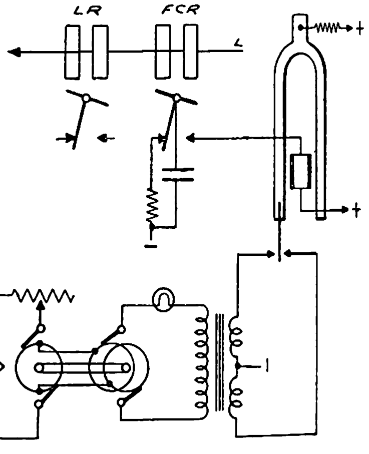


Fig. 40.—Angel's control of d.c. motor by line-signal control of a tuning fork.

Control of Tuning-Fork Speed and Phase by Line Signals.

The speed and phase of a tuning fork may be controlled in two or three ways by means of the line signals.

It is possible:—

To modify the speed of the fork by correction impulses generated by the signals.

To cause the line signals to exercise an interference effect in the fork driving circuit.

Positively to drive the fork by driving pulses generated from the line signals.

An example of the first is furnished by Fig. 36, while a requisite condition for the second and third is that the fork frequency should bear a definite relation to the signalling frequency.

Heurtley and Foll's Method.—Fig. 38 is an example of the second method of fork speed and phase control and is due to Messrs. Heurtley and Foll. In this arrangement the driving magnet DM exercises the necessary control. The circuit of this magnet is taken through the back and front contacts of a correcting relay CR, which is operated each time a line-signal element is received.

If the fork is out of phase with the incoming signals, the driving impulse is given at the instant when the fork

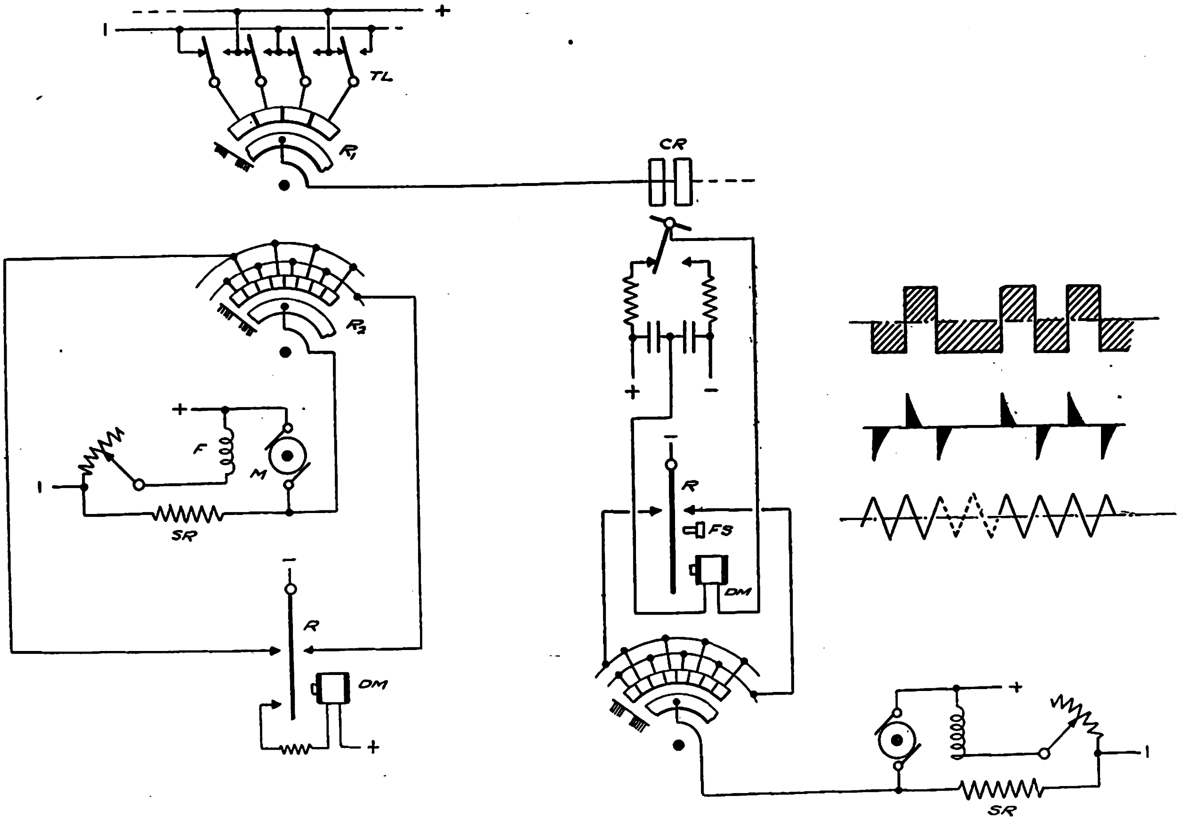


FIG. 41.—Potts's control of speed and phase of d.c. motors by synchronous reeds.

would normally be free and the fork is forced into the correct phase relationship. The driving fork does not cease to vibrate when the line signals stop, the driving circuit being closed at the back contact of CR and the usual spring contact on one tine and its adjacent fixed contacts. Under these conditions it vibrates at the speed for which it is adjusted, the line signals correcting phase when required. If no signals are passing, then, before commencing transmission, it is only necessary to send a few reversals to bring the fork into phase.

Bille's Method.—Fig. 39, due to the late Harald Bille, employs the well-known Gulstad relay as the timed vibrator. It vibrates by means of its local windings, and the rate of vibration is adjusted by resistances R_1, R_2, and condenser C_2. In addition its vibrating tongue pulses the magnets of the phonic-wheel motor PWM. Any slight difference between the rate of vibration of the relay and the rate of reversals from the distant transmitter is compensated by the control exercised by the signals on the line winding of the relay which is pulled into phase each time the line relay reverses its armature. This control is exercised through a condenser G, so that only transient correcting pulses are generated. If the condenser were not provided, a long signal pulse would temporarily stop the vibration and PWM would cease to rotate.

Angel's Method.—Fig. 40 is an arrangement of H. Angel in which a fork, timed to vibrate at the rate of transmission of dot-signal cycles, is driven by a fork control relay FCR in series with the line relay and moving similarly to this in response to line signals. The fork is used to control the speed of a d.c. motor in the manner described with reference to Fig. 6. If a long signal pulse is received, it only exerts an effect at the initial stage, and the fork continues to vibrate by its own persistence until a reversal in the line-signal current takes place and generates a further driving pulse.

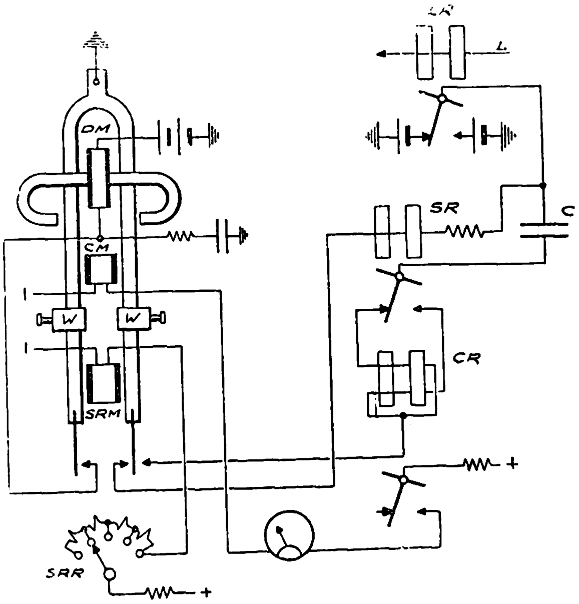


FIG. 42.—Connery's speed and phase control of a fork by line signals.

Potts's Method.—Fork or reed control of d.c. motors at both ends of the line may be effected by the arrangement detailed in Fig. 41 and due to L. M. Potts. When no signalling is taking place, the transmitter levers normally send out alternative negative and positive pulses. The d.c. motor at the sending end is kept to a certain mean speed by the accurately timed reed R, which acts through the speed control segments of R_2 in the manner described with reference to Fig. 7. At the receiving end a similar motor is controlled by a vibrating reed R driven by the signal pulses in the manner explained in connection with Figs. 39 and 40. The operation of the controlled reed at the receiving station is clear from the inset diagram at the right.

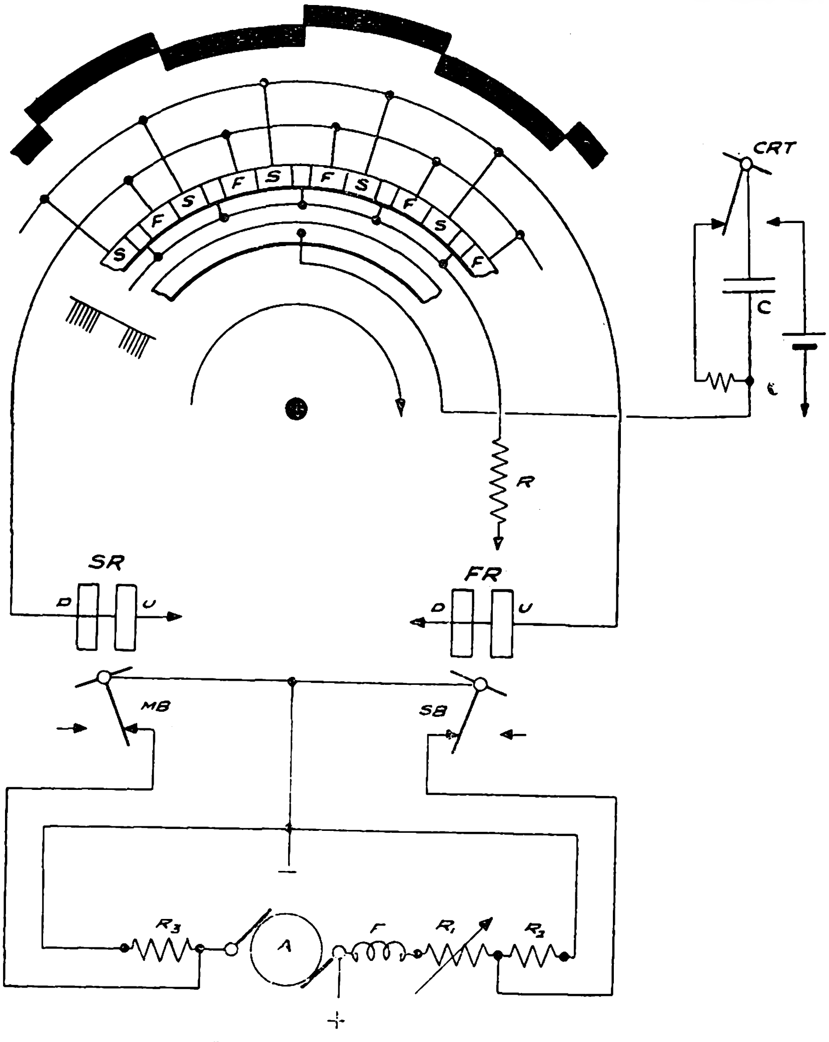


FIG. 43.—Speed and phase control of d.c. motor by line signals.

Connery's Method.—A fork may be kept vibrating at constant speed by correction pulses generated from the line signals. Such an arrangement, due to A. F. Connery, is illustrated by Fig 42. The fork is brought to approximately correct rate of vibration by means of the usual sliding weights WW. A speed-regulating magnet SRM carries a current adjusted by a speed-regulating resistance SRR and constitutes a vernier adjustment, SRM varying the stiffness of the tines. The driving magnet DM is operated in the usual way and a correcting magnet CM is operated by a relay chain formed of a switching relay SR and correcting relay CR. Two contacts adjacent to a contact spring on the right-hand tine of the fork, together with the relay chain, form a correcting arrangement identical with that of Picard (Fig. 35), the two fork contacts corresponding to the fast and slow segments of Picard. The rate of vibration of the fork is so adjusted that with no current flowing through the corrector magnet CM slightly less than one cycle of vibration occurs for each unit length of line signal. When a current is passed through the correcting magnet CM the fork speed is increased so that it vibrates at slightly more than one cycle per unit time. When the fork gets out of phase the correcting condition is set up and CM operates.

Forward and Backward Correction of D.C. Motor.—If both forward and backward correction are used, then, with suitable control, synchronism can be obtained with motors having no inherent time-keeping properties, i.e. d.c. motors. Fig. 43 represents such an arrangement. The usual slow and fast segments are provided, separated by a third, shorter segment connected through a resistance R to earth. The three groups of segments are multipled together within the group, the fast segments being connected to a slow relay SR and the slow segments to a fast relay FR. These relays have spacing and marking biases as indicated. CRT is the tongue of a correcting relay operating with the line-signal relay—not shown—in response to the line signals. In the normal position of CRT a condenser C is short-circuited through a resistance R. In the operative position of CRT a charging circuit is prepared for C from earth, battery, right-hand contact of CRT, condenser C, and solid ring of correction segments. If the distributor brushes are in phase, the condenser charges up through the small segment between the slow and fast segments and the resistance R. If the distributor brushes lag, the charging pulse passes through the fast relay, which operates momentarily and removes a short-circuit from a field resistance R_2, thus accelerating the motor. If the brushes are in advance, the condenser-charging pulse is effected through the slow relay and this inserts a resistance R_3 in the armature circuit, slowing the motor down. The correcting effects are only transient; both relays return to their normal positions, as shown, due to the bias. Correction is only effected on a change of line signal from negative to positive. With suitable speed adjustments, the brush arm floats round the correct phase position, the phase varying slightly in front of and behind the correct position.

Salmon's Method.—An extremely simple and effective method of speed and phase control of a d.c. motor by the line signals, due to R. D. Salmon, is diagrammatically indicated in Fig. 44. On the shaft of the motor DCM is a disc D on which are mounted two governors consisting of pivoted, spring-controlled weighted arms. One is adjusted to control the motor at a certain speed S_1; CRT is a 2-position switch which is operated when the shaft acquires a phase difference above or below that of the distant shaft with which synchronism is to be effected. The position of CRT is dependent upon the detection of phase difference by means of the incoming line signals. In the position shown in the diagram, governor S_2 is operative, S_1 being disconnected at CRT. In course of time the phase of the motor shaft will have advanced so far that the position of CRT will reverse. Immediately this occurs the circuit of S_1 is completed and the shunt field resistance SR is short-circuited, thus slowing the motor down. This will proceed until the phase lags sufficiently again to occupy the position shown in the diagram. S_1 no longer has any effect and the motor speeds up until S_2 again takes charge. Thus the phase of the shaft is kept floating about the correct position and this variation can be made as small as we please by suitable choice of the two control speeds S_1 and S_2. The spring tension is such that if it were possible for the pivoted arms to be at the geometrical centre of the disc it would be zero. By previously calibrating the springs in the factory it is possible to apply the governor to any d.c. motor and rely on obtaining the speed range equivalent to the difference between the speeds of S_2 and S_1.

Start-Stop Synchronism.

A relatively coarse synchronizing method is that applied to start-stop printing telegraph systems (Fig. 45). Here the contact brush-arms of the distributors start and stop for each letter signal transmitted and received. This allows of about 7 per cent difference of speed between the motors at the two ends of the line, since the phase difference is not allowed to accumulate. The motors M are controlled, as regards speed, by means of a centrifugal governor G controlling a contact arm CA adapted to short-circuit a shunt regulating resistance SRR. The exact speed at which the governor exercises control is fixed by a speed-adjusting screw SAS. The motor speed is adjusted to a suitable value by the aid of a stroboscopic disc SD viewed through a calibrated fork CF mechanically operated by a push-button PB and hammer H.

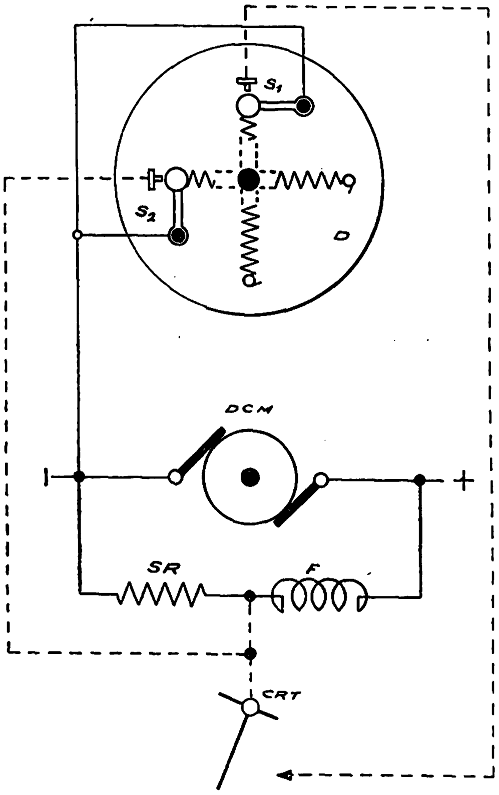


FIG. 44.—Salmon's governor method of speed and phase control of a d.c. motor.

The distributor brush-arms are yieldingly driven and held against revolution by release arms such as RA. At the sending end RA is released every time a character key lever CKL is depressed, this being effected by a universal bar UB linked to the release arm RA. At the receiving end the release arm is electromagnetically controlled by a start magnet SM, which is operated by a start pulse prefixed to the 5 signal pulses and sent out as soon as the sending distributor brush-arm commences its movement. The cycle of operations is set out in the inset diagram.

Start-stop synchronism is easy to obtain and maintain, the only adjustment necessary being intermittent checking of the motor speed.

Local Synchronism.

Local synchronism is the synchronism required between printer and distributor units of a multiplex system. Where the printers run continuously, as in the Baudot system, they may be run slightly faster than the distributor unit and periodically checked, or they may be provided with synchronous motors driven by reversals generated at the distributor.

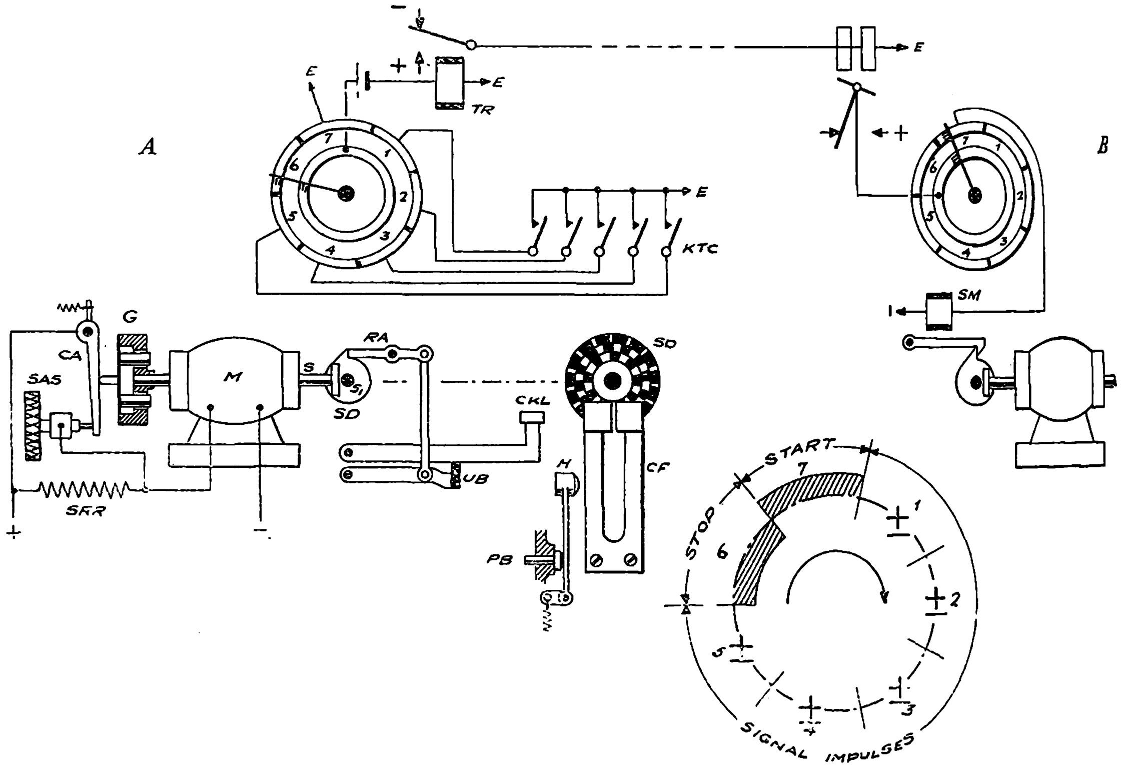


FIG. 45.—Start-stop synchronism.

In Fig. 46 S_1 is the distributor shaft driven by a motor (not shown), and S_2 is the printer shaft driven by the motor M. A cam C on S_2 partially closes a circuit to a magnet CM, the circuit being completed by a contact on the distributor, the solid ring, the brushes, and an earthed battery. The closing of the cam contacts and the distributor contacts coincides more or less frequently, depending upon the difference in speed of the two shafts, and CM operates, disconnecting the power supply from the mains and short-circuiting the motor, which then runs as a generator and slows down momentarily, thus annulling the phase difference which has accumulated. Some form of governor is fitted to the motor M to keep the speed of S_2 roughly constant.

In Fig. 47 the printer unit is driven by a synchronous motor from a commutator on the distributor. The method of operation is obvious. The synchronous motor is not self-starting but comes into step after two or three revolutions by hand. This system has the advantage that there is no governor to adjust on the printer unit, while the phasing of the printer with respect to the distributor is automatically secured. This is also true of Fig. 46, the adjustment of cam C on shaft S_2 effecting automatic phasing.

General Principles of Synchronizing Schemes.

Practically all of the arrangements previously described will be found to consist of:—

(i) A variable phase-detecting means operating by the rotating shaft to be controlled.
(ii) A device responsive to the received signals, and
(iii) A speed- or phase-variation means by which correction is effected.

The process of maintaining synchronism is as follows:—A continuous comparison is instituted between (i) and (ii), (ii) being identical in phase with the controlling end of the line, and the positive or negative divergence is used to operate (iii).

Speed and Phase Indicators.

Fork-speed Adjustment.—In Fig. 48 the fork is adjusted to vibrate at a rate which will drive the phonic motor at the desired speed. With the switch S thrown into the reverse position to that shown in the diagram the solid ring of SDF connected to positive battery makes alternate connection with two groups of segments which are in turn connected to the two pairs of motor magnets through S. When any segment is bridged to the solid ring by the brushes (not shown), one tooth of the motor is between the pole-pieces of one pair of magnets. The motor starts up and gradually accelerates. The drive is transferred from the distributor segments by placing S in the position shown in the diagram, and this moment is indicated by the flashing of the synchronizing lamp SL.

When the brush is on a segment connected to the lamp at the same instant that the fork-vibrating contact is touching its left-hand fixed contact, the lamp glows. As the motor gains speed, a series of flashes will be observed which become slower and of longer duration.

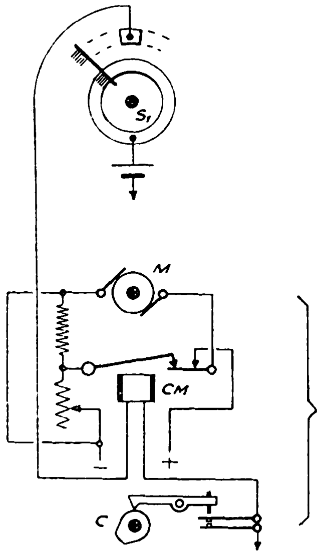


FIG. 46.—Local synchronism.

When the lamp appears to be on the point of glowing continuously, the switch is thrown and the fork then takes on the motor drive.

Fork-speed Adjustment to Speed of Distant Fork,—Fig. 49 shows an arrangement by which the fork speed at the distant station B can be adjusted by reference to that at A. At station A when the switch is thrown to the left, alternating current is sent out as indicated by the circular diagram L. When the switch at B is thrown to the dotted position, line relay LR controls a second electrically-biased relay, which responds to the alternating currents sent out from A and drives the phonic motor at the same speed as that at A. A stroboscopic disc SD is mounted on the shaft of the motor and can be viewed through a window formed by two small metal strips fastened to the tines of the fork. The fork at B is so adjusted that it is, say, slightly fast when the resistance in series with the driving magnet is in circuit.

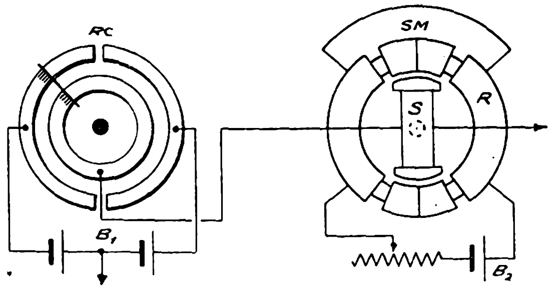


FIG. 47.—Local synchronism.

The adjustment of the distributor at B, so that it is in phase with that at A, is effected as follows: The switch at station A is turned to the right and the distributor then sends out positive current for half a revolution and negative for the other half, as indicated by the inset diagram marked R.

Switch S_2 at station B is now thrown to the right and divides the segments there into two groups of 10 each, as shown by the sketch R at the right-hand corner of the diagram. The two groups are each connected to separate windings of a polarized relay which, in its operated position, short-circuits the series driving magnet resistance, thus lowering the speed of the fork. If the distributor at B is in phase, no effect is produced on the fork speed-control relay, since its windings are so arranged that positive and negative pulses, if confined to the left- and right-hand groups of segments as at station A, only hold this relay to the inoperative or spacing position. If there is a phase displacement of B with respect to A, either the positive or negative pulse will run over from one group of segments to the other, and the fork speed-control relay will be operated. This will continue until the speed corrections applied to the fork give rise to exact coincidence of phase.

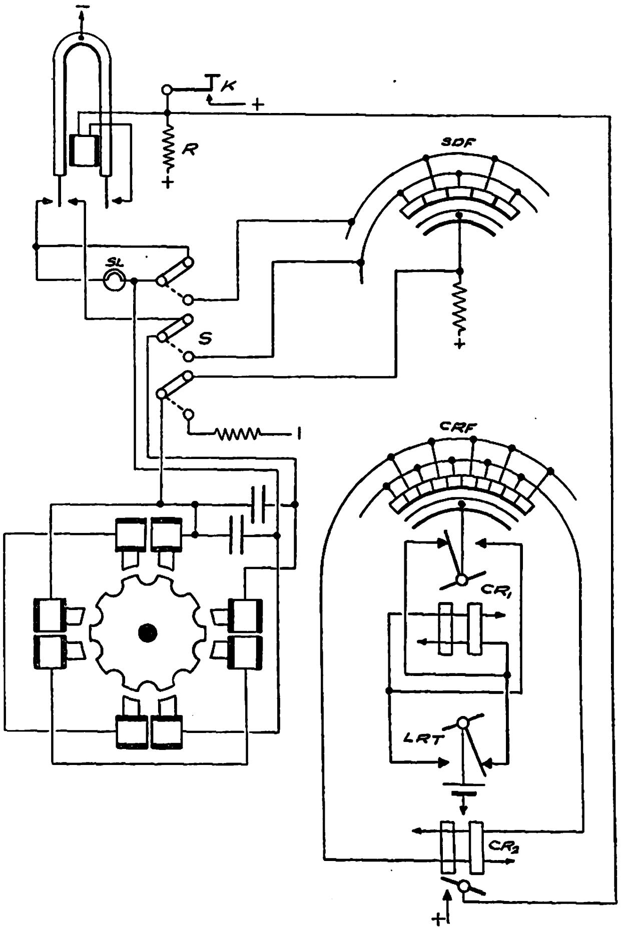


FIG. 48.—Fork-speed adjusting circuit.

When the speed and phase adjustments have been effected in the manner explained, other switches (not shown) connect up the apparatus at both ends of the line for traffic.

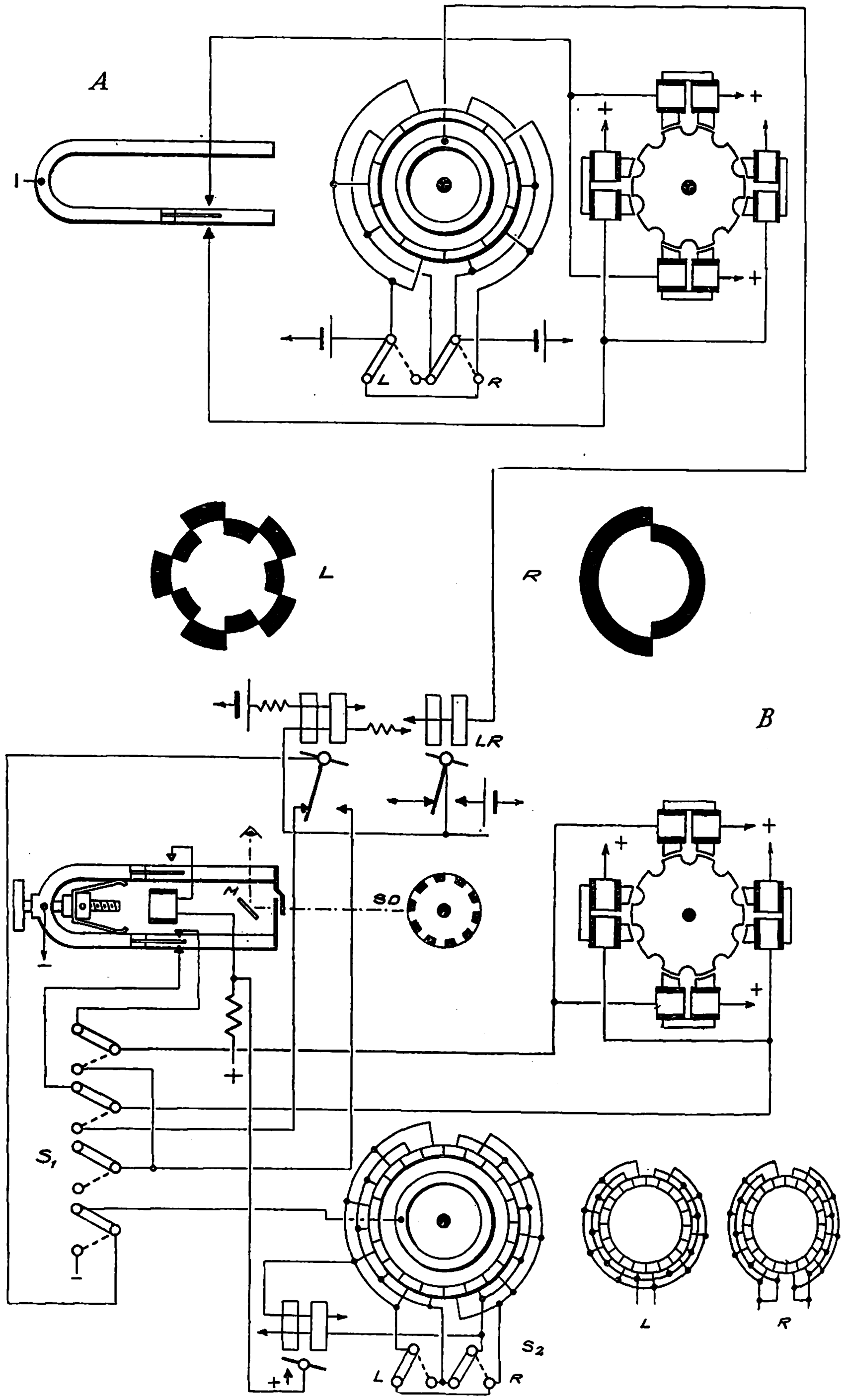


FIG. 49.—Speed and phase adjustment means between two stations.

Morkrum's Speed Indicator.—An ingenious and effective speed indicator by means of which a motor may be adjusted to the same speed as another distant motor is illustrated in Fig. 50. Alternating current received over the line operates the line relay tongue, the marking contact of which is connected to alternate segments of ring R_2 on the distributor. Ring R_1 is provided with two groups of segments connected to fast and slow lamps F and S. Each alternate segment is separated by short insulated segments 1, 2 . . . 5, and the two rings are bridged by brushes CB. The indications of the two lamps show the state of affairs, which is explained by the lower portion of the diagram, in which a black circle represents a lighted lamp and a blank circle that the lamp is out. The period at which an observation is taken is when both lamps are either extinguished or glowing.

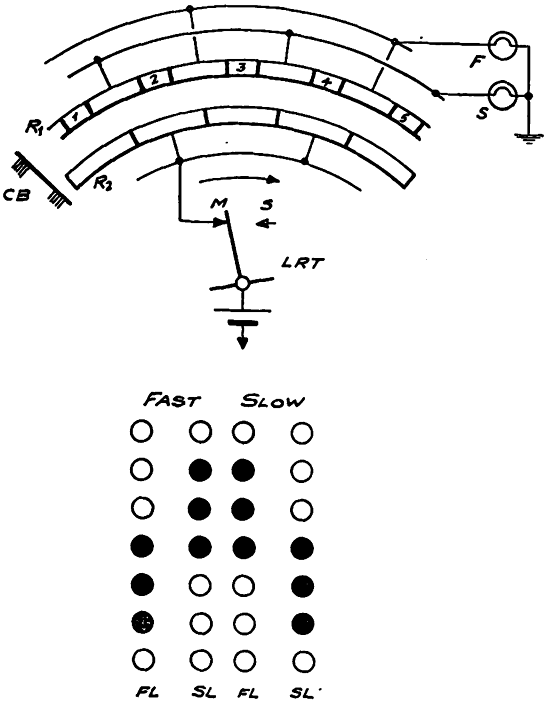


FIG. 50.—Morkrum's speed indicator.

The motor speed is seen to be fast when

After both lamps are extinguished, the fast lamp remains extinguished.

After both lamps are glowing, the fast lamp remains glowing.

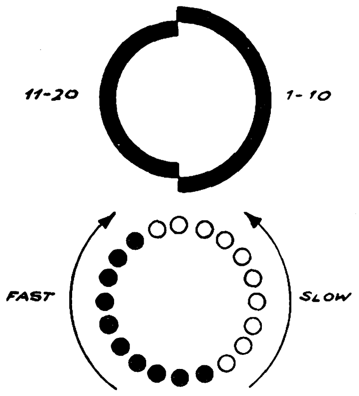


FIG. 51.—Speed and phase indicator.

If the motor speed is low, then

After both lamps are extinguished, the slow lamp remains so.

After both lamps are lit, the slow lamp remains lit.

If the difference of speed is considerable, the cycle between both lamps "out" to both lamps "in" is very short, but as the difference becomes smaller and smaller the cycle of change becomes longer and longer.

The author has had considerable experimental experience with this method and has found it easy to acquire the correct interpretation of the lamp indications, while

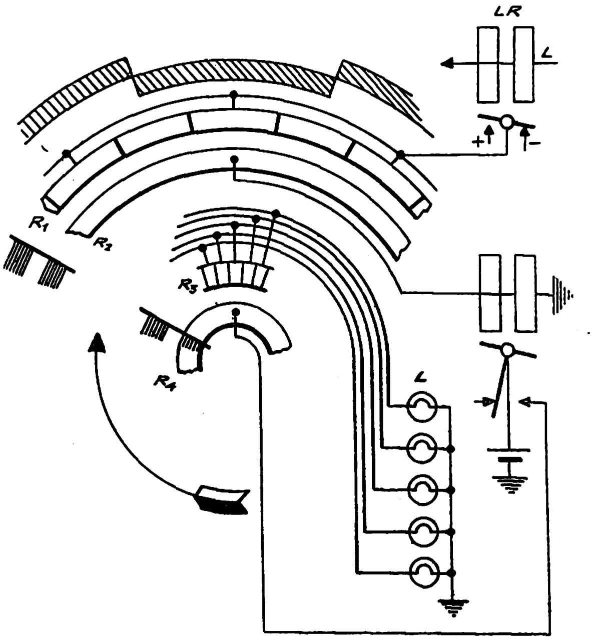


FIG. 52.—Western Union Co.'s speed and phase indicator.

it permits of a very close speed adjustment of the one motor to the speed of the other.

Simultaneous Speed and Phase Indicators.

If indicating lamps are connected to each of the receiving segments of a distributor and the distant distributor sends out positive current for one half-revolution and negative for the other half, then speed and phasing can be adjusted by observing the lamps. In Fig. 51 the distributors are provided with 20 segments which at one end are connected in two groups by a switch and arranged to send out positive and negative pulses, as shown in the upper part of the diagram. Any 10 of

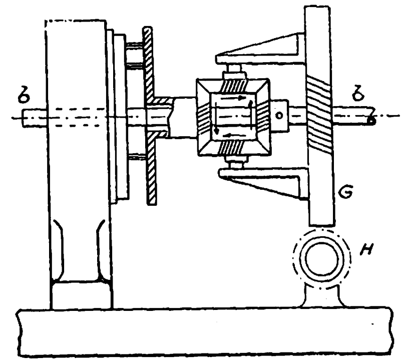


FIG. 53.—Phase adjustment of rotating brushes.

the 20 receiving lamps will be lit up, as seen in the lower diagram, and the actual 10 lighted indicate the instantaneous phase difference between the two distributors. The progression of the 10 lamps indicates whether the receiving distributor is fast or slow with respect to the distant one, and the rate of progression indicates the extent of the speed difference. When synchronism is attained, the lighted lamps remain stationary and then indicate the angle through which the receiving distributor has to be moved in order to come into phase with the distant distributor.

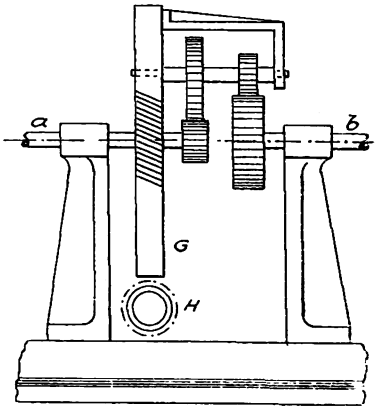


FIG. 54.—Phase adjustment of rotating brush shaft.

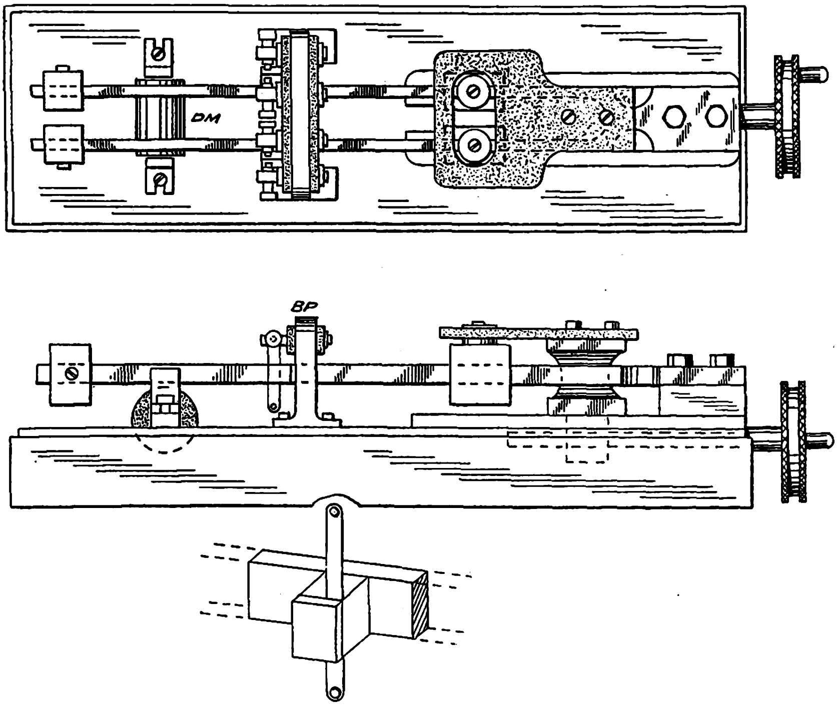


FIG. 56.—Muirhead's tuning fork.

Western Union Method.—Fig. 52 is an arrangement in use on the London–New York high-speed cable operated by the Western Union Co. Here 5 lamps are multipled to 5 segments of ring R_3 of a distributor. The direction in which these lamps light up (top to bottom, or vice versa) furnishes a speed indication and the lamps are afterwards used for adjustment of phase.

Phase Adjustment or Orientation.

It is the practice in America to secure orientation by adjusting the brushes while they are in motion. This is not only accurate and rapid but it obviates the mounting of segments on sliding sectors and the use of flexible trailing cables. Figs. 53 and 54 show two arrangements for effecting this which hardly require explanation.

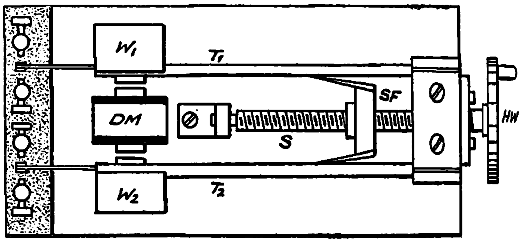


FIG. 55.—Carpentier's tuning fork.

Construction of Tuning Forks.

Carpentier's Fork.—Fig. 55 is a tuning fork constructed by Carpentier of Paris and adopted by the French Administration of Posts and Telegraphs for driving phonic-wheel distributors on Baudot multiplex installations. The two tines T_1 and T_2 are simple forged steel bars gripped at one end in a heavy cast-iron clamping block integral with the base. Sliding weights W_1 and W_2

effect a coarse adjustment of the rate of vibration, and a spring fork SF moved backwards and forwards by the hand-wheel HW constitutes a vernier means of setting. The two tines carry contact springs which butt against fixed contacts mounted on an insulated strip attached to the cast-iron base. The Baudot system runs at a standard speed of 3 revolutions per second and there is therefore no need for great refinement of method in the adjustment of the fork speed.

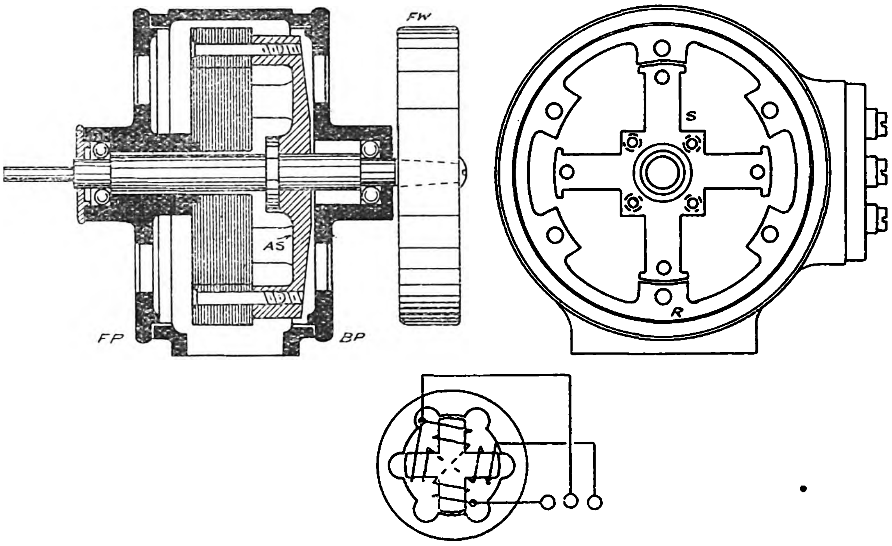


FIG. 57.—Eastern Telegraph Co.'s pattern phonic-wheel motor.

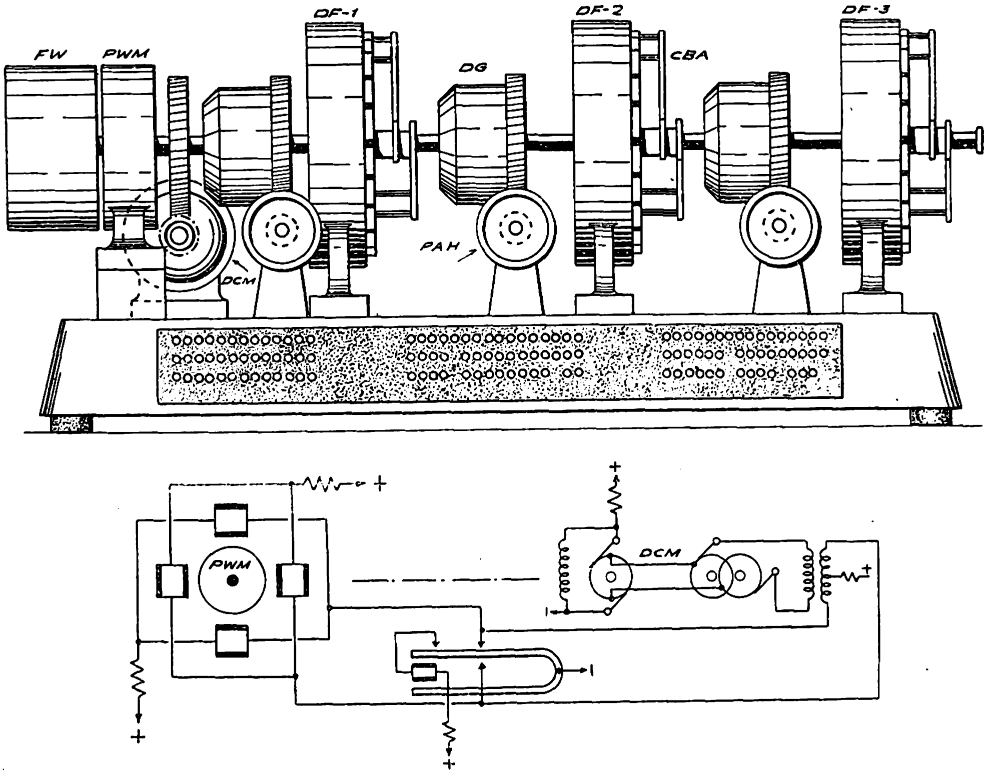


FIG. 58.—American pattern distributor.

Muirhead's Fork.—Fig. 56 shows a fork designed and constructed by Messrs. Muirhead and Co. The fork is, in this instance, a solid forging, the tang being bolted to a heavy block at the right-hand end of the base. Towards the free end a metal bridge piece BP straddles the two tines and carries two pairs of fixed contacts suitably insulated. The tines are each provided with a light leaf spring carrying platinum contacts, as is clearly shown in the second and third sketches. The free ends of the tines carry loading weights, a series of which are provided to give the fork a certain speed range. The vernier adjustment, which can be effected while the fork is running, consists of two sliding weights friction-tight on each tine, which weights can be moved to and fro by means of a bakelite shifting piece screwed to a sliding carriage controlled by a hand-wheel. Each weight has a ball-bearing roller pivoted to it, and these rollers enter a slot in the bakelite shifter. In this way the weights can be adjusted without interfering with the vibration of the fork, the rollers reducing the friction due to the contact of the bakelite shifter with them. The author has used two of these forks for over two years and has found them quite satisfactory.

Construction of Phonic-Wheel Synchronous Motors.

The usual construction of phonic-wheel motor is a laminated-iron toothed wheel surrounded by one or two pairs of driving magnets.

Muirhead's Motor.—A novel design used by the Eastern Telegraph Co. and made by Messrs. Muirhead and Co. is illustrated in Fig. 57. The stators are cruciform in shape and are bolted to the casing. The rotor is provided with internal teeth and embraces the stator. It is bolted to an aluminium spider AS which is, in turn, bolted to the shaft. FW is the usual mercury flywheel. This construction reduces the overall diameter considerably, as compared with other types.

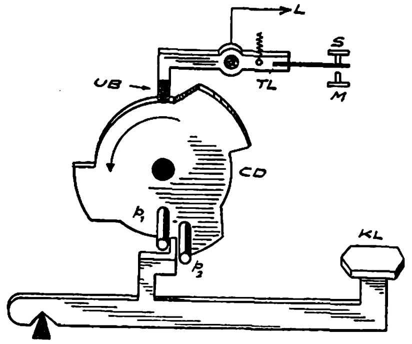


FIG. 59.—Elementary keyboard transmitter.

Distributor Construction.

The influence of American designers on distributor construction has been considerable. In place of the single-face distributor more or less general in Europe, they employ separate distributors for receiving, transmitting, correction and the other purposes that a distributor serves (stepping tape transmitters, synchronizing printer units, etc.)

Western Union Distributor.—Fig. 58 represents a distributor as used on the Emden–New York high-speed cable. Three distributor faces DF_1, DF_2, DF_3 are mounted on a common base. The three sets of brush arms CBA are driven from a main shaft and each can be separately and independently orientated by the hand-wheels PAH by means of differential gears DG. The shaft is driven by a phonic-wheel motor PWM having a mercury flywheel FW. In addition, a d.c. motor DCM is geared to the shaft and the phonic-wheel motor is impulsed and the speed of the d.c. motor controlled by a common fork, as shown in the lower diagram. The combined drive is thus powerful and yet has time-keeping-properties by reason of the tuning-fork control of the two motors.

All connections are cabled to a terminal block on the front of the cast-iron base, and, in use, this is protected by a dust-cover (not shown).

Distributors are driven at from 3 to 6 revolutions per second and phonic-wheel motors have from 6 to 9 teeth. Fork speeds vary therefore from 18 to 60 complete vibrations per second.

Section (2). TRANSMITTERS OR COMPOSING MACHINES.

General Considerations.—There are two general types of transmitter:—

(1) The keyboard controlled transmitter; and
(2) Transmitters of the Jacquard mechanism type, in which the control is effected by a paper fillet or tape.

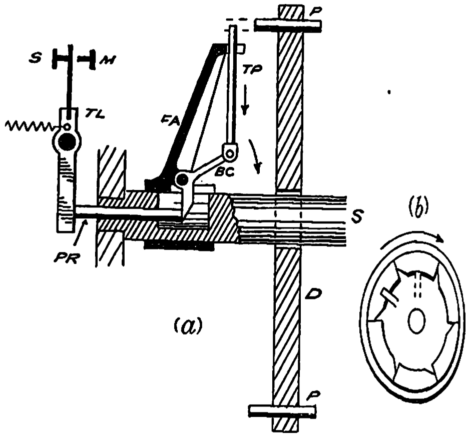


FIG. 60.—Siemens's keyboard transmitter.

Type (1) is not readily adaptable to the transmission of unequal-letter alphabets such as the Morse Code, as it takes its simplest form when the transmitting cycle time is invariable. The second type is equally efficient, regardless of the nature of the code employed. This is due to the fact that the tape forms a storage reservoir which removes the restriction as to the time of the transmitting cycle. Type (1) can be made to approach the universal character of type (2) by adopting metal storage means such as a group of pins in a cylinder or disc, but it then becomes very costly, especially if an unequal-letter code is employed.

The second type of transmitter can be operated either

(i) Continuously, at high speed, where it handles the output from a number of manually-operated keyboard perforators; or
(ii) Intermittently, letter by letter, when controlled by an equal-letter code.

When intermittently operated, the feed wheel is stepped forward by a ratchet-and-pawl mechanism operated by an electromagnet impulsed by contacts on a distributor.

Under these conditions it transmits the output of one keyboard perforator only. It may also be intermittently operated by a shaft released to make one revolution or some even part of a revolution. The shaft is then intermittently clutched to a continuously rotating power shaft and is either coupled to it by a mechanical operation when a key lever is actuated, or it can be controlled from distributor contacts operating a clutch magnet.

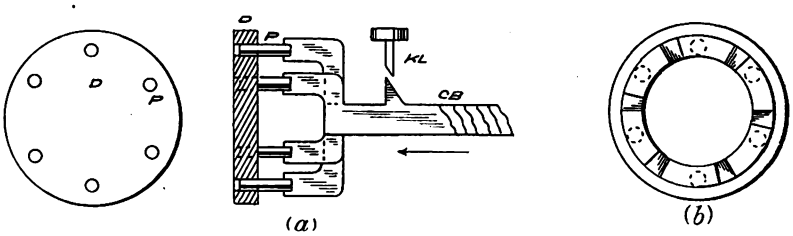


FIG. 61.—Alternative forms of differential cam devices.

Elementary Keyboard Transmitter.—Fig. 59 represents an elementary form of keyboard transmitter in which there are a number of code discs CD corresponding to an equal number of key levers KL. The code discs are friction-tight on a continuously driven shaft, but are restrained from rotation by a lug on each key lever against which rests a pin " p," fixed to the code disc CD. If a key lever is depressed, its restraining lug is moved out of the path of pin " p_1," and the disc is entrained by the rotating shaft through the friction coupling and makes one revolution. If the key lever is kept in the operated position indefinitely, the code disc does not make more than one revolution due to the provision of a second stop pin " p_2" which is caught by the lug on the key lever when the latter is in the operated position. Under these conditions the code disc is not quite in its normal position, but when the key is released the stop lug rises, freeing pin " p_2," but finally stopping the disc by coming into the path of " p_1." As the selected code disc rotates, the projections and depressions oscillate a bar UB which rests on the depressed surface of all the code discs, and this movement controls a single transmitting lever TL to send out marking and spacing currents over the line. The code disc is a copy of the current pattern corresponding to the letter signal transmitted.

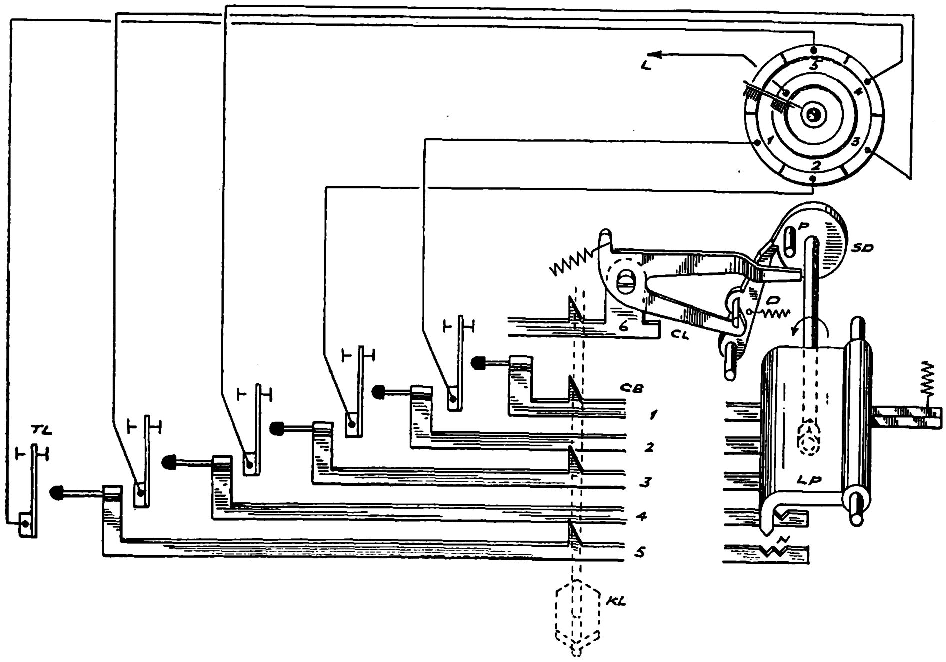


FIG. 62.—Elements of keyboard transmitter.

This type of keyboard transmitter involves:—

Individual code discs for each letter.
An invariable time for the transmission cycle.

It is therefore only applicable to an equal-letter code and, except for the cost of the individual discs, would serve quite well as a means of operating any of the modern start-stop machine telegraph systems.

Siemens's Transmitter.—The individual cams could be replaced by a single cam if it were possible to rearrange the projections and depressions on the edge of the cam by a selective process effected on the operation of any key lever. This was accomplished over 75 years ago by Werner Siemens. Fig. 60(*a*) illustrates Siemens's keyboard transmitter in which the variable cam surfaces are formed by pins P arranged circularly in a disc D, S is a rotating shaft on which is mounted a fixed arm FA which rotates with it. Fixed to FA is a bell-crank BC, to the upper arm of which is pivoted a transmitting pin TP. The lower arm of the bell-crank rests against a presser rod PR which, in turn, rests against the lower end of a single transmitting lever TL. As the pins P are pushed out from their normal position they encounter the pin TP which is momentarily forced below them. As this depression takes place, BC is rocked clockwise and pushes the presser rod PR to the left. PR, acting on the lower end of lever TL, reverses the position of this, and marking current is sent to line.

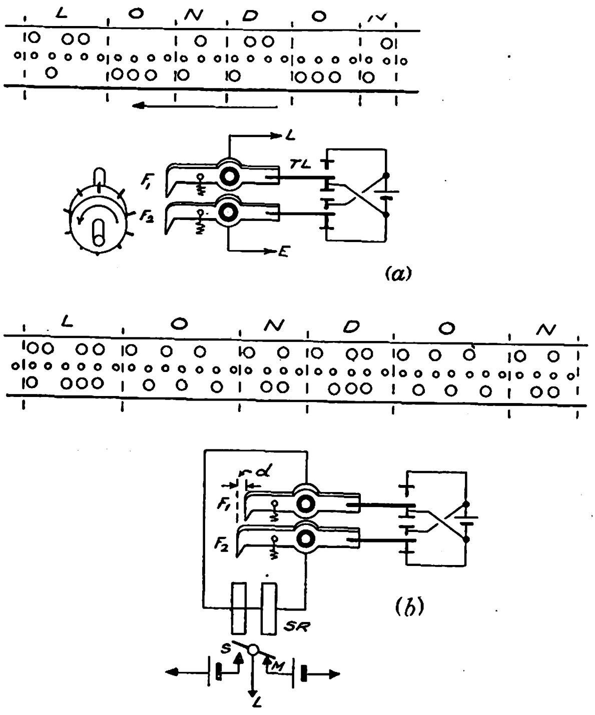


Fig. 63.—Elementary forms of tape-controlled transmitters.

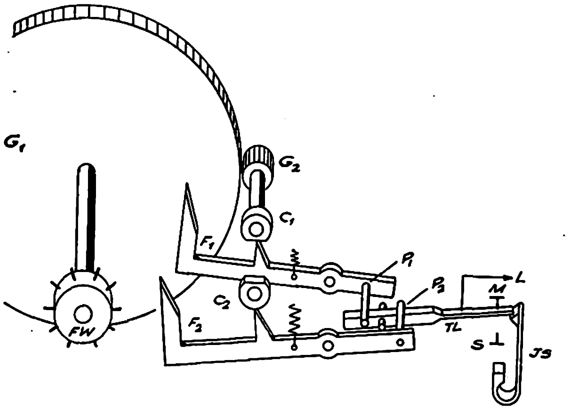


Fig. 64.—Diagrammatic form of Wheatstone transmitter.

In place of the pins, segments capable of displacement out of the plane of the paper may be used, as shown in Fig. 60(*b*). The variable setting of the pins may be accomplished by the usual combination bars set by any one of a number of key levers in accordance with the current permutations representing the letter signal corresponding to the key lever operated [Fig. 61(*a*)]. Fig. 61(*b*) shows the pins replaced by segments. Both arrangements, if the transmitting arrangements of Fig. 60(*a*) are applied to them, correspond to a single code disc to which a differential cam effect can be imparted by the setting action of any one of a number of key levers.

The discs with their pins or segments may revolve and the transmitter lever mechanism be stationary. If, however, the capacity of the disc is only one letter signal, the disc must be stationary during the setting process and clutched to a rotating shaft for one revolution only.

All-electric Keyboard Transmitter.—An all-electric type of keyboard transmitter is illustrated in Fig. 62. The single transmitter lever is here replaced by a distributor with rotating brush-arm. The brush arm is mounted on a shaft which also carries a stop disc SD and a cam which normally keeps a lock plate LP free of the combination bars 1 to 5. Each key lever operates the bars CB variably in accordance with the letter signal to be transmitted. The left-hand end of each bar carries an insulated rod adapted, when a bar is moved to the left, to reverse the position of the 5 transmitter levers singly or in combination. A sixth bar CL is operated by any one of the operated key levers KL and removes the detent D from the single tooth of the stop disc SD. The brush arm, the stop disc and the lock plate cam now start revolving. The lock plate drops and its front edge enters one of two notches N in the combination bars, thus locking them in their operated and non-operated positions so that premature release, by the operator, of the key lever which has been depressed cannot mutilate the signal. Indirectly it locks the keyboard, as the depression of a second key while the first is down is without effect. As the rotation of the shaft, yieldingly driven by a motor—not shown—proceeds,

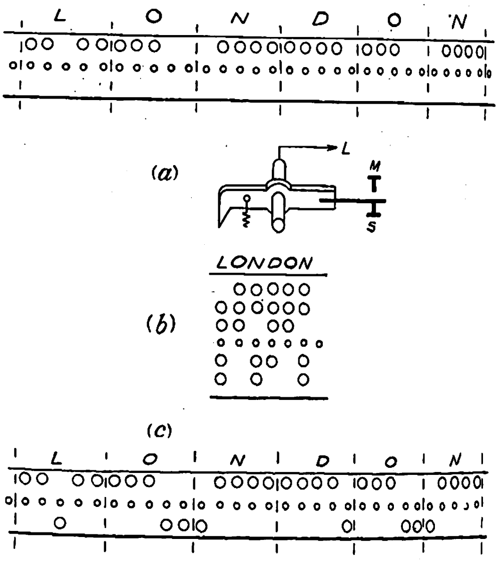
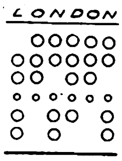


Fig. 65.—Various forms of 5-unit transmitting tape.

the letter signal pulses are swept out to line by the distributor as the brushes make contact successively with the segments to which the transmitter levers are connected. At an early stage of the revolution, a pin P on stop disc SD comes in contact with the upper arm of the bell-crank attached to the sixth bar CL. As P moves downwards it depresses the bell-crank until its lower arm is clear of the pin on the detent D. The latter, thus freed, is drawn to the right under the action of a spiral spring and is ready to arrest the stop disc and brush arm when the single tooth comes round at the end of the revolution. Thus the key lever may be kept down indefinitely, but the letter signal will only be transmitted once. At the end of the revolution, the lock plate is lifted by its cam and the keyboard is unlocked, thus becoming free for the setting up of another letter.



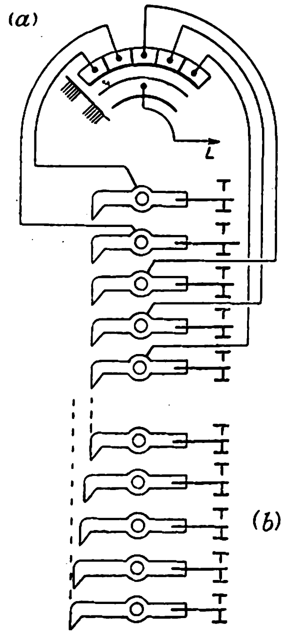


FIG 66.—Alternative forms of 5-unit transmitter.

This elementary form of keyboard transmitter illustrates very well the conditions which have to be met in start-stop machine telegraphy. These are:—

Only one letter signal must be sent out when a key lever is actuated.

The keyboard must be immediately locked when a key is operated so that:—

(a) Premature release of the key does not mutilate the signal, and

(b) The improper depression of another key, while transmission is proceeding, is without effect.

Tape-controlled Transmitter.—The second type of transmitter, controlled by a perforated paper tape, takes a variety of forms depending upon the code of signals to be transmitted. Fig. 63 represents in elementary forms the cable Morse Code transmitter and that for land-line Morse Code or Wheatstone Code. Each transmitter is provided with a pin or sprocket wheel which is rotated through gearing by a suitable motor and engages the centre line of small feed-holes formed in the tapes by the perforating mechanism. Each transmitter is provided with two feelers F_1 and F_2, insulated from one another and from a common pivot, and so placed with respect to the paper tape that their noses are pressed downwards on this, which is supported on a platform (not shown). The cable code is such that signal perforations occur both above and below the centre line of feed holes with portions of imperforate tape representing spaces between the letters. It will be noted that on any vertical line across the tape only one hole can occur, but that it may be either above or below the line of feed holes. The feelers explore across the tape and along any one of the imaginary vertical lines, and since there are two possibilities the exploring action of the two feelers must be simultaneous. If either feeler encounters a perforation it is forced into it and, oscillating on its pivot, reverses the position of its transmitting lever TL.

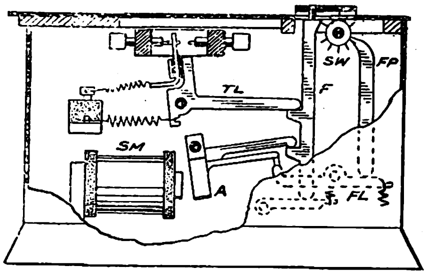


FIG. 67.—Step-by-step 5-unit transmitter.

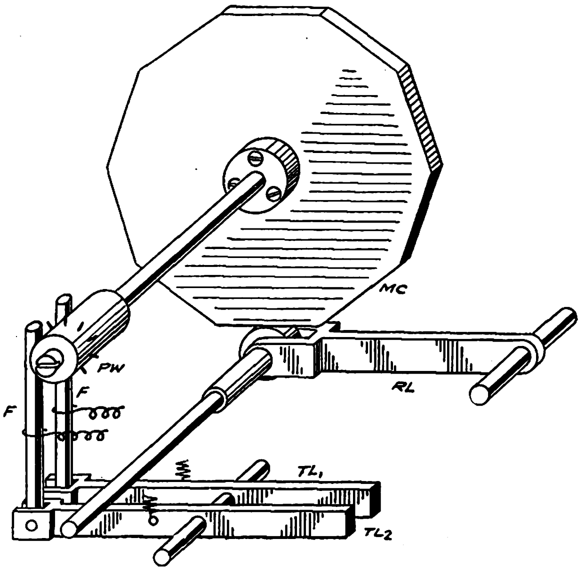


FIG. 68.

In the case of the land-line morse, two holes do occur in the same vertical line on the tape [Fig. 63 (*b*)]. The simultaneous operation of the two feelers would then be ineffective, as both transmitter levers would be connected to one pole of the battery, while the other would be insulated. The feelers in this case have their noses displaced by a distance *d* equal to half the pitch of the feed holes in the tape. As the tape moves from right to left, feeler F_1 enters the first hole in the top row and half a centre hole-space later is rejected, while F_2 enters a hole in the lower row if one exists. Such a case as this occurs on the first vertical line of the letter L in the word "London." A positive marking signal is first sent out, followed by a negative spacing signal, these two pulses constituting a morse dot (double-current operation). The next signal is a dash, which consists of an upper hole opposite to which is an unperforated portion of tape succeeded by an upper unperforated portion opposite which is a hole in the lower portion. The effect on the feelers is as follows:—F_1 falls into the top hole and reverses the position of the tongue of the sending relay SR so that this sends positive (marking) current to line and initiates the dash signal. SR, being a polarized relay, remains in this position, and as the tape advances F_1 is rejected and held against its lower spacing contact. SR is not interfered with.

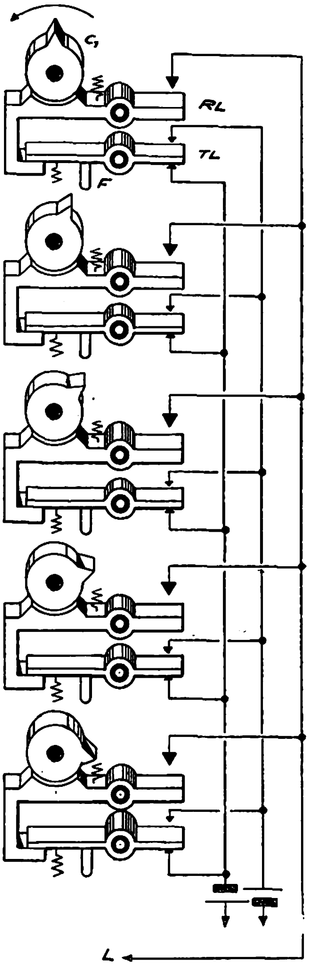


FIG. 69.—Baudot's 5-unit transmitter.

As the tape advances further, feeler F_2 encounters the lower hole, reverses its position and sends a current through the sending relay in a direction to move the tongue to the spacing contact S. This elementary transmitter only initiates the beginning and end of a signal, dot or dash, the sending relay ensuring that these are of full length by its property of remaining on whichever contact it is placed until receiving a pulse to reverse this.

Wheatstone Transmitter.—The well-known Wheatstone transmitter does not require a sending relay as its two peckers control the movement of a transmitting lever which is mechanically held on the contact on which it, at any moment, rests.

Fig. 64 gives the principles of the transmitter in diagrammatic form. A weight or other form of motor drives a gear wheel G_1, which is rigid on a shaft provided with a pin feed wheel FW. A second shaft geared to the first carries two cams C_1 and C_2 which alternately depress and release two feelers F_1 and F_2 pivoted to the framework of the transmitter. Cam surfaces on the feelers are kept up against cams C_1 and C_2 by spiral springs. At the right-hand ends of F_1 and F_2, pins P_1 and P_2 act alternately on a pivoted transmitting lever TL. The latter is held on either contact, M or S, by a jockey spring JS. The operation of the transmitter will be obvious from the preceding matter. The gear ratio is such that one signal cycle takes place while FW moves through the angle between two feed pins.

Five-unit Code Transmitters.—Perforated tape for the 5-unit code takes three forms. Fig. 65(*a*) shows one such in which the letter signals are parallel to the line of feed holes. A single-lever transmitter is successively actuated as the tape is drawn past the pointed end of the feeler. Fig. 65(*b*) shows a tape in which the letter signals are at right angles to the feed holes or across the tape. This effects economy in tape but requires a different type of transmitter. Fig. 65(*c*) shows a form of 5-unit tape in which marking and spacing holes are on opposite sides of and parallel to the line of feed holes. This tape is of the same form as a cable code tape and the transmitter shown in Fig. 63(*a*) can be used with it.

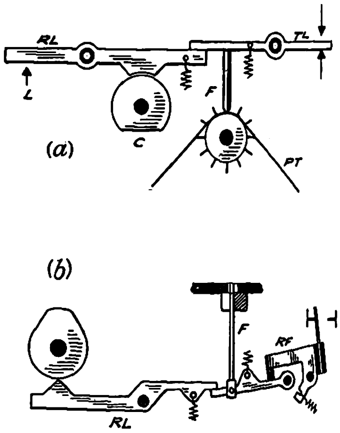


FIG. 70.—Kleinschmidt's 5-unit transmitter.

The transmission of cross-perforated tape is effected in two ways. The tape may be fed forward letter by letter, feeding taking place after the letter has been transmitted. Five transmitter levers are used in this case, each being connected to a sending segment on a distributor (Fig. 66*a*). The second method is to feed the tape continuously forward by a pin feed wheel suitably geared to the distributor brush-arm shaft. The feelers must then operate in succession and are therefore varied in length [Fig. 66(*b*)] to secure this.

A well-known type of step-by-step transmitter is shown in Fig. 67. Five feelers F, side by side, control five transmitting levers TL. SM is the stepping magnet which, when energized, withdraws all the feelers from the tape and acts on a feed lever FL to raise the feed pawl FP which moves the star wheel SW through an angle so that the latter draws the tape on one feed hole in extent.

In a cable code transmitter it is now general practice to use a phonic-wheel motor controlled by a tuning fork in order to obtain that constancy of speed which is so necessary for cable working. By using a multiple-faced cam for controlling the feelers, the motor may be applied directly to the transmitter without the use of gearing. Fig. 68 shows the arrangement, which is due to Messrs. Muirhead and Co.

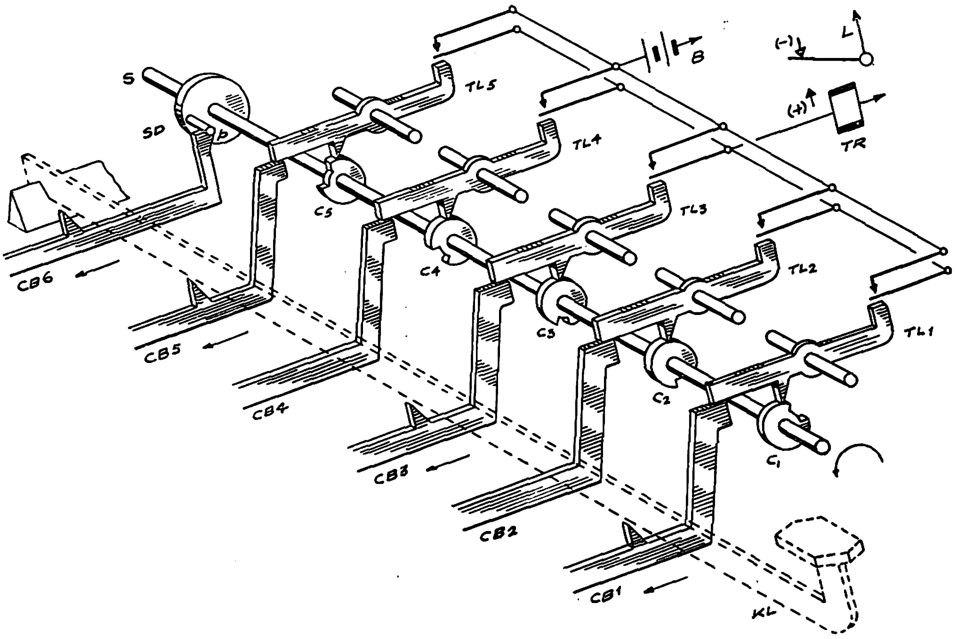


FIG. 71.—Principle of Morkrum's 5-unit keyboard transmitter.

In all the types of tape-controlled transmitter so far examined, the following charactersitics will be noticed:—

Wherever a cross-perforated tape, of the type where more than one perforation occurs on the same vertical line, is used, the transmitter feelers must act in succession.

Where more than one feeler is used, they may have individual transmitter levers or may act separately on a single transmitter lever.

The perforated and unperforated portions of the controlling tape constitute the equivalent of the cams of Fig. 59 and, in the case of equal-letter codes, may be considered as a single cam with its cam faces variably adjusted.

Baudot's Transmitter.—In 1880 Baudot designed a transmitter for cross-perforated tape in which 5 feelers (Fig. 69) attached to individual transmitter levers TL are released in succession by means of a series of release levers RL, and allowed to explore the series of perforated and unperforated portions of tape lying immediately beneath them. Levers RL are depressed successively by a series of cams C_1 to C_5 and connect the line to the transmitting levers in turn. The currents sent out to line will depend upon the letter signal punched in the tape and presented to the feelers. The release levers not only allow the entrance of the feeler into a perforation and reject it subsequently, but as they also connect the line to the feelers one after the other they replace the usual distributor and the mechanism may be termed a "transmitter-distributor," although Baudot described it as a "mechanical distributor."

If we rearrange Baudot's transmitter somewhat as in Fig. 70(*a*), it is still identical with Fig. 69, in principle, the tape feed wheel and perforated tape PT now being shown.

Fig. 70(*b*) represents a well-known type of 5-unit transmitter in which the only variation from Fig. 69(*a*) is that the feelers are connected to pivoted levers, and oscillate a rocking frame RF on which is mounted a single transmitting lever moving between spacing and marking contacts.

This transmitter of Baudot shows that the first principle relating to tape transmitters is perfectly general and not restricted to any particular number of cross-perforated holes. Also, it will be seen that in such transmitters where the feelers are operated in succession through one signal cycle the tape produces an interference effect—where unperforated portions occur—and constitutes a series of variable cams. Thus if each letter signal during one revolution of a battery of cams is caused to operate a number of transmitting levers or not, according to whether the motion of these is interfered with, the modern keyboard transmitter is arrived at.

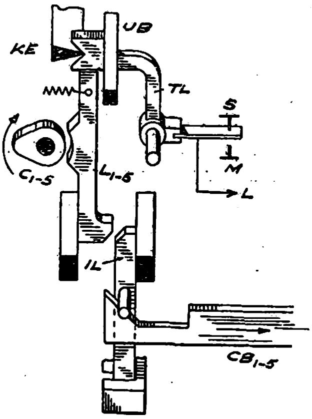


FIG. 72.—Potts's 5-unit keyboard transmitter.

Morkrum's Transmitter.—An example due to Morkrum is illustrated by Fig. 71. S is a shaft yieldingly driven and arranged to be stopped and started by means of a combination bar CB_6 set by a plurality of key levers of which KL is one. Five two-armed transmitting levers TL_1 to TL_5 are adapted to close the circuit of a battery B by which a transmitting relay TR sends positive marking or negative spacing currents over a line L. If the whole of the combination bars are shifted to the left in the direction of the arrows, they will have no interfering action on the transmitter levers and the latter will successively fall into the depressions on cams C_1 to C_5, thus causing 5 positive pulses to be sent out to line. If a combination bar is not withdrawn it will interfere with its own transmitter lever and this cannot fall into the depression of the corresponding cam. Thus, a battery pulse from B will be suppressed and transmitting

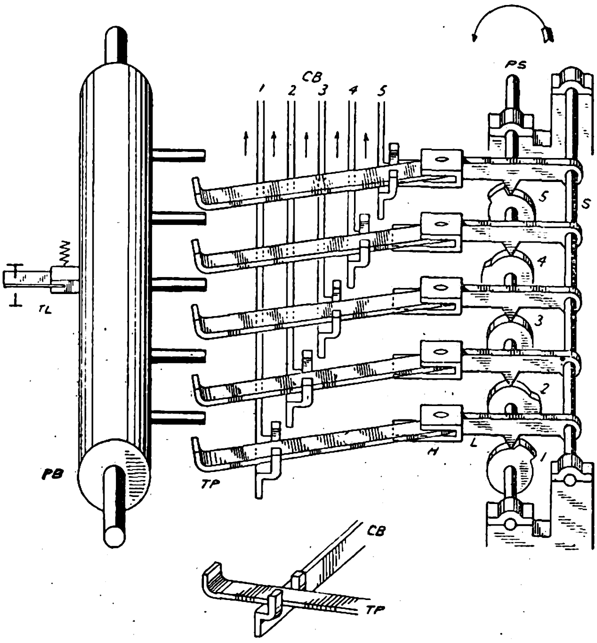


FIG. 73.—Cardwell's 5-unit keyboard transmitter.

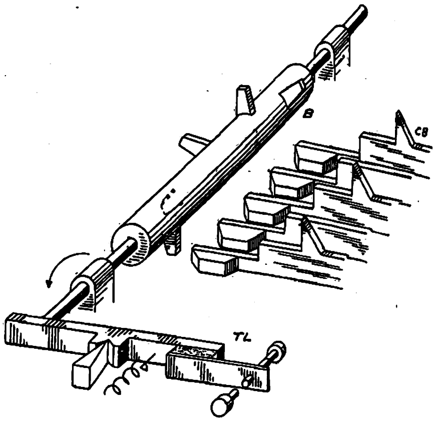


FIG. 74.—Kleinschmidt's 5-unit keyboard transmitter.

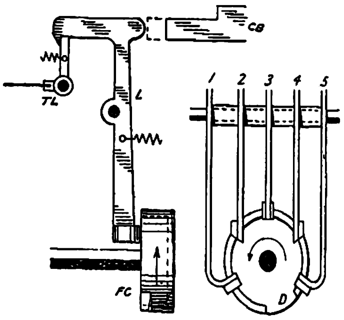


FIG. 75.—Siemens and Halske's 5-unit keyboard transmitter.

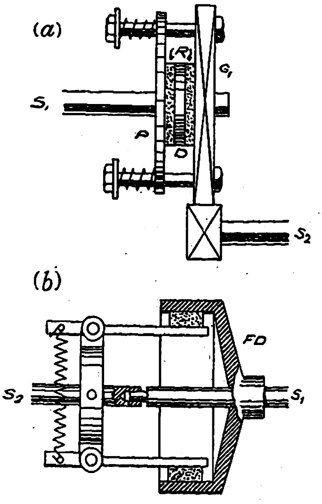


FIG. 76.—Alternative forms of friction clutch.

relay TR will release sending a negative or spacing current to line. This transmitter is in principle identical with that of Baudot, the cam surfaces, when not selected, acting as unperforated portions of the controlling tape used by him.

Potts's Transmitter.—A single transmitting contact lever may be used, as shown in the construction of Fig. 72 due to Potts. Here, 5 levers pivoted at their upper ends on a knife edge KE are successively operated by a series of 5 cams, and act upon a single transmitting lever by means of a universal bar UB. Normally, the lower ends of the vertical pivoted levers are free and when the cams come into contact the lower ends of the levers are pushed to the right, KE acting as a fulcrum.

The combination bars CB_1 to CB_5, when displaced, raise intermediate pieces IL which cause the levers L_1 to L_5 to fulcrum on these, so that when a cam is now active the upper ends of the levers are moved to the right and, acting on UB, reverse the position of TL to send a marking current. These selections are variable in accordance with the letter represented by the key lever operated.

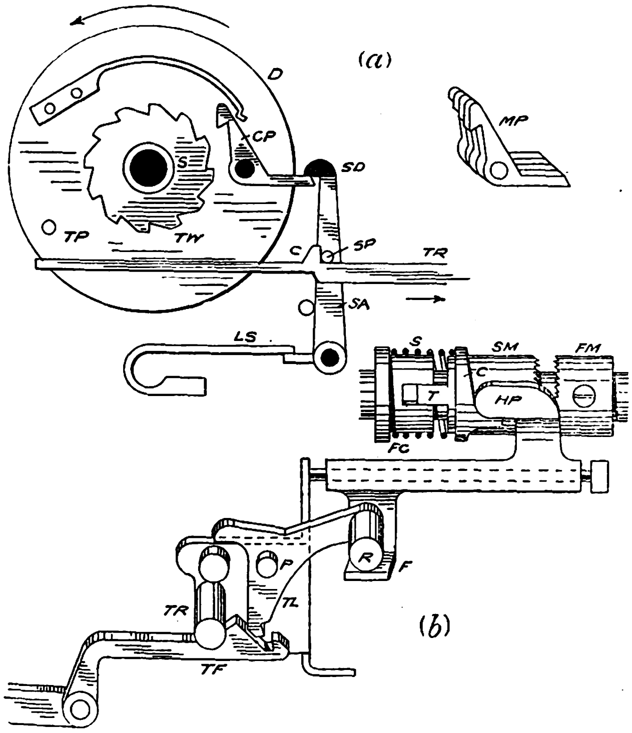


FIG. 77.—Alternative forms of single-revolution clutch mechanisms.

Cardwell's Transmitter.—Cardwell's single-contact keyboard transmitter is illustrated by Fig. 73. The transmitting lever TL is controlled by a pin barrel PB which is rocked at appropriate instants by a series of cam-controlled levers L having hinges H to which are attached a series of plates TP which can be selectively brought under the pins on the barrel by means of the combination bars CB. As the corresponding lever L is raised by its cam, the hinged plate TP, if under one of the pins in the barrel PB, rocks the latter and reverses the lever TL.

Kleinschmidt's single-contact transmitter (Fig. 74) consists of a barrel B capable of rotation and also endwise motion. It is provided with 5 cams arranged spirally and these engage other cams at the ends of selected combination bars which shift the barrel endwise, reversing the position of the transmitting lever TL.

Siemens and Halske's transmitter is shown in Fig. 75. In this apparatus, 5 levers L act on a common transmitting lever TL and are freed in succession by a cam FC having a single depression D. Combination bars CB interfere with the movement of levers L, if they are in the selected position.

Single-revolution Clutches.—The transmission, letter-by-letter, of equal-letter codes from a keyboard transmitter necessitates means by which the cam shaft makes one revolution per letter. It is not practicable to start and stop a motor revolution by revolution, and consequently means have to be provided by which the cam shaft is coupled to the power shaft for a single revolution. Clutches for this purpose may be broadly divided into two classes:—

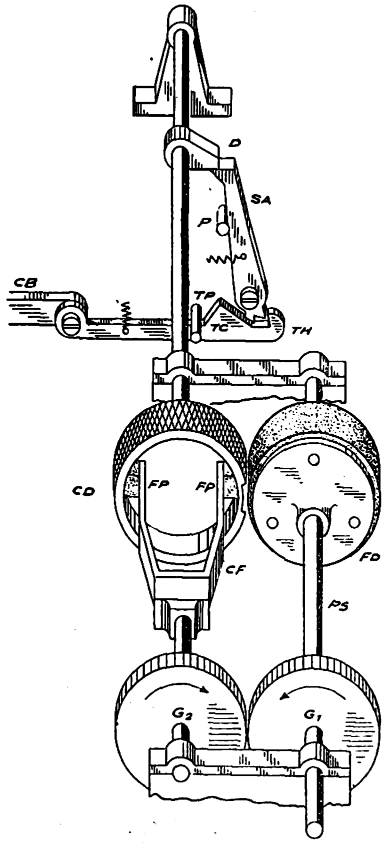


FIG. 78.—Single-revolution 2-stage friction clutch.

> Friction clutches in which the cam shaft is positively stopped against the couple exerted by the clutch, and
>
> Positive clutches in which the shafts are mechanically connected and forcibly uncoupled when the single revolution is completed.

The coupling action must be effected when a key lever is operated, and must be independent of the duration of key-lever operation. Two types of friction clutch are shown in Fig. 76. Their operation is obvious. Two examples of the positive type of clutch are shown in Fig. 77. In Fig. 77(*a*) the power shaft is in the form of a sleeve S and carries a toothed wheel TW. S and, with it, TW, are continuously rotated. The cam shaft is surrounded by the sleeve S and carries a disc D on which is mounted a spring-pressed coupling pawl CP. CP is normally clear of TW, being held so by a stop detent SD. When a key lever is operated it pulls a trip rod TR to the right. TR is provided with a cam C which acts on a pin SP and withdraws the detent SD from the tail of the coupling pawl SP. CP, under the control of the curved spring, forcibly enters the teeth of wheel TW, coupling sleeve and cam shaft together. The tripping mechanism is now reset independently of the operation of the key lever in the following manner. A pin TP on disc D engages the free end of the trip rod TR and frees it from SP so that the detent SD immediately flies back to the stop position in readiness to act on the tail of CP and uncouple the sleeve and cam shaft when the revolution is completed. The momentum of the moving parts assists the uncoupling operation. When the key lever is finally released TR returns under the action of a spring to the normal position shown. To ensure prompt coupling action a multiple pawl is sometimes provided, as shown in the inset, and a number of similar wheels equal to the number of pawls, but with their teeth staggered, are employed.

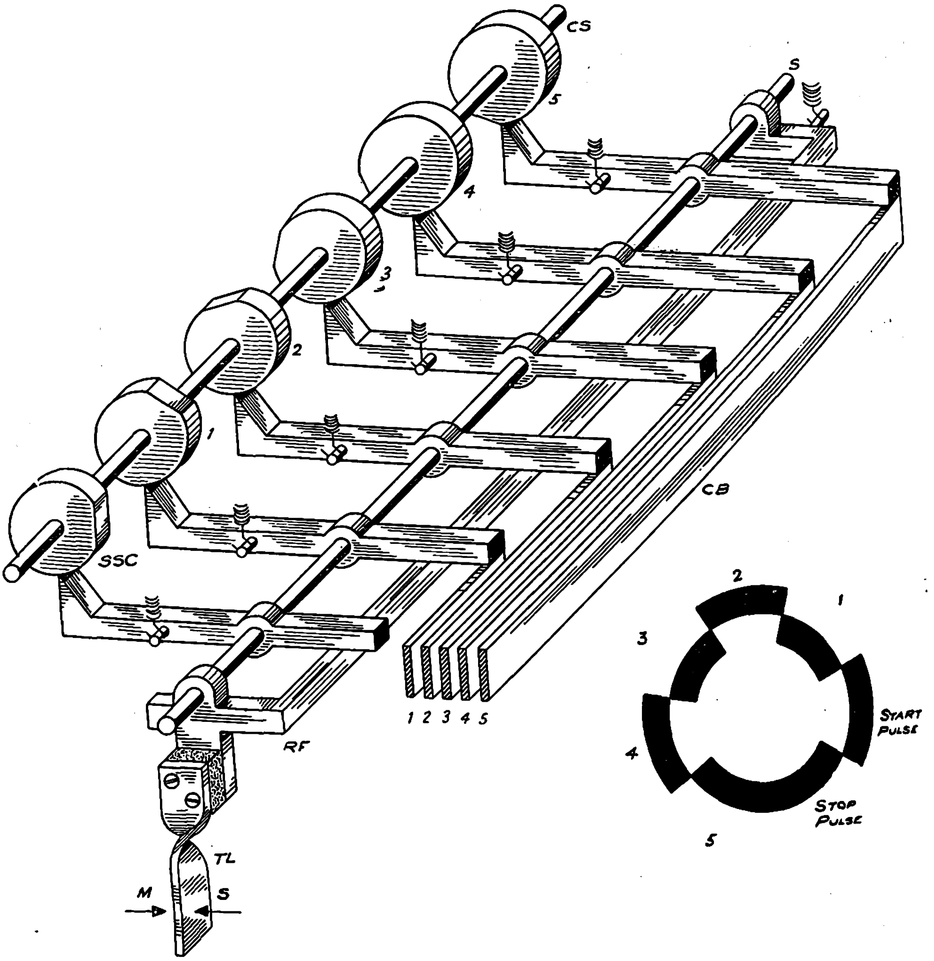


FIG. 79.—Creed's 5-unit keyboard transmitter.

Fig. 77(*b*) shows a keyboard-controlled clutch mechanism, in which the clutch is formed by two circular toothed members, one, FM, fixed to the revolving shaft and the other consisting of a spring-controlled sliding sleeve SM. The latter is coupled by means of tongue T to a fixed collar fastened to the cam shaft. Release is effected by a holding pawl HP which is released and reset by the trip mechanism shown and which acts on a cam C to uncouple SM at the end of the revolution.

Friction clutches have the disadvantage that they cannot deal with a heavy load. If they are arranged to do this, then the force required to stop them is considerable and the wear on the friction coupling is excessive. If they are to start up the secondary shaft promptly when release is effected, they must exert considerable torque and the release then becomes difficult, while the stoppage occasions violent shocks.

A friction clutch which meets the conflicting requirements very ingeniously is shown in Fig. 78. The power shaft is geared by wheels G_1, G_2 to the clutch fork CF the extremities of which carry friction pads FP engaging with the internal walls of a coupling drum CD. CD is mounted on the secondary shaft which is restrained from movement by detent D. Release is effected by the usual tripping arrangement, as shown, and CD commences to revolve. Directly it has moved through a small angle the knurled outer walls of the coupling drum engage an auxiliary friction disc FD on the power shaft and additional power is supplied to drive the secondary shaft. Towards the end of the revolution, the slot in the outer wall of CD comes opposite to FD so that the latter is no longer in contact, and the secondary shaft can be stopped with comparatively little effort. The clutch is thus made sensitive with respect to the start or stop conditions and yet is able to transmit adequate power to the secondary shaft.

Modern Start-Stop Transmitter.—The leading features of the modern start-stop transmitter are set out in Fig. 79. The transmitter sends out a start pulse, the 5-letter signal pulses and a stop pulse. Six cams are provided, mounted on a shaft CS, and they engage the noses of 6 horizontal spring-controlled levers mounted on a shaft S. Suspended on the same shaft is a rocking frame RF carrying a single transmitting lever TL.

If the horizontal levers are unrestrained they will oscillate counter-clockwise in succession and operate the rock frame so that it reverses TL. They are, however, variably interfered with by the combination bars CB in the usual way. This construction is due to Creed.

If the transmitter had been tape-controlled the cams would have been replaced by a paper tape and the horizontal levers provided with feelers or peckers.

Classification of Tape-controlled Transmitters.—Most transmitters of the tape-controlled type are operated indirectly, the tape being the controlling means by which the transmitter lever is power-driven from one position to the other.

Fig. 80(*a*) represents the well-known Wheatstone transmitter in which a rocking beam alternately presents a pair of peckers to the perforated tape. The transmitting lever is shifted by means of the energy stored in the springs controlling the bell-cranks, and this energy is obtained from the transmitter motor. Fig. 80(*b*) represents the Willmot transmitter for cable code. There are two bell-cranks and two levers TL but only one of each is visible, as one set is behind the other. Fig. 80(*c*) shows Stonell's cable code transmitter and Figs. 80(*d*) and (*e*) are arrangements due to Muirhead. Fig. 80(*f*) shows an arrangement of reciprocating means due to John Gell which consists of a pin disc in place of the reciprocating beam. It reduces the necessity for gearing. A considerable simplification in transmitter mechanism is secured by adopting reciprocating cams of the type shown in Fig. 80(*g*). They would be mounted on the shaft carrying the small eccentric E shown in Fig. 80(*a*).

Fig. 81(*a*) shows a cable code transmitter employing two sending relays SR_1 and SR_2. These are provided with operating and reset windings OW and RSW. In transmitters of the cable code type it is only possible to get 50 per cent marking for a complete signal element. By adopting the arrangement shown, the percentage of marking can be varied between 50 and 100 per cent. RD is a revolving disc on the transmitter shaft having two groups of segments. Once the sending relays are set they would remain so indefinitely if they were not reset, and the reset condition is controlled by RD. The reset circuit is formed via brush B, segment " b," a second segment " b " and brush A to negative. By moving brush A, carried on arm PA, backwards or forwards, the amount of coincidence of A and B can be varied and thus the time at which the relays are reset and the cable put to earth. A scale " s " enables the degree of marking and earthing to be known for any position of PA.

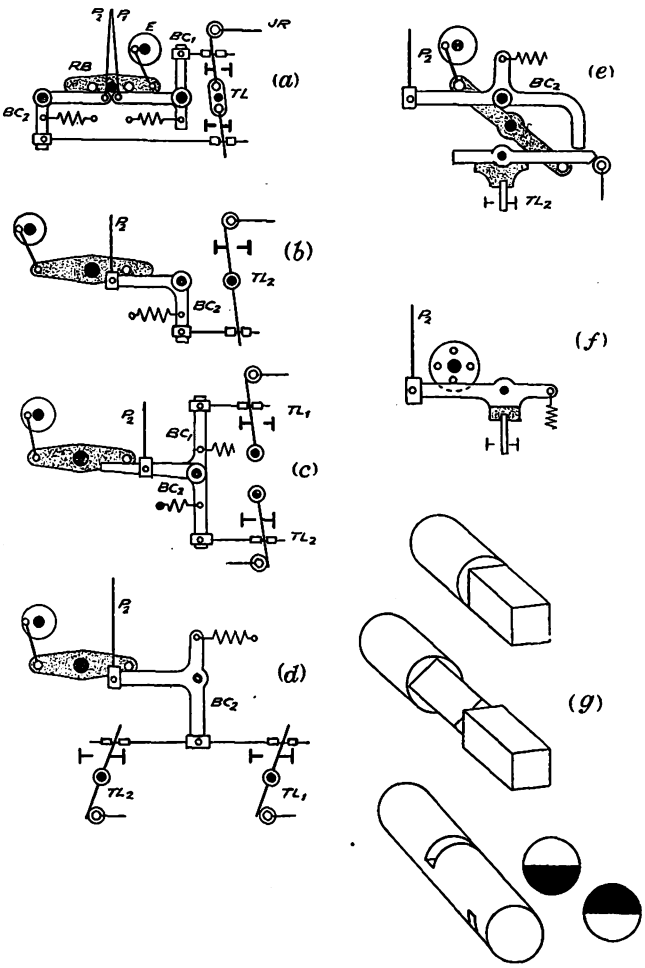


FIG. 80.—Various forms of Wheatstone-type tape transmitter.

In Fig. 81(*b*) the same effect is obtained mechanically by a cam C_2 which can be orientated with respect to cam C_1. Fig. 81(*c*) shows an arrangement by which a curbing battery is employed so that a current in the opposite direction is sent towards the end of a signal element. The proportion signal curb is varied by means of an adjustable cam arrangement shown in Fig. 81(*d*).

Transmitter levers are subject to bounce and also have a definite transit time. These have a distorting effect on the outgoing signals and a disturbing effect on the duplex balance. It is a well-established fact that

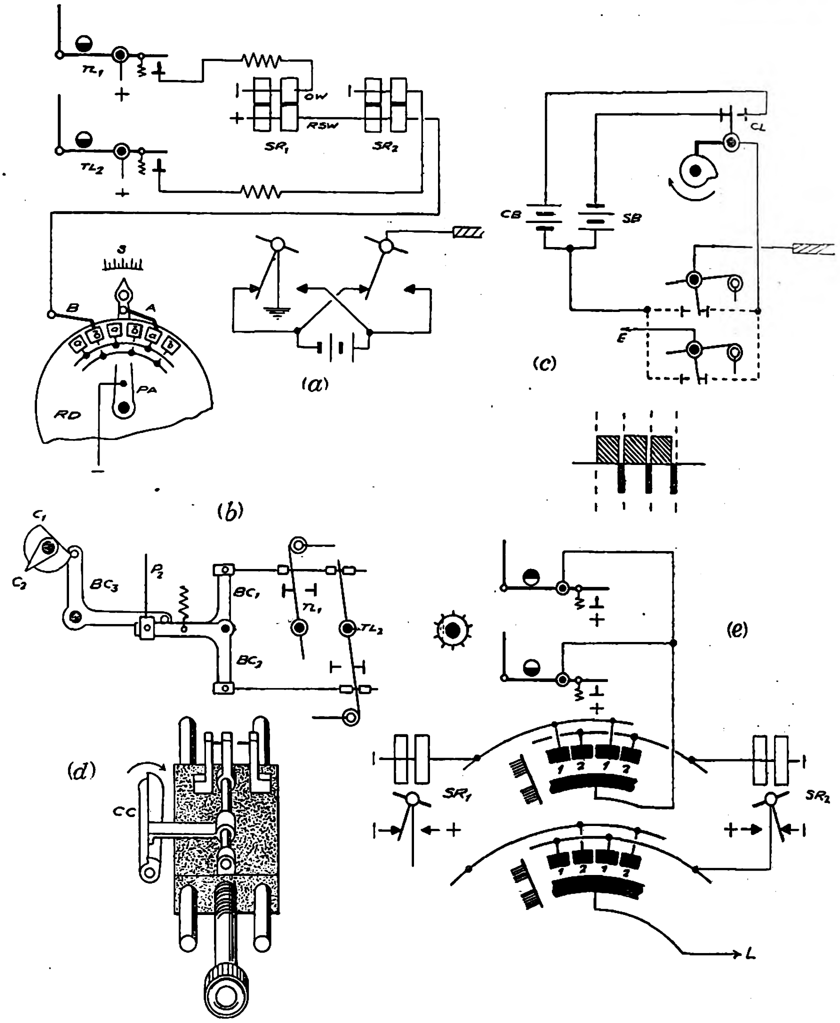

TL1
TL2
OW
RSW
SR1
SR2
S
B
A
PA
RD
(a)
(b)
CB
SB
CL
E
(c)
C1
C2
BC3
P2
BC1
BC2
TL1
TL2
CC
(d)
(e)
SR1
SR2
1 2 1 2
1 2 1 2
L

FIG. 81.—Curbing arrangements for cable-code transmitters.

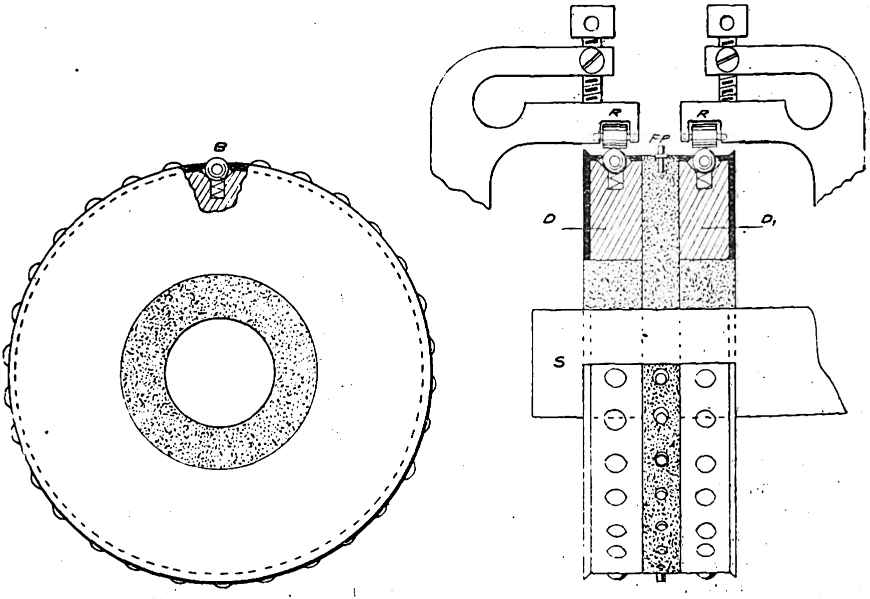


FIG. 82.—Riddle's high-speed cable-code tape transmitter.

the most perfect signals are obtained from a distributor. The reason for this is, of course, that the transmitter levers are already set and quiescent before transmission and there is no transit time.

It is becoming general practice now on long lines to employ the method of transmission shown in Fig. 81(*e*). The transmitter levers set up the signal elements alternately on two sending relays SR_1 and SR_2 via a distributor, and the signals are sent out one signal element later by a second set of distributor segments. The arrangement is identical with the regenerative repeater and amounts to placing this directly at the transmitter.

The high-speed cables in existence nowadays have been operated with cable Morse Code, while other methods of operation have been under trial. This has necessitated modifications in the design of both transmitters and receivers in order to take full advantage of the signal capacity of the cable (2 000 to 2 500 letters per minute). The ordinary Wheatstone transmitter will not stand up to these speeds when continuously operated, and an interesting departure is the transmitter constructed by the Telegraph Construction and Maintenance Co. and invented by Mr. John Riddle.

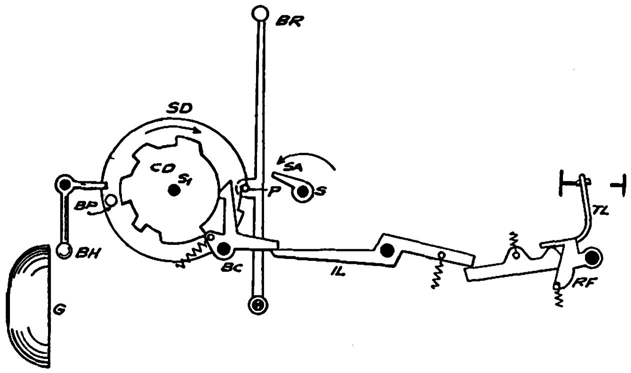


FIG. 83.—Kleinschmidt's bell-ringing arrangement for 5-unit code tape transmitters.

It consists (Fig. 82) of two discs D and D_1 in the periphery of which are a number of holes housing balls B. These balls are each pressed outwards by a spiral spring but are kept in position by two flanged discs, seen in the sectional view. The discs are insulated from the shaft S on which they are mounted and are also insulated from each other by an insulating centre disc in which are screwed the feed pins FP for propelling the tape. Opposite to each line of balls are two spring-pressed rollers R which, with the balls and discs, form part of the signalling circuit. The tape passes between the rollers and balls and, where perforations occur, the signal circuit is closed. The ability of this transmitter to operate at high speed is due to the use of a number of transmitting mechanisms (the spring-pressed balls) in succession, so that these have after use practically the whole of a revolution in which to reset themselves to normal. On the Bay-Roberts–Fayal cable good signals were obtained with this transmitter at 2 500 letters per minute and for over a 3 weeks' run no trouble arose. The balls help in the propulsion of the paper tape and as a result of this an endless band of slip, 8 ft. long, was run for 8 hours at 2 000 letters per minute without any sign of wear. This would be an impossibility with the ordinary type of transmitter, and speaks well for the operating qualities of the Riddle transmitter. The apparatus is also provided with means for varying the periods of marking and earthing, and, in addition, provides for periodic synchronizing signals when there is no tape in the transmitter, a condition necessary where regenerative repeaters are employed.

Bell Signalling on Start-Stop Transmitters.—Five-unit code tape transmitters controlling start-stop receivers and of the type which run continuously, sending out start and stop signals with the letter signal pulses, are arranged to be stopped between the transmission of adjacent letters for the purpose of sending bell-code signals for service purposes. One method of doing this is the arrangement of Kleinschmidt, shown in Fig. 83. SA is a stop arm mounted on shaft S which carries the transmitter cams, not shown. If bell rod BR is moved to the right a pin P mounted on it encounters SA and stops transmission at the right point between two letter signals. At the same time SD, which is yieldingly driven and is mounted on shaft S_1, is released. S_1 carries a code disc CD which, in one revolution, sends out the figure-shift signal, a secondary signal which rings a single-stroke bell at the distant printer and the letter-shift signal. This will continue as long as BR is held to the right, and the transmitting operator is advised of the number of bell signals sent by a pin BP on SD flicking a hammer BH so that it strikes a gong G once for each revolution. The code disc operates a bell-crank BC which by an intermediate lever IL controls the rocking frame RF carrying the transmitter lever TL. The tape-controlled intermediate levers, not shown, have no effect on TL while SA is held stationary.

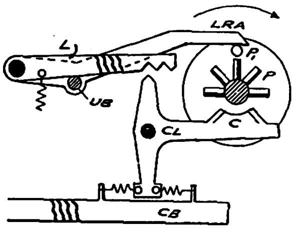


FIG. 84.—Kleinschmidt's mechanical overlap for keyboard transmitters.

Overlap on Keyboards.—Where a transmitter keyboard is free during the transmission of a letter signal, it is desirable to provide means by which a preliminary storage of one letter can be effected. This is to take care of sudden increases in the rate of operation due to a favourable sequence of letters occurring in a message being transmitted. An arrangement due to Kleinschmidt is shown in Fig. 84. Five combination bars CB control a similar number of cam levers CL arranged to impart end-wise motion to a pin-barrel type of single-contact transmitters. When a letter is set up a pin P_1, on a disc revolving with the pin barrel, moves out of the path of a latch release arm LRA which lowers a universal bar UB, allowing the latches L to fall and lock the cam levers either in their operative or non-operative positions. The keyboard is now free for another letter, since, although all the levers CL are locked up, the movements of the bars CB into the new letter signal combination are stored in the small springs coupling the bars CB to the levers CL. As soon as the previous letter has been transmitted, P_1 raises LRA, freeing the latches L, and levers CL can now set themselves in the new combination under the action of the coupling springs.

Condensers as storing means have also been proposed for obtaining overlap on keyboard transmitters.

Receiving Perforator Transmitter.—It is sometimes necessary to retransmit from one channel of a multiplex morse or cable code system to a line which cannot be directly connected to the multiplex system. This can be done by storage relays, but the most efficient means is a receiving perforator which perforates a tape in accordance with the signals received. The Creed receiving perforator is too well known to need description, but in Fig. 85 a simple receiving perforator for cable code invented by Foll is diagrammatically explained. The perforator operations are controlled by the joint action of a centre-zero relay and the local segments of the main distributor. The first part of a signal pulse is utilized to effect the punching process by means of the dot-and-dash punch magnets PM_1 and PM_2, while the second part of the pulse operates the feed magnet FM. FM controls an escapement E and releases a yieldingly-driven shaft carrying the feed wheel. The motor shaft and the perforator shaft are coupled to each other by a permanent magnet on one and a soft-iron fork on the other embracing the magnet, as shown in the inset. This forms an effective and simple method of providing a yielding drive of the character necessary to propel the perforated tape.

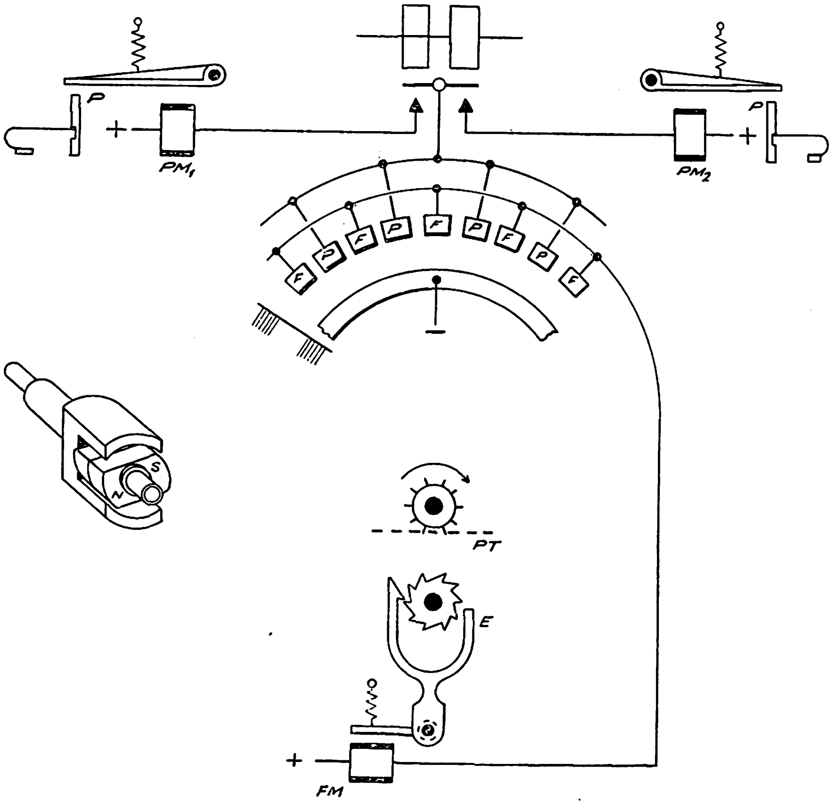


FIG. 85.—Foll's cable-code receiving perforator.

Rational Keyboard Design.—One feature of keyboard design which appears to be thoroughly bad is the small circular key tops taken from typewriter practice. The typewriter keys are small and round in shape and unsuitable for human fingers. The five fingers of the hands are of different lengths and the typewriter keyboard is irrational in this respect and is unsuitable for touch typing operation. The typewriter keys must be operated with sufficient force to operate the entire mechanism—type bar and spacing—and must be hit with a staccato touch and immediately released to clear the way for the next type bar and for carriage and ribbon to move on. There are no such requirements in keyboard transmitters or perforators.

A practised pianist will depress with one hand twice as many keys in a given time as a typist with two hands. He will, for instance, depress 12 keys per second while playing the accompaniment with his left hand. The keys on a pianoforte are long and broad. It is suggested that keyboard transmitter or perforator keys should be large and square and correspond to the length of the fingers, and be so arranged that each finger rests naturally on the key. The proper position for the fingers will thus be found without looking at the keyboard. The keys should be arranged in three rows and on the same vertical line to facilitate selection from row to row, while the pressure and play of the keys should be reduced to a minimum. In this way we shall approach to the sure aim and dexterity of the pianist. If a pianist made as many errors in fingering as does the average typist a public pianoforte recital would be an impossibility.

Evolution of Modern Transmitter.—The modern transmitter has been shown in this section to have been evolved from the single transmitter lever controlled by a plurality of code discs each associated with a character key lever, to a comparatively small number of code discs or cams each representing one signal element of the code. These code discs or cams are operative or not, accordingly to whether their action is interfered with by a second set of cam members furnished either by a number of pins set by code bars controlled by individual key lever bars, or by projections on the code bars themselves, or by a paper tape having perforated and unperforated portions either along or across it. Where a tape transmitter is used the combination of keyboard perforator and transmitter, strictly speaking, constitutes the transmitter proper, the two parts being indirectly associated by the tape and being capable of different and partly independent rates of operation.

The Wheatstone transmitter with its single transmitting lever and the modern 5-unit transmitter are fundamentally identical and only differ in arrangements imposed by the codes employed in the two cases.

Section (3). THE TRANSLATOR OR RECEIVING MECHANISM.

General.—Printer mechanisms have remained essentially the same during the last few years. Combination bars or discs have been employed, set by 5 electromagnets from the usual multiplex type of distributor.

There are two general types—one in which the selection from among 5 combination bars is used to choose a type bar which is forcibly driven against the paper platen by a cam-driven actuator clutched to a power shaft at the right moment. The Murray and Morkrum machines are examples of this class. Combination discs may be employed to set up a differential stop device which stops a rotating type-wheel with the desired letter at the printing point. The Creed printer furnishes an instance of this type. In America the type-bar machine is now modified to print on a tape instead of a page, experience having shown that the maintenance costs of page printers are very heavy.

Single Selecting Magnet.—The really fundamental change in practice is the revival of a 50-year-old idea, viz. the use of a single magnet and a battery of cams acting in succession on a series of selector bars or discs according as the magnet is in the operated or unoperated condition during a signal element.

Baudot's Methods.—In 1878 Baudot invented and constructed the single-magnet translator diagrammatically indicated in Fig. 86.

A tee lever TL pivoted at "x" has pivoted to its right-hand end a forked rod FR. There are 5 such rods and levers. By means of a cam C_1 the tee lever is forced downwards by the raised surface of the cam so that the right-hand prong is presented to the wedge-shaped end of the armature lever controlled by the single magnet M. If the magnet M is in the operated position the forked rod is diverted to the left, where it slides down the left-hand side of a fixed knife-edge E which holds it deflected until it is finally raised to the normal position again. When the tee lever encounters the second (raised) surface "b" of cam C_1 it forces rod FR still further downwards until a horizontal arm A encounters the lug L of a combination disc CD and displaces this slightly. If the magnet had been in the unoperated position (as shown in the diagram) the forked rod would have been shifted to the right side of E, and, when its downward motion was completed by cam surface "b" of C_1, A would be clear of CD and would have no effect on this. The forked rod has thus two directions of movement, being capable of one or the other according to whether the electromagnet enters into or does not enter into a letter signal combination.

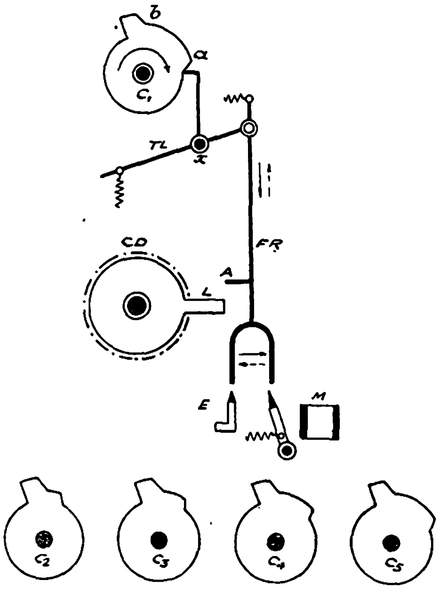


FIG. 86.—Baudot's single-magnet printer.

It is to be understood that there are 5 tee levers TL and 5 forked rods FR, and the knife-edge E and top of the armature of the magnet M can act on all of these. The remaining 4 cams are shown in the lower part of the diagram. It will be noted that the raised surfaces "a" come into operation in succession as the camshaft rotation proceeds, but that the second surfaces "b" all operate at once, the setting process consisting of a preliminary and a final stage.

A little earlier Baudot had invented and described another single-magnet method for translating the 5-unit code into typescript. This idea is extremely interesting on account of its similarity to some of the translators which have subsequently appeared. He describes it as a "mechanical distributor" and it uses one magnet only to set 5 selectors, as in the previous case.

C [Fig. 87(*a*)] is one of 5 cams angularly displaced with respect to each other and mounted on a rotating shaft which is stopped and started for each letter signal. Each cam controls a bell-crank BC, the lower end of which carries a selector bar S pivoted to it and friction-tight to such an extent that considerable force is required to move it round its pivot. The electromagnet is of the Hughes type in which the armature is repelled when a current passes through the magnet coil and is subsequently replaced mechanically. It has an armature A pivoted to the framework and a second one A_1 connected to the first by a link L. As the cam C rotates, the lower end of the bell-crank and with it the bar S is presented to the two armatures. If the magnet is not operated, the upper end of S abuts against the upper armature A_1 and turns on its pivot in a counter-clockwise direction. If the magnet is operated, the lower armature abuts against the lower end of S and the rotation is clockwise, A_1 having moved out of the path of the upper end of S. S is used either to close contacts mounted on BC, or, as Baudot suggests, it may be caused to hit or miss a combination bar CB.

Sacco and Giacomini's Distributor.—Fig. 87(*b*) represents in principle another mechanical distributor invented in 1891 by Sacco and Giacomini. Here a selector bar SB is given two kinds of motion, an angular motion over a number of combination bars CB and a reciprocating motion along its length. It is pivoted to an oscillating bar OB which is moved to the right when a marking signal pulse is received, but is stationary for spacing pulses. The selector bar is carried round past the ends of the combination bars CB by a disc D on a rotating shaft carrying a pin P which engages SB. If at the time SB is opposite a given combination bar a marking pulse is received, OB is rocked in a direction to cause SB to push the bar to the right. This will be recognized as the principle on which the setting of the combination discs in the Creed printer is based.

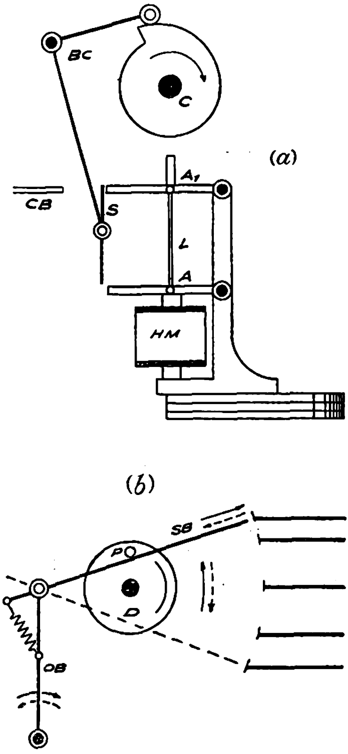


Fig. 87.—Baudot's and Sacco and Giacomini's mechanical distributors.

Morkrum-Baudot Printer.—In each of the methods previously described the setting of the combination bars is accomplished by power, the single magnet merely determining the selection. Fig. 88(*a*) is an arrangement due to the Morkrum Co., in which a rotating arm A sweeps over a field of pins P arranged in a circle. A is mounted on a sleeve S rotating on a shaft but free to slide on it to and from the circular plate in which the pins P are slidingly fixed. If the magnet M is inoperative during the entire revolution, none of the pins are disturbed, but if the magnet M is excited while A is passing over a pin, the sleeve S moves the arm A towards the pin through the medium of the fork F, and the pin is displaced. In this case the magnet has to do the work of setting, though this can be made very small.

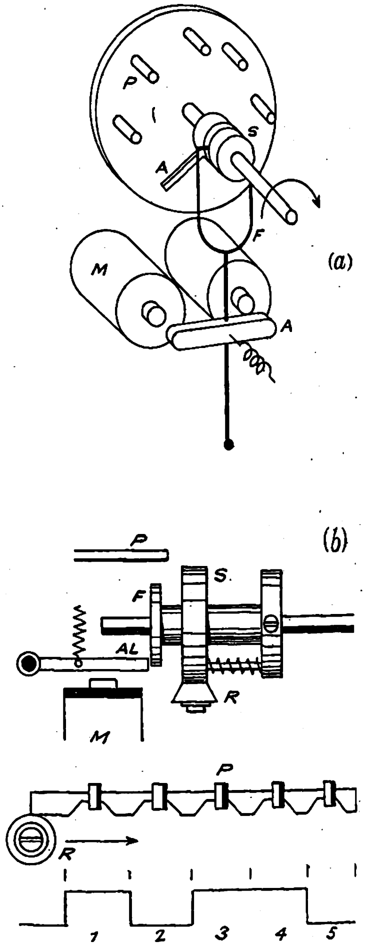


Fig. 88.—Morkrum's single-magnet selector mechanisms.

Another method introduced by the Morkrum Co. and actually used in their "Teletype" is shown in Fig. 88(*b*). S is a sliding sleeve which rotates with the shaft and on the periphery of which is a roller R. The sleeve is pressed to the left by a spring between it and a collar locked on the shaft. The armature of the magnet M restrains the motion of S as long as M is inoperative, by forming an abutment for the flange F. If, during any part of the revolution, M is operated, AL clears the flange F, and the sleeve moves to the left, setting any pin P which may be opposite to it. The pressure of F on AL is removed midway between the 5 pins by means of a circular disc (shown developed), so that the armature is free to move up or down to determine the setting of the pins. This relief is effected by the circular disc, the raised portions between the pins taking the thrust of the roller R. The changes from spacing to marking and vice versa will occur at about mid-distance.

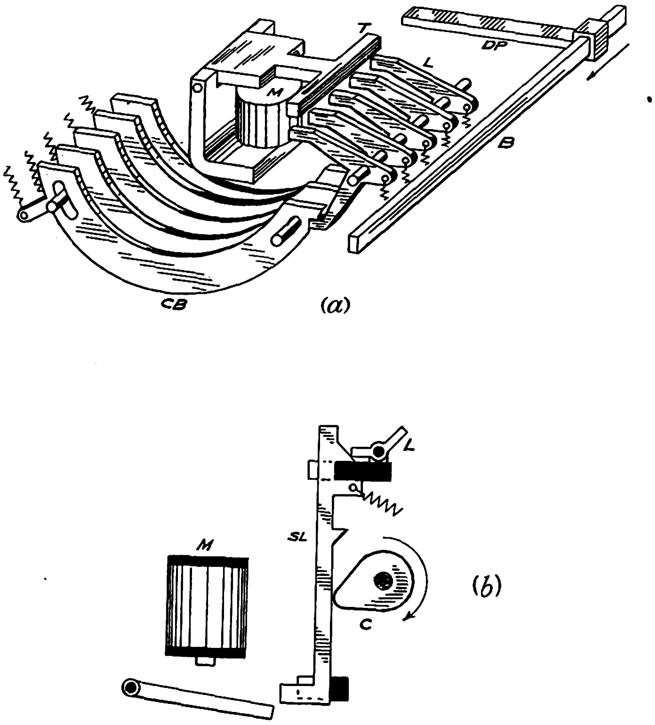


FIG. 89.—Murray and Potts's single-magnet selector mechanisms.

Murray's Single-Magnet Printer.—Fig. 89(*a*) is a scheme of Murray's based on the Sacco-Giacomini principle. Five quadrantal bars CB are held in their normal position by a series of latches L against the tension of individual springs. A single magnet M has an armature T tee-shaped at its free end and so disposed that in the operative position it does not affect the position of the latches. If, however, a distance piece DP is interposed between the nose of a latch and the tee-shaped extremity of T, the corresponding latch L is depressed and frees its combination bar. DP is traversed in the direction of the arrow across the noses of the latches.

Potts's Printer.—Fig. 89(*b*) is an arrangement due to Potts. Here a selector lever SL is slidably mounted at its upper end on a comb against which it is held by a spring. Its lower end is threaded through a second comb in which it is free to move to the left. There are, of course, 5 such levers and a group of 5 staggered cams such as C. If M is inoperative the cam C acting on the toothed cam surface on SL forces the lower end out in passing, the upper comb acting as the fulcrum. If the magnet is in the operative position, SL fulcrums on the armature lever and the upper end of SL is forced to the left and locked there by the small latch L. This is only a preliminary setting, as further selector mechanism is brought into engagement with those selector levers which have been set, the combination is transferred to the printer mechanism, and the latches L are operated to release the bars SL which have been set and allow them to return to normal for the next letter.

Kleinschmidt's Single-Magnet Distributor.—An ingenious form of mechanical distributor by Kleinschmidt is diagrammatically indicated in Fig. 90. Mounted on a horizontal shaft is a pin barrel PB having 5 angularly displaced pins P so arranged that when making a single revolution their circular path lies between a series of latches L. The shaft is driven by a sleeve S and by means of a friction clutch (not shown). The armature lever AL of a normally operated magnet M holds the shaft to the right against the action of a spring, seen in the upper part of the diagram. In this position a stop pin SP is caught by a stop lug SL and the shaft is stationary. If the magnet M is momentarily de-energized the shaft moves towards M, thus freeing SP from SL, and the shaft then makes one revolution until SP is again caught by SL. The pins P are allowed to come into the path of the setting lugs on the latches L each time M is de-energized, and by varying the number of times M is inoperative during the single revolution the latches L will be variably displaced counter-clockwise and made to release a set of combination bars (not shown).

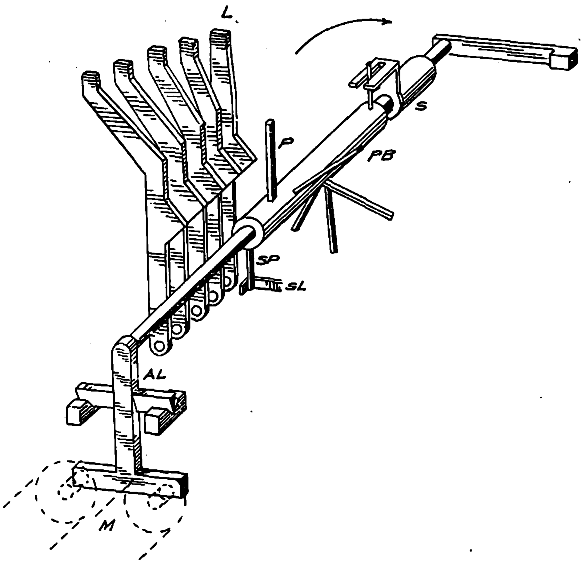


FIG. 90.—Kleinschmidt's single-magnet selector mechanism.

Interfering and Non-interfering Selectors.—An examination of the various types of mechanical distributor or selector will show that these fall into one of two divisions. The interfering type is one in which a camshaft operates a group of selecting elements in succession and when a marking condition prevails (marking signal element) the armature of the single magnet interferes with the movement of the selectors [Fig. 91(*a*)]. In the non-interfering type, the selector members move only when a marking signal pulse is received [Fig. 91(*b*)].

The selector mechanism applied by the Morkrum Co. to their type-bar Teletype is an improved form of the Baudot single-magnet selector mechanism shown in Fig. 87. The armature lever AL (Fig. 92) has a tee-shaped end, the two extremities of the horizontal portion of which are bent downwards and constitute two universal bars. This arrangement replaces the two coupled levers of Baudot's arrangement and is an improvement. The selector lever SL is also tee-shaped and pivoted in the free extremity of a bell-crank BC controlled by the cam C. There are 5 cams C acting in succession on 5 bell-cranks such as BC, each with its selector lever SL. The operation of this device is identical with that of Baudot. The selector levers, after being set and moved by the cam away from the armature lever AL, encounter a small tee lever "t" and move this to displace a code bar, as will be obvious from the sketch.

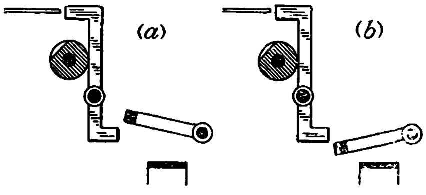


FIG. 91.—Interfering and non-interfering single-magnet selectors.

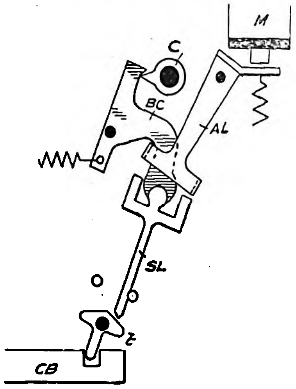


FIG. 92.—Morkrum single-magnet selector mechanism.

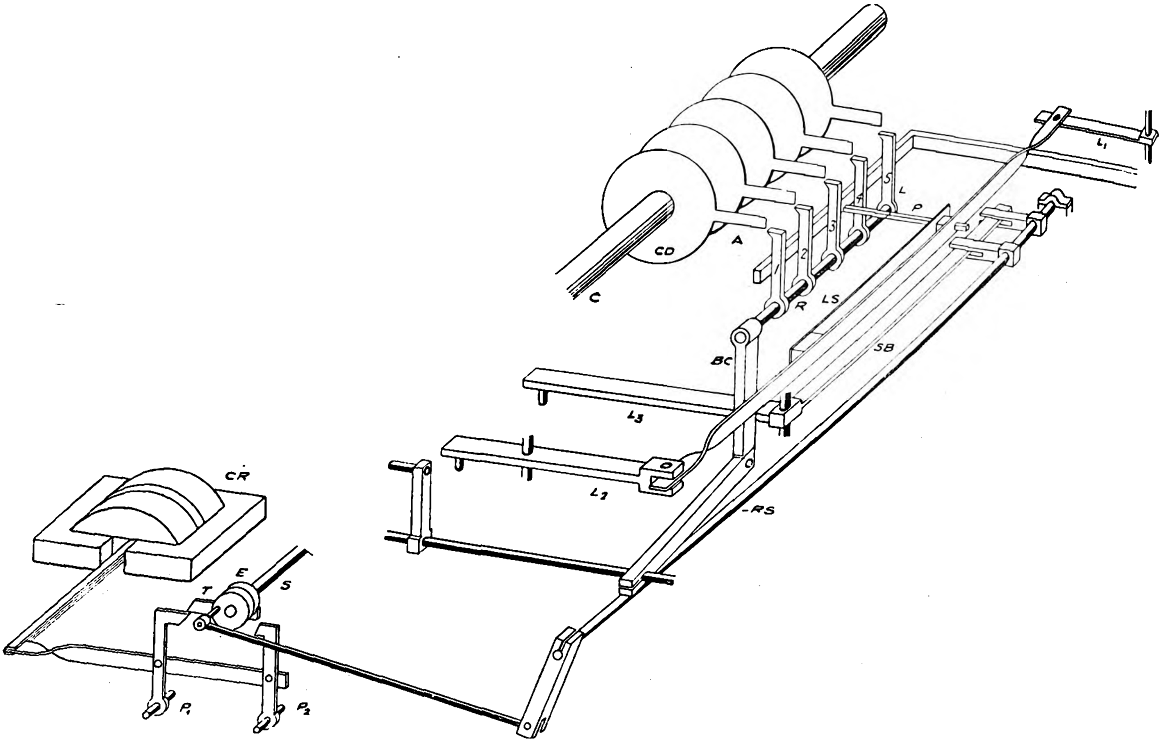


FIG. 93.—Creed's single-magnet selector mechanism.

Creed Teleprinter.—Fig. 93 represents diagrammatically the method of setting the combiner discs of the Creed teleprinter. The five discs are revolvably mounted on a cylinder C and have horizontal arms A for effecting their slight angular displacement. Their movement is accomplished by a set of 5 disc-setting latches L pivotally mounted on the horizontal rod R attached to a bell-crank BC, and adapted to be rocked at the right instant by a bell-crank CB so that those which have been pushed underneath the horizontal shifting arms of the combination discs will displace these. The latches L are set by means of a pin P which explores them in succession as it is moved in a horizontal direction by means of pivoted links L_1 and L_2. L_2 is controlled by a cam and the cam groove is so shaped that P is normally opposite the third latch but is carried to the first, then past the 5 and finally brought back to the third. In the normal position P is held away from the latches by means of a leaf spring LS but is moved against all or any by a spring blade SB oscillated by a lever L_3 controlled by a suitable cam. SB is supported in two forked slides rigidly attached to a rock shaft RS which can be so moved that SB is either in or out of the plane of P. The spring blade is moved towards the pin P 5 times while the latter is travelling over the 5 latches, and a marking pulse tilts the striker blade into the path of the pin while a spacing current removes it. Selection of the latches can thus only occur on receipt of a marking pulse while a letter signal is being received. The starting pulse is positive or marking and the letter signal pulses variably positive and negative, while the stop signal is negative. The control of the selector mechanism under control of the line signals is effected in the following way.

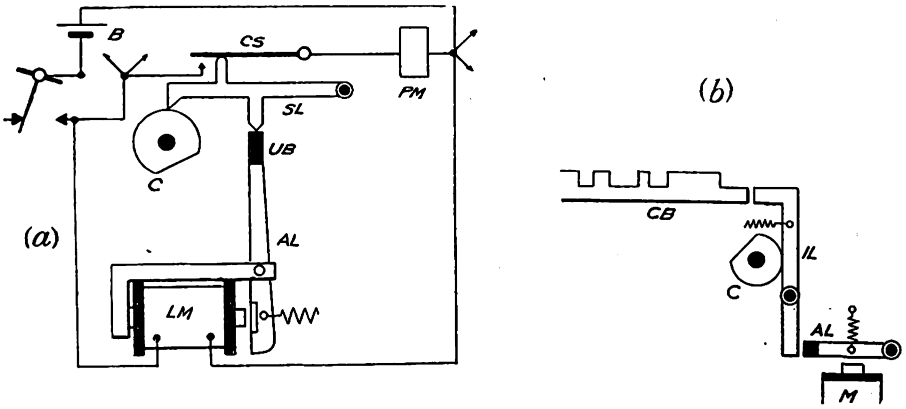


FIG. 94.—Comparison of electro-mechanical and mechanical selectors.

CR is a power relay of the Creed type which is either directly in the line or in a local circuit of a line relay. It controls an escapement mechanism consisting of two pallets P_1 and P_2 which allow a yieldingly-driven shaft S to make half a revolution each time the line current changes sign. The shaft is terminated by a single tooth T which is alternately caught by the pallets P_1 and P_2. The escapement drives a small eccentric E which rocks the shaft RS and affects the selective action of spring blade SB on P. The rock shaft also controls a single-revolution clutch which drives the battery of cams operating the different levers. This is not shown.

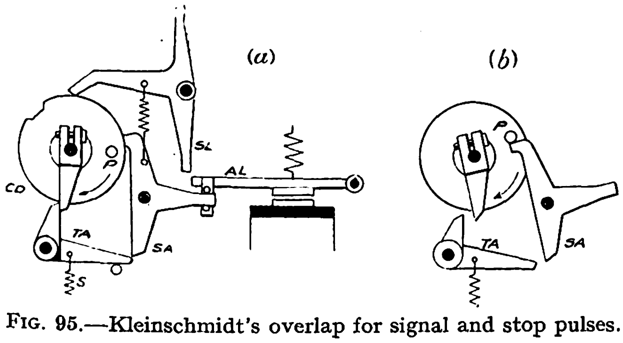


FIG. 95.—Kleinschmidt's overlap for signal and stop pulses.

The advantages of the " mechanical distributor " for single-channel working can be clearly realized by reference to Fig. 94. Fig. 94(*a*) is a single-magnet distributor in which, however, the selector levers variably close the circuits of five magnets PM to effect the setting of combination bars (not shown). Fig. 94(*b*) shows the simplification effected by causing the selector levers to act directly on the combination bars, thereby dispensing with five magnets and a similar number of contacts.

Overlap of Signal and Stop Pulses.—In mechanical start-stop selectors, the receiving mechanism is operated at a faster rate than the transmitting mechanism, so that the receiver will be stopped at the end of each revolution of the transmitter. If the impulses making up the whole letter signal are uniform in length, difficulty is experienced with the stop mechanism at high speeds. This is due to the fact that the time in which the receiving magnet and stop device must act is progressively shortened. The reduction of time for operating the stop reaches a dangerous limit; Kleinschmidt overcomes this by arranging for the stop pulse to overlap the last signal pulse of a letter signal. Referring to Fig. 95(*a*), SL is one of 5 selector levers controlled jointly by 5 cam discs CD and the armature lever AL of a single magnet. In the normal inoperative condition, the magnet is energized and holds a stop arm SA against the tail piece of a trip arm TA which, in turn, engages a stop clamped

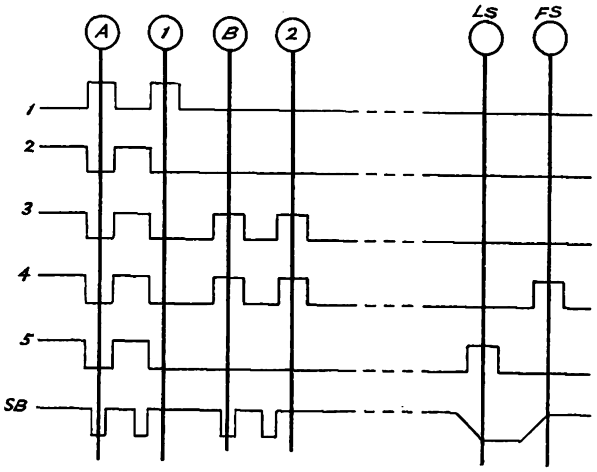


FIG. 96.—Inversion device for code bars or discs.

to the shaft on which the discs CD are mounted. The shaft is yieldingly driven through a friction clutch. When the magnet de-energizes in response to a start pulse, SA is removed from the tail piece of TA which is now no longer able to restrain the shaft from rotating, as the torque due to the friction clutch can overcome the weak spring " s."

If the last signal pulse is such that the magnet is de-energized, the head of stop arm SA comes in contact with a pin P and effects a preliminary stop of the shaft and cams, and on receipt of the final stop pulse the magnet depresses SA, which will lock TA in the stop position. If the last signal pulse had been a marking one, then, since the stop pulse is also marking, SA would have locked TA in the stop position before stoppage actually occurs. Thus, whether the last signal pulse is marking or spacing, the stop condition is set up at this stage and the stop condition overlaps the last signal pulse. This permits greater speeds of operation and finer speed differences and results in better margin.

Inversion.—Inversion or change from letters to figures is accomplished by axial or radial shift of the type wheel on its shaft in the case of a type-wheel printer, or shifting the type basket or platen of a type-bar printer. Both involve some amount of energy to accomplish and this can be avoided by using an extra bar or disc by which the primary and secondary characters may be selected at will by sending the appropriate signal. This is the arrangement used in the Creed printer and was first introduced into the art by the French engineer Munier in 1870. The principle is shown in Fig. 96. The primary and secondary characters are arranged alternately, on the type face of the wheel in the one case and adjacent type bars in the other. A sixth bar SB for shifting purposes has two sets of notches and two positions. In the position shown, the notches in SB allow only primary characters to be selected for any combination of bars 1 to 5. If bar 4 is shifted in response to the figure-shift signal, lever FS falls and shifts SB to the right. The notches under all the letter-signal type bars are now replaced by teeth and can no longer be selected, while the second group of notches is now shifted to a position which will allow only secondary characters to be selected. The return to the primary characters is obtained by setting combination bar 5, when LS will drop and shift SB to the position shown in the drawing.

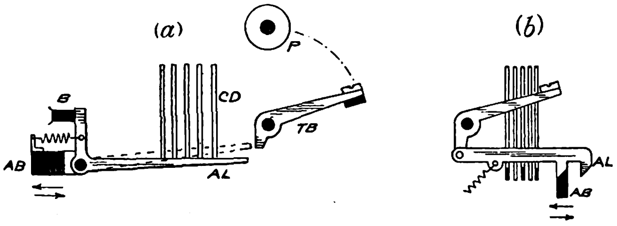


FIG. 97.—Murray's constructions for curved code bars.

Curved Code Bars.—Some simplification in design of type-bar printers with respect to the actuation of the type bars can be secured by using the curved code bars invented by Eglin. The code bars are of the same radius as the bar on which the type bars are hinged. Two constructions due to Murray are shown in Fig. 97(*a* and *b*). In (*a*) a number of actuating levers AL, one for each type bar, are pivoted to a curved actuator bar AB. Levers AL are normally held away from the curved code bars or discs CD by a curved bar B fixed to the frame. When the letter-signal combination is set up on discs CD, AB is moved to the right. All the levers AL leave bar B and one of them has an aligned slot presented to it, rises to the dotted position and engages the type bar TB as AB continues its movement.

In Fig. 97(*b*) the actuator levers AL are inside the code bars and as AB moves to the right the selected lever AL falls into the alined slot, its toothed end is engaged by AB and the type bar is actuated. The upper surface of AB is sloped so that on its return stroke it lifts the selected lever AL out of the line of slots in the code discs.

Curved code bars were independently invented by Murray and the Morkrum Co. in ignorance of their anticipation by Eglin.

Section (4). RECENT IMPROVEMENTS TO THE BAUDOT SYSTEM.

Improvements on the Baudot system have been directed to increasing its usefulness and reducing the work of maintaining a Baudot circuit in satisfactory operation.

Murray's Modifications.—Among the first-mentioned class may be quoted Murray's application of the phonic-wheel drive to the distributor drive. This resulted in much steadier speeds and dispensed with the skilled adjustment required by the Baudot governor hitherto used. There is still a certain amount of adjustment required to keep the reed or fork operating correctly, but such adjustment is of relatively simple character.

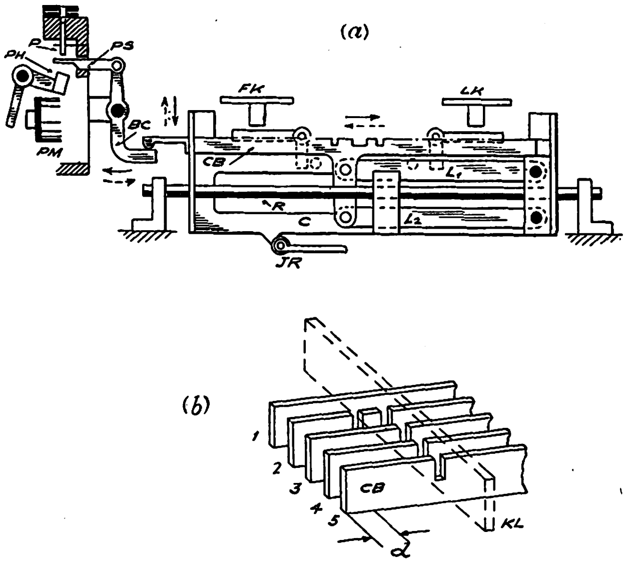
Murray also replaced the 5-key keyboard by a perforator and automatic transmitter, thereby dispensing with the necessity for the observation of the cadence signal and leaving the keyboard absolutely free. The substitution of a free for a bound keyboard should, theoretically, result in a higher operator output. The actual rate of transmission over the line is fixed by the distributor speed, and with a free keyboard and storage means, such as is furnished by a perforator-transmitter combination, the rate of setting up signals will normally exceed the rate of transmission. This allows for pauses in setting up without the lost time being transferred to the line, which thus works at constant maximum speed.

In this arrangement of Murray's the tape passes directly from perforator to transmitter, forming a loop the length of which depends upon the difference between the set-up and transmission rates. On a prolonged pause, the loop shortens and actuates a lever, thereby stopping the transmitter which, if allowed to proceed, would ultimately mutilate the tape. The general principle of automatic stop and start introduced by Murray is now in universal use.

Duplex Operation.—A further modification to the original Baudot system is the application of the duplex balance to the line. This has been extensively introduced in the British Post Office under Mr. A. C. Booth and is also in general use in America and elsewhere.

France, the home of the Baudot system, does not rely to any extent on the duplex balance for 2-way working but obtains this by simple division of line time. They have ample wire plant for their telegraph needs and prefer the greater stability of simplex operation which obtains both at terminals and repeater stations.

Duplex operation dispenses with the necessity of propagation contacts, but the same thing may be effected by the use of two lines. The capacity of a duplexed line is only $1\frac{1}{3}$ times its simplex operating speed as a maximum. This arises from imperfections of balance due to the fact that the charge and discharge quantities at the sending end of a line differ from one another and also that both the quantities and their difference vary with line leakage. The standard balancing networks ignore these facts and it does not seem possible to devise a network which can be rapidly and accurately adjusted to simulate the line with sufficient approximation to yield a double traffic capacity when operated under duplex conditions. With the increasing co-ordination of telephone and telegraph line plant which will result in making available an enormous number of telegraph channels, far in excess of traffic needs, both-way operation by the use of two lines—one for each direction—will probably become standard practice.



	1	2	3
Q	1—3 4 5	—2———	——3—5
W	—2 3—5	1——4—	

(c)

FIG. 98.—Booth-Willmot keyboard perforator.

The duplex balance merely gives 2-way operation over a line at reduced traffic-carrying capacity.

Booth-Willmot Keyboard Perforator for Baudot Circuits.—One of the difficulties in applying the so-called " universal " keyboard to Baudot circuits lies in the different assignments of letters and figures in the two cases. This difficulty has been very ingeniously overcome by Messrs. Booth and Willmot of the British Post Office and the method is illustrated by Fig. 98(*a*, *b* and *c*) as applied to a Western Electric keyboard perforator. Five combination bars CB differentially notched are in the form of T levers and supported by two parallel links L_1, L_2 pivoted in a sliding carriage C supported on two rods R so that it is capable of moving backwards and forwards in a horizontal direction. The carriage can be moved to either position by means of bell-cranks actuated by the figure and letter keys FK, LK, respectively. The bell-cranks operate on pins fixed on the carriage, and the latter is held in either of its two positions by a jockey roller JR. With the carriage in one position one group of notches in the bars CB confronts the whole of the key levers, and in the other position the first group of notches is removed and replaced by a second group. When a key lever is actuated it selects the bars that are opposite to it *and unnotched* and presses these down. The left-hand extremities of the bars press on 5 or less of a number of bell-cranks BC which withdraw the punch selectors PS so that, when the punch hammer PH is operated, only those punches whose selectors have not been withdrawn are forced through the paper strip. If the carriage C is shifted to the other position, then a different punch selection is set up for the operation of the same key lever.

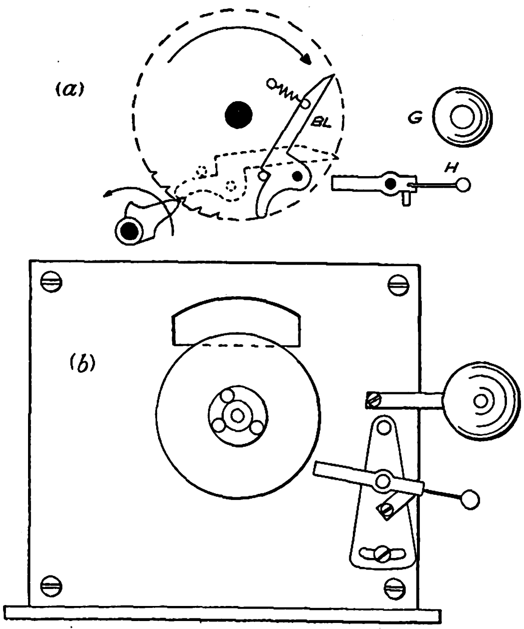


FIG. 99.—Bell-ringing arrangement on Baudot printer.

In Fig. 98(*b*), with the bars CB in the position shown the operation of key lever KL will operate bars 1, 3, 4 and 5, but if the bars are shifted to the left by the amount *d*, only bar 1 will be operated when KL is depressed. In this way the assignment of letters and figures on the keyboard can be as desired without interfering with the standard assignment on the Baudot type wheel. This is very important where a Baudot keyboard may be employed at one end of a circuit and a " universal " keyboard at the other. It will be seen that selection of the punches to form any desired letter is attained by withdrawing the punch selectors of those punches which are not required to form the letter or figure corresponding to the actuated key lever. This leads to a very interesting result. A frequent form of "stumble" when operating a keyboard at high speed is to depress two adjacent keys simultaneously. In the ordinary way this would lead to the perforation of a wrong letter. The punches common to the two letters would operate and, in addition, those not common would be effective. Back-spacing and obliteration of the wrong letter, and the re-punching of the letter required, would be carried out in the standard manner, but line time is lost by the transmission of the obliteration signal—5 punched holes—succeeded by the correct letter. Thus the error costs an amount of line time equal to one letter—the obliteration signal. When, however, the unwanted punches are made ineffective, only those common to the two letters are operated. This is clearly shown by Fig. 98(*c*), where the depression of key Q withdraws punch 2 and the depression of key W withdraws punches 1 and 4, the resultant effect on the tape being the punched holes 3 and 5. Since 3 and 5 enter into the signal combination for both Q and W, then whichever is the desired letter will be correctly punched by back-spacing once and operating the desired key. There is no necessity for the obliteration signal, and one letter signal's length of line time is very simply and ingeniously saved.

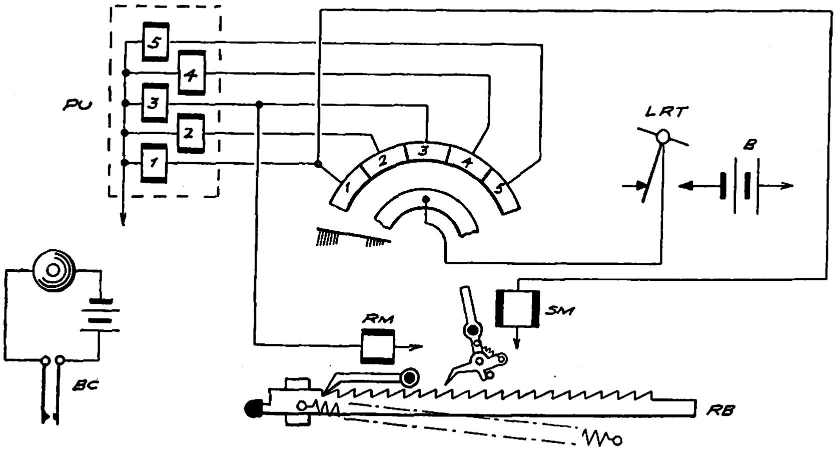


FIG. 100.—Selective calling arrangement for series Baudot circuits.

New Zealand Administration's Bell-Ringing Arrangements.—The provision of a single-stroke bell on a printer mechanism is becoming general practice. The bell is usually selected by sending a shift signal and is rung once per cycle of printer operation. Code ringing may be adopted to furnish service instructions such as "Stop," "Re-run," etc., and as an indication to the transmitting operator it is superior to code signals set up on the printer itself. The mechanism for applying bell signalling to a Baudot printer, as designed by this Administration, is shown in Fig. 99. To the impression disc behind the type wheel a lever BL is pivoted and is held in the normal position shown against a stop by means of a spiral spring. After the receipt of the figure shift signal and in the succeeding revolution, the impression arm is released by the secondary character following letter A, and the impression arm turns BL on its pivot so that its free end projects beyond the impression disc and strikes the hammer H, ringing the bell once. The bell can be rung one or more times in succession (once per revolution) and bell strokes can be suppressed for one or more revolutions, thus forming a signalling code. Fig. 99(*b*) shows the general arrangement. This method requires the printers to be continuously revolving.

Fig. 100 shows a method of selectively ringing idle arms at a number of stations on one line and is useful where Press items have to be distributed. RB is a rack bar stepped forward, one tooth at a time, by a stepping magnet SM against the control action of a spiral spring. It is returned to normal when the release magnet is operated, which occurs when a "third" is sent. The stepping is shown as being effected on receipt of a "first." The rack at another station would be stepped on receipt of a "second," and so on, but all return to normal on receipt of a "third." Normally the printer is at rest, but the distributors are running at all the stations on the line. When all arms are carrying traffic the bars at each station are intermittently stepped, but as "thirds" are constantly occurring the bars are continually becoming re-set to normal. As stated, this arrangement is specially designed for Press work and any number of stations may be rung to receive a certain news item, while those stations not rung will ignore it and will not start up their printers on that arm.

With this arrangement a number of stations provided with double, triple or quadruple distributors can be strung in series on one line wire and, with no traffic passing, the distributors only will be kept running. Any station can be selectively called on any arm, the whole arrangement being thus made suitable for news working.

Grünenwald Speed and Phase Control of Printer Units.—The two to four printers on a Baudot circuit are ordinarily driven by independent motors, speed control being effected by a modification of the Baudot governor. Approximate synchronism is secured by the arrangement shown in Fig. 91 of the author's previous paper.[*] The necessary phase relationship between the printer cycle and the distributor cycle is secured by orientating

[*] *Loc. cit.*

the synchronizing means on the printer unit. This arrangement entails two to four individual adjustments and although these are relatively permanent they must be verified from time to time, and, if a change in operating speed is called for, readjustments are necessary.

The ideal arrangement is one in which distributor speed and printer speed and phase is accomplished by one adjustment, viz. variation of distributor speed. This can be secured by providing synchronous motors on each printer unit and furnishing alternating current from the distributor.

Fig. 101 illustrates the electrical arrangements. The four printer motors have stators S_1 to S_4 furnished with alternating current generated from direct current passed through a series of reversing commutators C_1 to C_8.

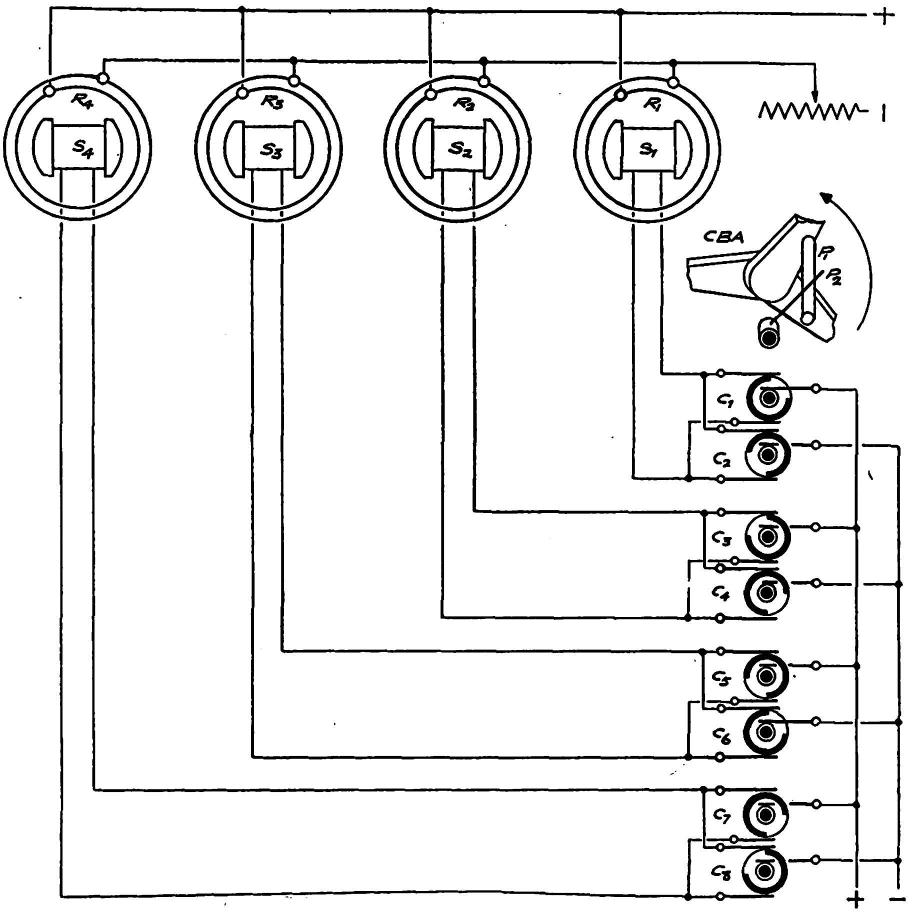


FIG. 101.—Grünenwald's automatic speed and phase control of printer units.

The rotors R_1 to R_4 consist of a heavy flywheel on which is mounted a toroidal coil, the two ends of whose windings are connected to slip-rings and excited from a d.c. supply through a regulating resistance.

The reversing commutators are suitably displaced with respect to each other, so that each printer has the correct phase relationship with respect to its distributor segments. They are mounted on a common shaft and insulated from each other and this shaft is driven by a pin engaging a second pin P_2 on the contact brush carriage CBA. This method of drive is necessitated by the fact that, at a corrected station, the phase of the brushes is intermittently varied and the phase of the printers must therefore be simultaneously varied, otherwise a phase error will creep in. Also, the orientation of the segments is variable in amount and it is not possible to drive the printers from fixed segments on the distributor itself.

The adoption of the Grünenwald printer drive effects simplification in the printer itself. The low-speed synchronous motors drive directly on to the type-wheel shaft and all gearing is suppressed. Owing to this it is possible to arrange the keyboard in the printer base instead of making it a separate unit, and this modification is illustrated by Fig. 102. The synchronous motor SM is housed at the back of the printer unit and covered in by a bell-shaped casting. The keyboard is instantly removable from the base by simply pressing down bolt B, when it can be pulled out together with the whole of its mechanism and electrical contacts. It is mounted on a sliding shelf. The method of locking and unlocking the key-levers KL will be understood from Fig. 102 and the sketch below. Each key is held in the normal, unoperated position by the spring S_1 anchored to the shelf on which the keys are mounted.

A cam C is provided on the type-wheel shaft and this depresses an unlocking rod once per revolution, the slight clicking noise forming a cadence signal for the operator. This rod ULR operates a small piston mounted in a circular recess in the printer base, and an extension to the piston presses on a cam plate CP adjustably fixed to an unlocking lever UL fixed on a shaft S passing right across the keyboard shelf and housed in two bearings integral with this. A coiled spring (not shown) tends to keep the rod in a horizontal position and keeps the piston in such a position that the rod ULR is pressed at its upper end against the cam C.

When a key is depressed, a steel plate at its free end is caught by a latch L loose on the main shaft and pressed forward by a spring S_2. The release of all keys so locked up is effected as previously described.

Fig. 102 also shows the arrangement of a keyboard independent of the printer. An electromagnet CM performs the unlocking function and acts to give an audible cadence signal.

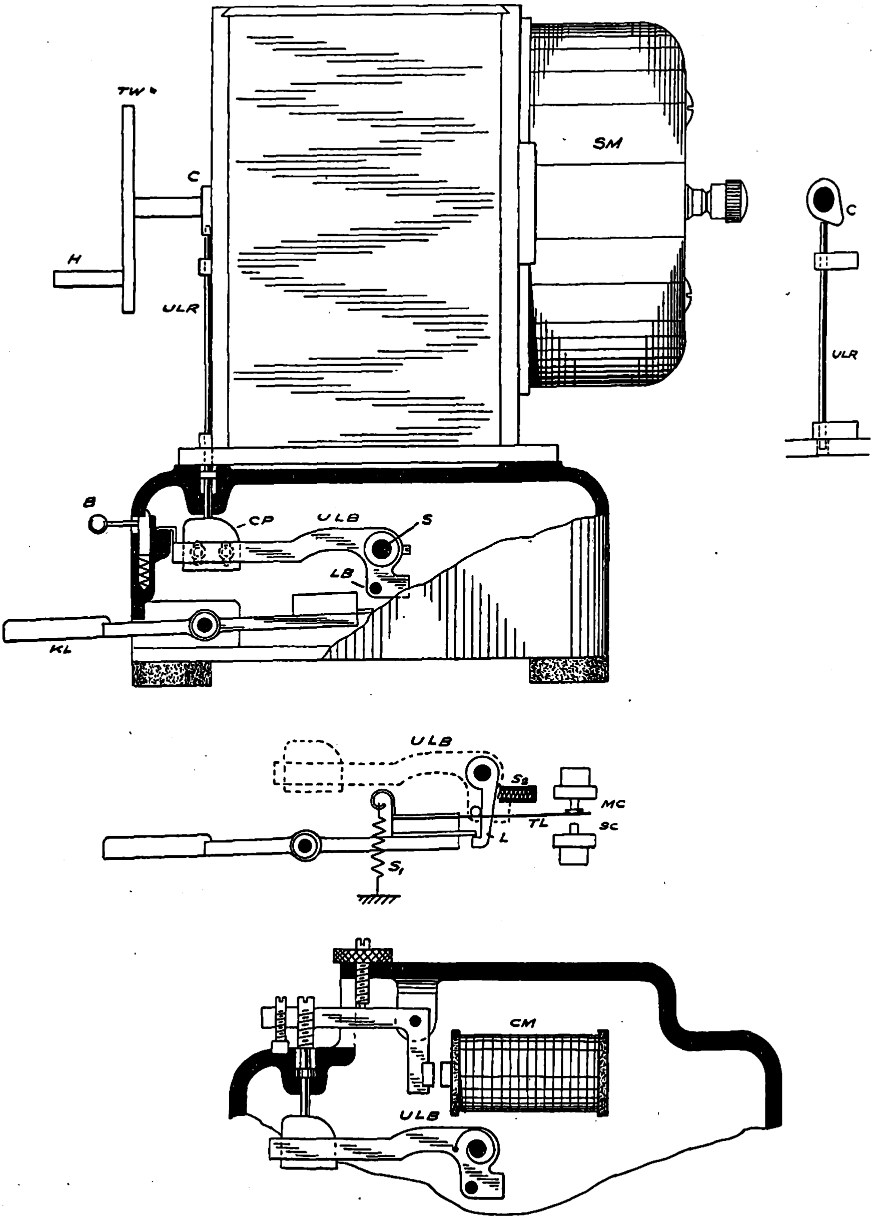


FIG. 102.—Grünenwald's modifications to Baudot printer.

Verdan-Baudot Anti-parasitic Device.—This arrangement is specially designed to deal with the Baudot apparatus when applied to a radio link and subject to atmospheric disturbances. The presence of atmospherics superposed on Baudot signals results in wrong letters being printed, and at times of bad disturbance an almost unreadable slip is produced.

The principle on which the arrangement is based is the following:—If the same letter is transmitted two or three times, separated by a certain interval, the actual signal elements will be absolutely regular, but atmospheric disturbances will be irregularly distributed over the total time. The effect of atmospherics will be to reinforce the desired signal elements and to add others. Under the conditions outlined, probability calculations show that there are a considerable number of chances that the atmospherics will not appear invariably at the same instants of time as the signal elements.

If the signal elements are repeated at intervals of time greater than the average duration of an atmospheric disturbance, they will not introduce the same " extras " at each transmission. By the adoption of a storage device at both sending and receiving ends arranged to repeat the letter signals at intervals of time corresponding to six revolutions of the distributor brush arm, the correct letter is finally passed to the printer. In Table 1 the " sifting " process at the receiving end is set out.

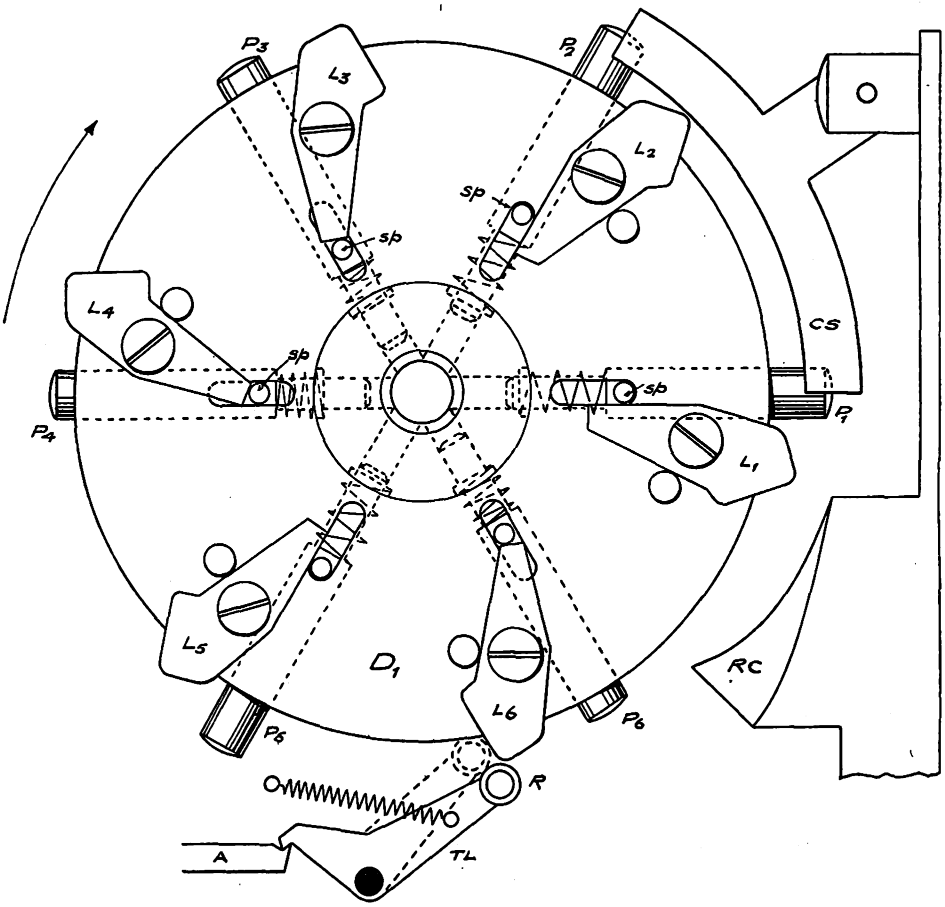


FIG. 103.—Verdan's storage transmitter.

In the table the letter Y is supposed to be sent (spacing current on segments 1, 2, 4 and 5 and marking current on segment 3). Atmospherics are shown by the crosses ×.

If we connect the five magnets of a Baudot retransmitter to the distributor sector, then magnets 2, 3 and 4 will be operated, setting armature levers 2, 3 and 4 to the operating position. If the working contacts of the retransmitter levers are connected to the magnets of a second retransmitter and the magnets of the first retransmitter disconnected from the distributor sector, while six revolutions later the retransmitter levers of the first apparatus are connected to the distributor, then the magnets of the second retransmitter will receive the first repetition of the letter signal via the transmitter levers of the first retransmitter and the distributor sector. At the second repetition the second retransmitter magnets are switched on to the distributor and extend the receiving circuit to the printer magnets.

TABLE 1.

Distributor revolutions	Signals					Letters		
	1	2	3	4	5	Sent	Received	Stored
1st		×	+	×		Y	F	F
7th	×	×	+		×	Y	V	I
13th			+	×	×	Y	R	Y

In Table 1, magnets 2, 3 and 4 are first operated and at the seventh revolution only the corresponding magnets of the second retransmitter are connected up. Consequently, atmospherics 1 and 5 are without effect and only atmospheric 2 and signal pulse 3 operate magnets 2 and 3 of retransmitter No. 2. At the thirteenth revolution, only printer magnets 2 and 3 are connected up (there is no atmospheric this time on segment 2), while atmospherics 4 and 5 cannot have any effect as the corresponding printer magnets are not connected. Only pulse 3, the correct signal pulse, is therefore recorded, the storage arrangements having sifted out the unwanted signals.

In practice, a 3-sector or triple distributor is used and the letter signal is switched on to these in turn. This makes it possible for the operator to set up other letters between the first transmission and subsequent repetitions of the same letter. The storage mechanism (of which there are two) is driven independently of, but in synchronism with, the distributor.

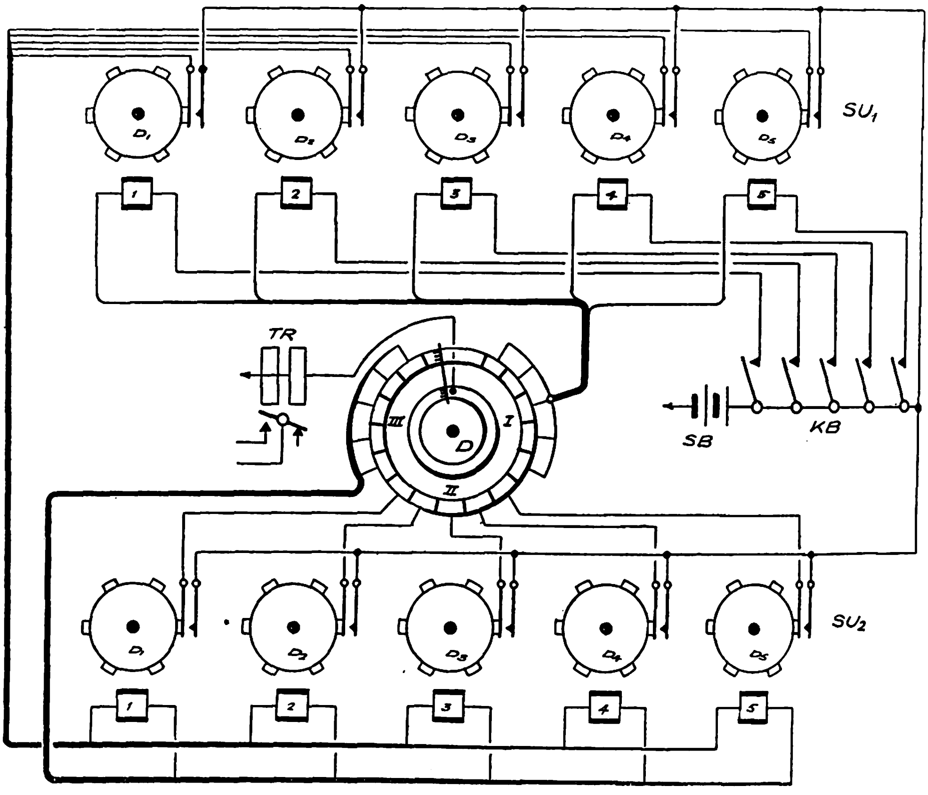


FIG. 104.—Verdan's anti-parasitic transmitter.

Referring to Fig. 103, each storage unit consists of five discs D_1 to D_5, each containing six radially disposed plungers P_1 to P_6. The plungers are pressed outwards by spiral springs surrounding their lower ends, but are normally held inwards by stop pins projecting through slots in the discs and held by latches L_1 to L_6. The latches are pivoted to the discs as shown. Adjacent to the lower portion of each disc is a setting magnet (not shown) the armature of which holds a spring-controlled trip lever TL, the free end of which carries a roller R. If the magnet is energized TL moves to the dotted-line position and as a latch comes round it is forced round in a counter-clockwise direction to release the stop pin of the plunger, and latch and plunger assume the positions shown at P_5. Five of such discs with their magnets provide for the storage of six Baudot letters.

When the displaced pin has passed beyond the vertical position, it enters between two contact springs CS, and completes a circuit for the next stage ahead. Pins which are not displaced clear the contact springs and have no effect so far as the next stage is concerned.

RC is a resetting cam which restores the plungers to normal in readiness for the receipt of another letter.

The transmitting arrangements are shown in Fig. 104. D is a triple distributor and SU_1 and SU_2 the two storage units. KB is the operator's keyboard, on which letters are set up in succession in accordance with the cadence signals. The two storage units are on a common shaft and rotate at a speed one-sixth that of the distributor.

When a letter is set up on the keyboard, the circuits of some of the five storage magnets are closed successively in series with the segments of sector I of the distributor D, solid ring of same, transmitting relay TR to earth at the sending battery SB. The letter signal is sent out to line and simultaneously stored in the storage unit SU_1. Six revolutions later, the displaced pins in SU_1 close circuits for the corresponding magnets of storage unit SU_2 in series with sector III of the distributor and relay TR. The letter signal is again sent to line and stored in the second storage unit, while the letter is cleared from the first storage unit by the resetting cam.

After a further six revolutions of the distributor, the second storage unit repeats it to line via sector II of the distributor, and the reset cam clears the second storage unit of this particular letter. The letter signal has now been sent out three times at intervals of six revolutions (2 seconds) during which time six other letters have also been sent out.

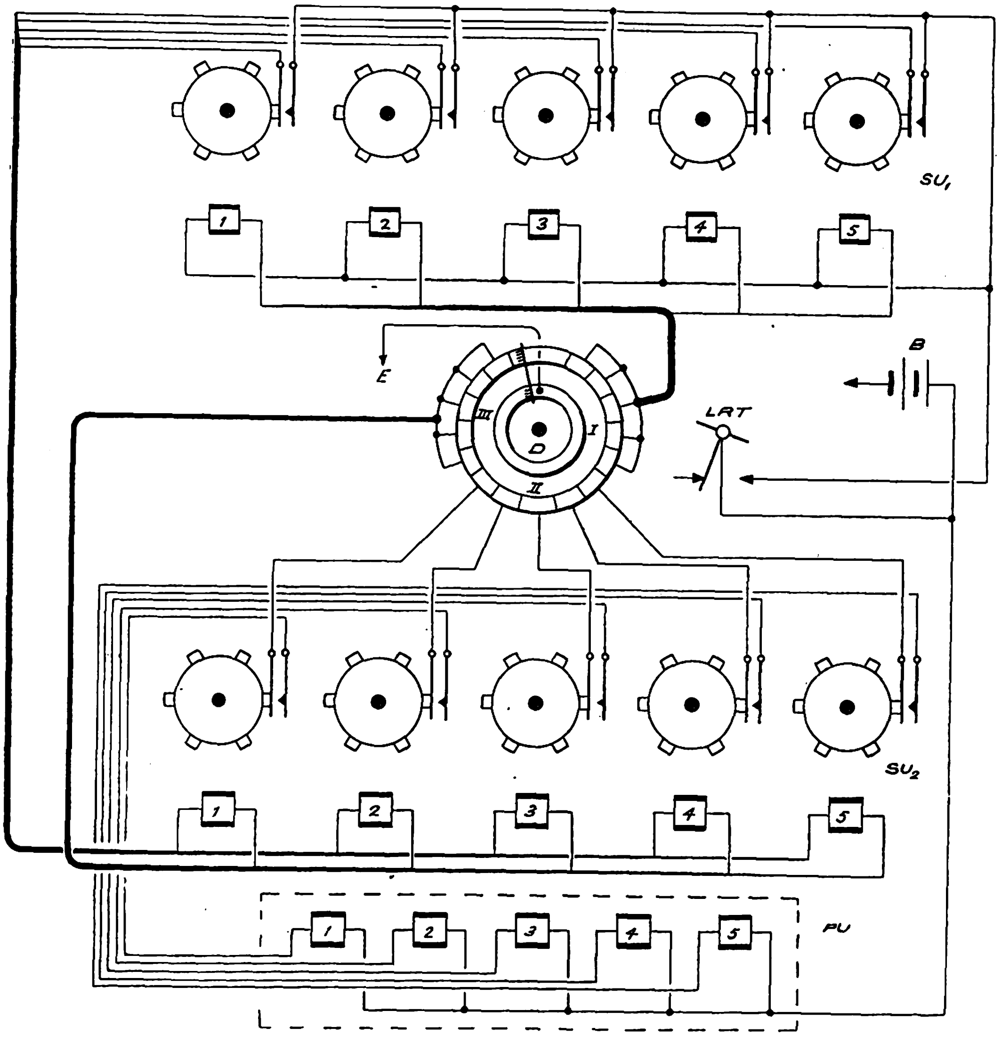


FIG. 105.—Verdan's anti-parasitic receiver.

TABLE 2.

Transmission	Revolutions of brush arm																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1st sector 1	T	E	L	E	G	R	A	P	H								
2nd sector 3	·	·	·	·	·	·	T	E	L	E	G	R	A	P	H		
Confirmation sector 2 ..	·	·	·	·	·	·	·	·	·	·	·	·	T	E	L	E	G

At the receiving end (Fig. 105) the arrangements are similar to those at the transmitter. Two storage units are employed and these are also on a common shaft and driven at one-sixth the distributor speed. The line relay controls by its tongue LRT the successive setting processes. The printer magnets of the printer unit PU are set on the third repetition of the letter signal from the relay tongue LRT via the contact springs of the second storage unit. The process in sending the word "Telegraph" is shown in Table 2.

Correction impulses are treated in the same way by an independent storage mechanism of relatively simple character.

This arrangement has been in successful operation between Paris and Algiers for some time. Paris transmits to Crois d'Hins (near Bordeaux) on a quadruple over an aerial line. At Croix d'Hins automatic retransmitters send the signals over a sextuple Baudot-Verdan arrangement which controls the radio transmitter. From 8 a.m. to 8 p.m., the most difficult 12 hours of the day from the radio point of view, a good service is assured. Two sectors with two repetitions are normally available, but at times of heavy traffic, and provided the atmospheric conditions permit of repeating only once, three sectors are available.

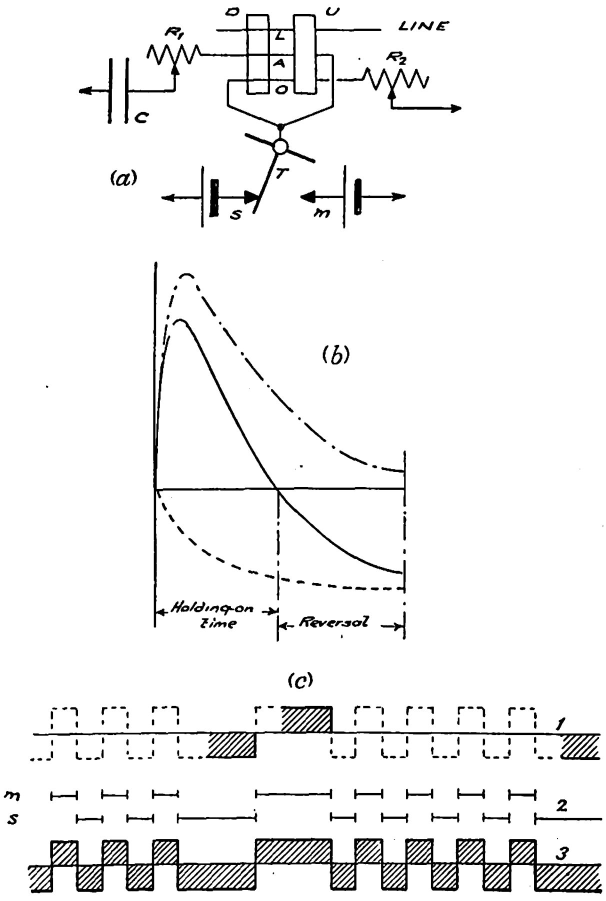


Fig. 106.—Gulstad relay operation.

The Baudot-Verdan arrangement gives an overall performance superior to other methods and, in addition, renders radio transmission absolutely secret.

Section (5). REGENERATIVE REPEATERS.

Gulstad Relay as Interpolator.—On long lines or cables the overall transmission speed can be raised by the insertion of suitable repeaters *en route*. The signals, especially those of higher frequency, are attenuated as they traverse the line circuit and attenuate at different rates, so that some do not survive when the receiving end is reached. Disturbances from neighbouring conductors will shorten or lengthen some of the signalling pulses, and the ordinary repeater, if inserted at a point where the attenuation of the higher-frequency pulses is below a certain limit, will repeat the signals as a fair copy of those imposed on the line by the originating transmitter. Such repeaters produce some measure of signal distortion themselves since no relay tongue is absolutely free from " bounce " when suddenly moved from one contact to the other and therefore does not at once make effective contact. Further, the transit time, although only a matter of 0·001 or 0·002 sec., is a fairly high percentage of the signal pulse time when the signalling frequency is high. The combined effect of " bounce " and transit time is to clip the repeated signals, which are thus not a faithful copy of the originals.

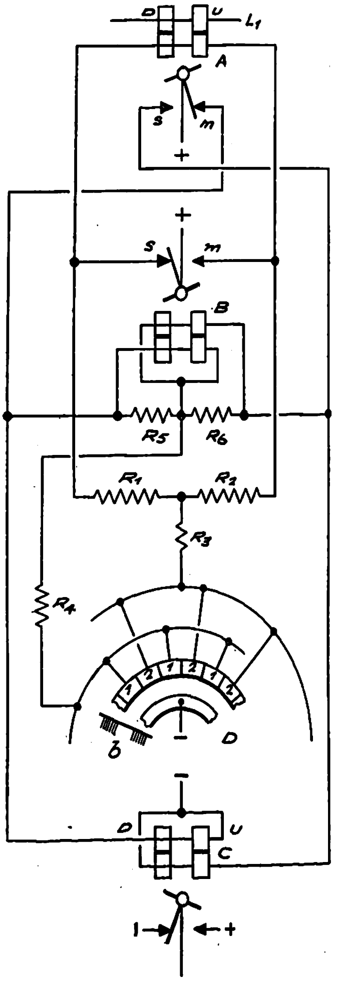


Fig. 107.—Synchronous Gulstad operation.

Both of these defects in ordinary relays are largely overcome by the system of operation invented by the late Oscar Kaye Gulstad, engineer-in-chief of the Great Northern Telegraph Co.

For cable working a special type of Gulstad relay is required, but for land-line operation the Gulstad method can be applied to any polarized telegraph relay. Briefly, it consists of a relay with three windings, a line winding and two others arranged to be opposite to each other in their effect on the relay cores. In Fig. 106(*a*) one winding, the accelerating winding, is shown in series with adjustable resistance R_1 and condenser C; while the other, the opposing winding, is in series with a resistance R_2. The coils are connected together at their other ends and to the relay tongue T. A split battery is joined to the marking and spacing stops M and S.

When T is on either contact and there is no current in the line winding L, the transient current in the accelerating coil exercises a "holding-on effect" which secures firm contact. Current in an opposite direction is building up in the opposing winding, and, as the transient holding-on current decreases, the opposing current reverses the armature as shown in Fig. 106(*b*) with appropriate values of R_1, R_2 and C; the relay, if left to itself, will steadily vibrate at a rate which can be made approximately equal to the rate of reversals from the distant transmitter. The current in the opposing winding must be less than the line current in order that pulses of longer duration than reversal pulses can take charge and stop the relay from vibrating. During the transit of the tongue from one contact to the other the condenser discharges through both windings A and O in a direction to accelerate the movement of the tongue and thus shorten the transit time. The Gulstad principle almost removes the two defects of the ordinary type of relay, but it does much more than this. Since the energy required to move the tongue from one contact to another is furnished locally, as is also the force necessary to ensure good contact pressure, the line current exercises a controlling function only and greater signal attenuation is permissible. This means that the length of a circuit may be extended without reducing speed, or, alternatively, that the speed may be increased on a line of given length. Thus in Fig. 106(*c*) the speed is such that the reversals do not get through, only the long negative or positive pulses surviving. Owing to the fact that the relay is made to vibrate at the reversal speed of the distant transmitter, the reversals are interpolated at the receiving end, while the line current exercises control and stops the relay vibrations for a dash or long space. Thus the relay repeats the signals from the distant end as an approximately correct copy of the originals. On any line the speed can be raised deliberately so that reversals do not get through, provided only that the longer pulses are sufficiently powerful to stop the vibration when required. The only other limit to this procedure is possible difficulty with the duplex balance at the sending end. In Fig. 106(*c*) instrument lag and transit time have been neglected.

Synchronous Gulstad Operation.—The Gulstad relay is most efficient when its vibrations are exactly synchronous. This adjustment is very difficult to attain and has given rise to a method of operation on long high-speed cables known as synchronous Gulstad working.

Briefly this method consists in the provision of a rotating distributor kept in synchronism with the distant station's transmitter. The local windings of the relay are then controlled from contacts on the synchronous distributor, and the relay, when not controlled by the line signals, vibrates in absolute synchronism without the necessity for skilled adjustment. One such arrangement is shown in Fig. 107. It comprises three relays, a line relay A, an auxiliary vibrating relay B and a repeating relay C together with a distributor D having a series of odd- and even-numbered pairs of segments for controlling relays A and B. Relay A is also subject to control from the line signals and it controls the operation of the repeating relay C. The distributor is maintained in synchronism by means not shown and the brushes "b" traverse one pair of segments (numbers 1 and 2) during the time of one half-reversal or cycle (one baud). When the brush "b" is on an odd-numbered segment, relay B is set by relay A, and when on an even-numbered segment relay B sets relay A. This reciprocal action is subject to A being free from line-signal control.

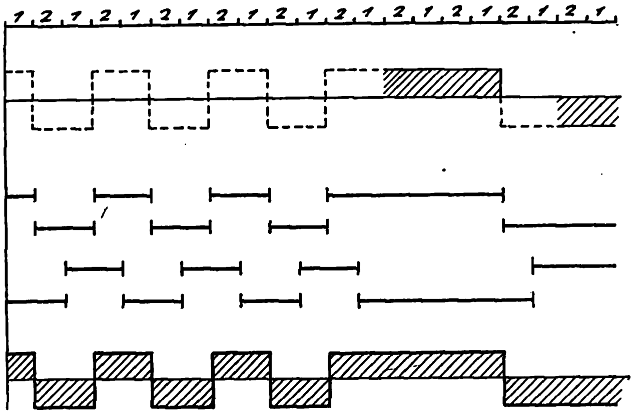


FIG. 108.—Current/time chart of operation of synchronous Gulstad relay.

The operation of the system is as follows:—With the brushes "b" on an odd-numbered segment and relay A at marking, relay B is thrown to spacing, the circuit being negative, marking contact and tongue of relay A, lower winding of relay B, R_4, segment 1 of D and solid ring via brushes "b" to negative. When the even-numbered segment 2 is bridged by brushes "b," a circuit is closed from positive spacing contact and tongue of relay B, lower winding of A, R_2, R_3, segment 2b and solid ring of D to negative. Each relay is thus set by the other half a cycle apart. Under these circumstances the repeating relay C is vibrated by relay A in exact conformity with the distant transmitters' reversals, due to the fact that D is running in synchronism.

The current/time chart in Fig. 108 shows the actual signals in the line, those shown dotted being the pulses which do not get through. The positions of the relay tongues (marking or spacing) of relays A and B are indicated below, while the original signals re-created and repeated and as sent out to line L_2 by relay C are given in the last line. This arrangement is due to the Bell Telephone Laboratories.

The arrangement shown in Fig. 109 is due to L. R. Foster, and has the peculiarity that the relays do not vibrate continuously when interpolating reversals, the advantage being that the contacts are not subject to wear from the continuous hammering as in other methods.

Four relays are required:—Relay A, the line relay, is of the 3-position type, relays B and C are ordinary polarized relays with three windings, two operating windings and one locking winding, while relay E repeats the signals to the next line section and has one operating and one locking winding.

D is a distributor running in synchronism with the distant transmitter as usual. It has two rings of segments bridged by a rotating brush " b." The upper ring of segments 1 is divided into two groups and alternately connected to the tongues of relays B and C. Each of these segments is swept over in the time of one half-reversal (baud). Opposite each of these segments is a pair of segments, the first of which is multipled to the corresponding segment of the other pairs and then connected to the operating winding of relay E. If line relay A receives a long positive or negative pulse it operates relays B and C so that they both pass to marking or spacing, the control being effected through their line windings connected to the tongue of relay A.

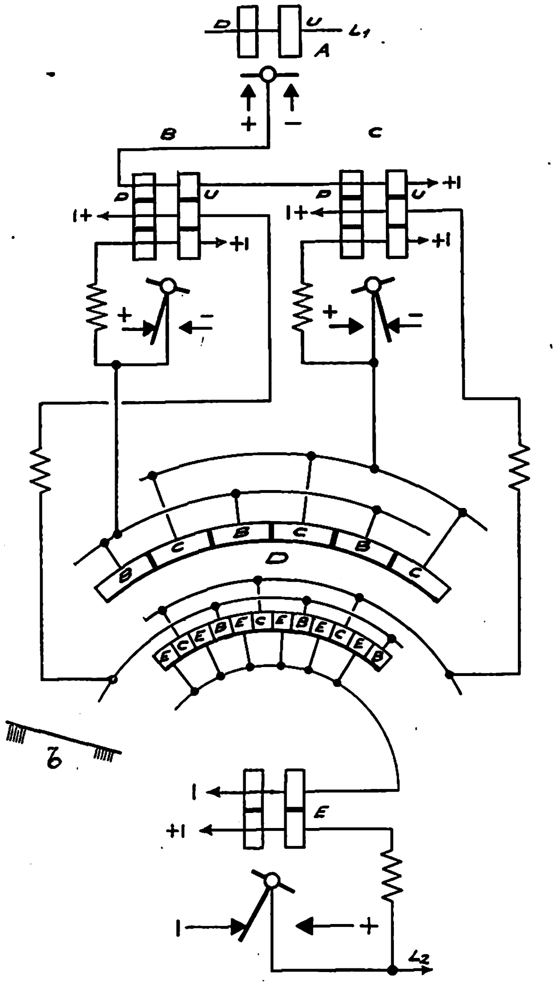


FIG. 109.—Synchronous Gulstad operation.

When brush B comes on a B segment it connects the tongue of relay B at first to the operating winding of relay E and then to the local operating winding of relay C. This current is able to overcome the locking winding current of C and if B is on its marking contact at this time C is operated to place its tongue on its marking current. The polarities of marking and spacing contacts of relays B and C are opposite to each other as shown. When a C segment is reached, relay C, which is now on its marking contact, closes a circuit from negative, segment C, half-segment E, reversing the position of relay E and later half-segment B, keeping relay B on its spacing contact. With no interference from line relay A, relays B and C retain the positions shown in the diagram, but relay E is regularly vibrated in synchronism with the distributor.

The current/time chart (Fig. 110) will explain the behaviour of the combination when actual signals are received. The top line shows the line signals as originated, the second line the signal pulses received and controlling relay A, the third line the positions assumed by the tongue of relay B, the fourth those of relay C and the fifth the current pulses sent out by relay E. Relay E is the real interpolator of missing dots, the distributor chopping up the continuous pulses of relays B and C.

Neither of these arrangements constitutes a regenerative repeater; they are interpolators only and the outgoing signals are still subject to slight distortion from bounce and transit time, although in this respect they are much superior to the ordinary type of repeater. Fig. 111 shows an interpolating repeater due to Heurtley and Foll. Incoming signals operate the line relay LR which controls a re-transmitting relay TR connected to the next section of the line L_2. A lever CL is operated by a rotary cam C mounted on a rotating shaft and synchronized to make one revolution for each signal pulse sent from the originating station. The closure of contact C_3 is arranged to take place at the mid-portion of a signal pulse, and only during this time is LR able to operate TR. The operation of the arrangement is set out in the chart below the diagram, the orientation of the lever CL being purposely shown incorrectly. When this adjustment is properly made the outgoing signals will be free from distortion and only clipped

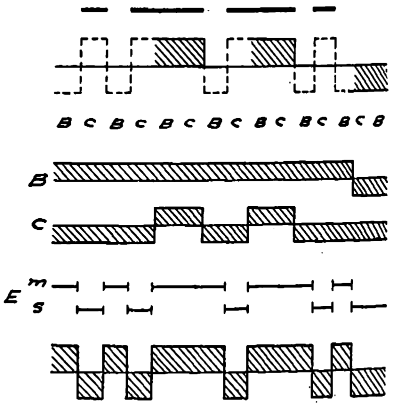


FIG. 110.—Current/time chart of synchronous Gulstad operation.

slightly by the effect of the transit time of relay TR.

True Regenerative Operation.—A truly regenerative type of repeater may be defined as one in which, at the initiation of a retransmitted signal, the repeating relay tongue has reached the desired contact, marking or spacing, and all bounce has subsided. There is thus a setting cycle preceding the transmitting cycle and these must not overlap. The received signal must therefore be effective for a length of time equal to twice that of a signal pulse, and the sending-on relay is set during the first half-period and retransmits during the second half-period. In this way the retransmitted signal is free from irregularities due to transit time, etc., and is an exact copy of the original. The regenerative repeater was invented by Baudot.

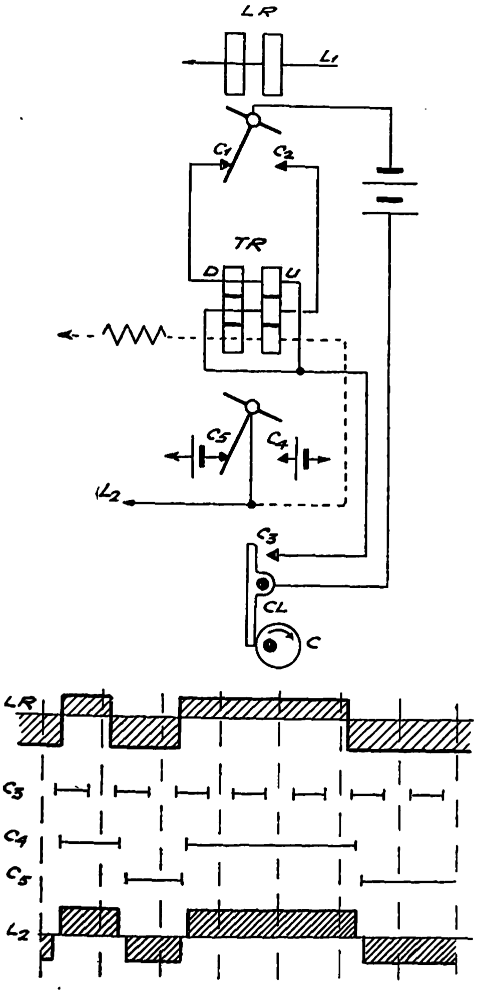


FIG. 111.—Heurtley and Foll's interpolator.

A typical regenerative repeater is shown in Fig. 112. It consists of a receiving line relay, LR, and two retransmitting relays A and B in combination with a synchronous distributor having a receiving face RF and a transmitting face TF. Incoming line signals from L are repeated by LR via the solid ring of RF, brushes "b," and shortened segments "a," "b," to relays A and B alternately. Relays A and B, when set, are held in position by a weak locking current. The brushes "b_1" and "b_2" sweep over the "a" segments simultaneously and in this way relay A is set on an "a" segment and transmits via the succeeding "b" segment on the transmitting face TF. The transmitting segments are full-length and the retransmitted signals are therefore of correct length also and start immediately the brush "b_2" commences to sweep over a segment. The current/time chart will make the operation of the arrangement quite clear. It will be noticed that the clipping effect on the received signals due to LR is entirely removed from the regenerated signal, and this is due to the fact that when either relay A or B is sending out a signal pulse it is already at rest firmly on its marking or spacing contact.

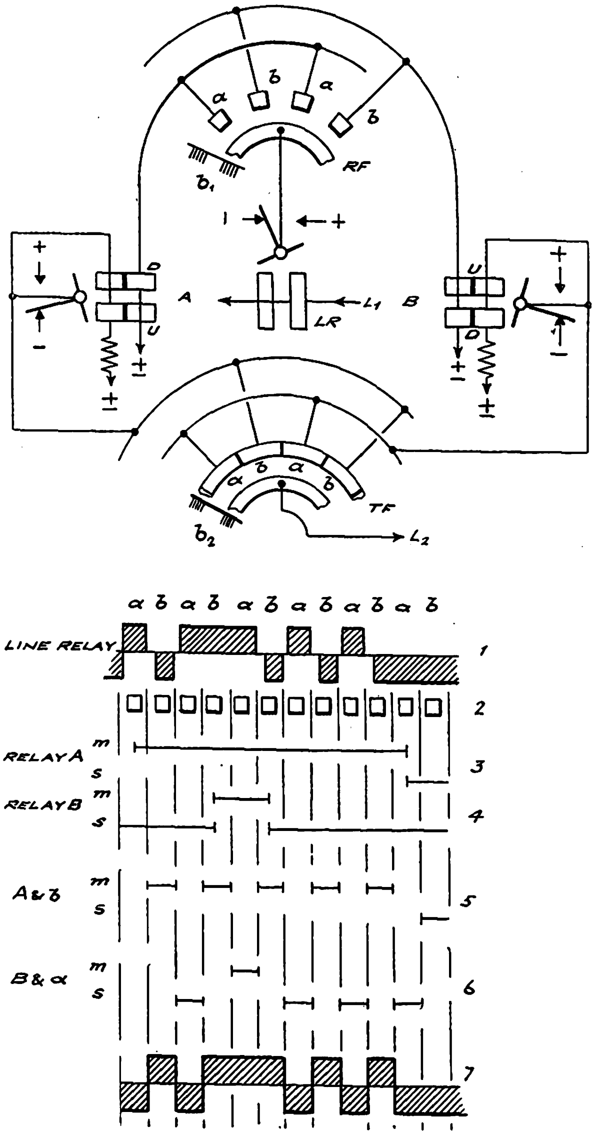


FIG. 112.—Principle of regenerative repeater.

The same arrangement can obviously be applied at the sending end, the transmitter taking the place of the tongue of line relay LR. In this way the transmitted signals are also rendered free from blemishes. This is now the general practice on long lines.

Eastern Telegraph Co.'s Regenerative System.—Fig. 113 represents diagrammatically the interpolator-regenerator used by the Eastern Telegraph Co. at an intermediate station forming one of a number of repeating points on a multi-section submarine cable. The incoming signals control a cable relay CR, the moving portion of which has a thin U-shaped contact-making member. The contact-making member has two antennæ which normally make contact with two pins mounted on a bridge piece of insulating material. The polarized relays PR_1, PR_2, are biased to their marking stops but are held to spacing by the local circuit of the cable relay CR.

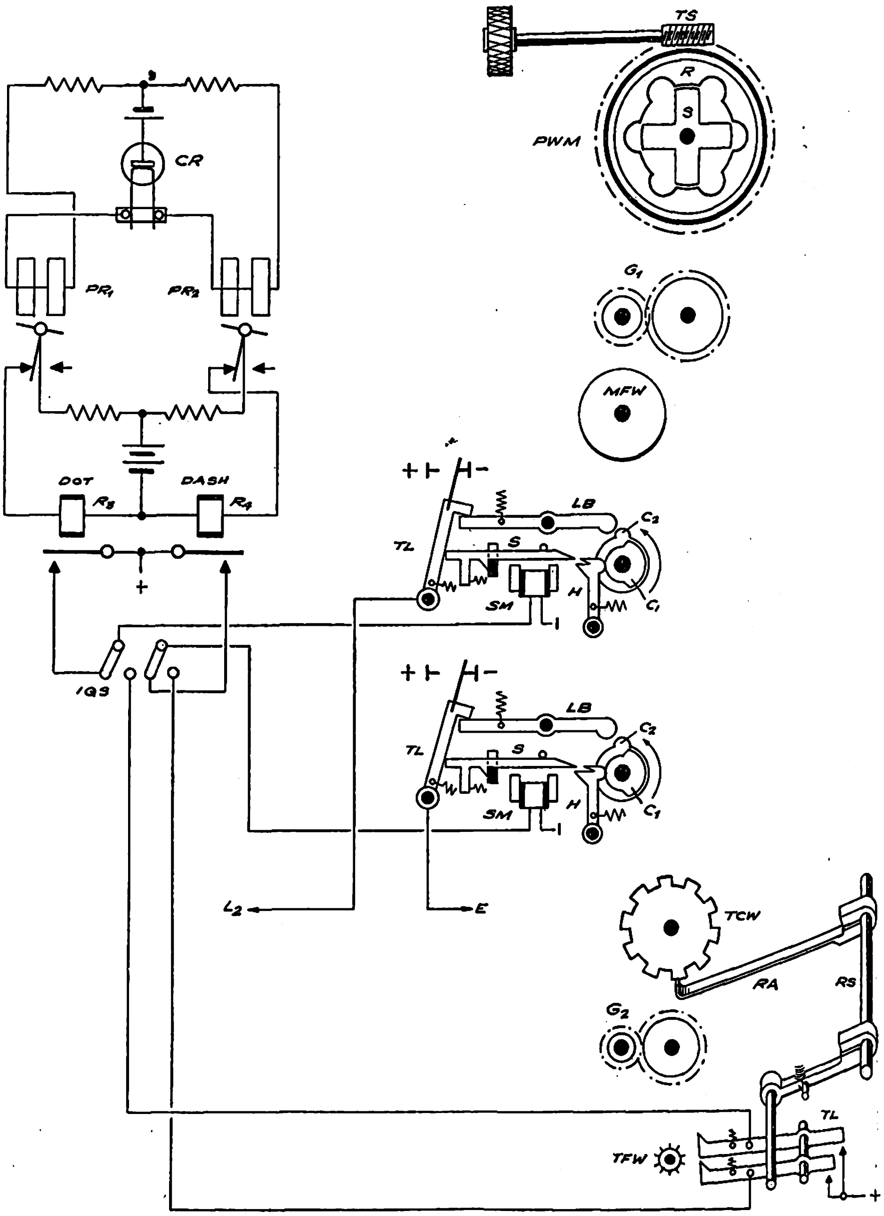


FIG. 113.—Eastern Telegraph Co.'s regenerative repeater.

If relay CR moves to right or left, one of the antennæ leaves its pin and the corresponding polarized relay is de-energized and proceeds to its marking stop by reason of the bias previously mentioned. The dot or dash relays, R_3, R_4, which are normally energized, are released by their corresponding polarized relay and close a circuit from positive through the switch IQS to the selector magnets SM of the interpolator. The interpolator mechanism consists of two transmitter levers TL, one for dots and the other for dashes.

PWM is a phonic-wheel motor driven at a speed equal to that of the motor driving the distant transmitter. PWM drives, through a step-up gear G_1, a secondary shaft on which is mounted a mercury flywheel MFW and two sets of cams C_1 and C_2. At the lower end of this shaft is a second set of gears driving a transmitter code wheel TCW which, by means of rocking arm RA mounted on rock-shaft RS, controls the oscillations of two transmitter levers TL forming the usual cable code transmitter. The transmitter operates continuously but is without effect as long as IQS is in the "through" position shown in the illustration. Dot or dash signals operate the selector magnets SM and depress the selector member S into the path of a hammer H. The latter is driven forward by cam C_1 and retains S in the operated position while pushing it to the left to reverse the position of the lever TL. When TL reaches the reverse position, latch-bar LB springs up and locks it. At the end of the signal period C_2 raises the right-hand end of LB, depressing the far end and releasing TL, which snaps back into the normal position (as shown).

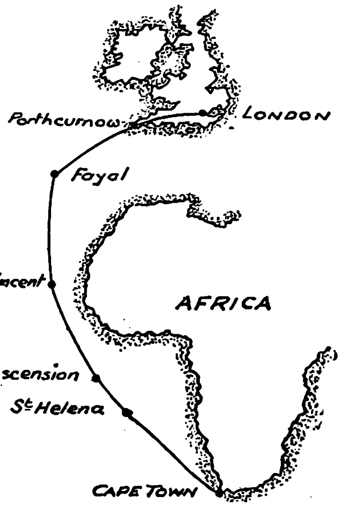

Porthcurnow
London
Fayal
St Vincent
Africa
Ascension
St Helena
Cape Town

Fig. 114.—Regenerative repeater arrangements of Eastern Telegraph Co.

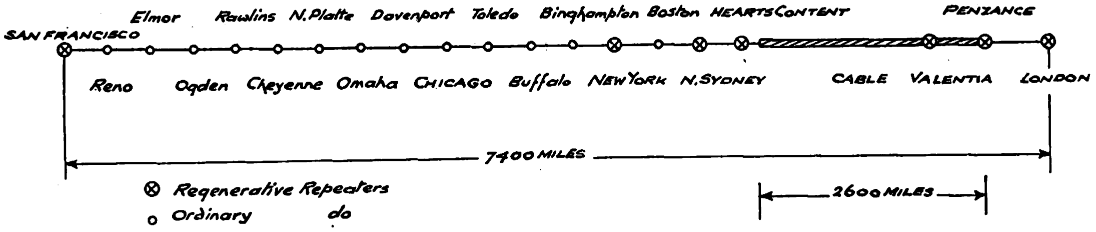

San Francisco
Elmor
Rawlins
N.Platte
Davenport
Toledo
Binghampton
Boston
Hearts Content
Penzance
Reno
Ogden
Cheyenne
Omaha
Chicago
Buffalo
New York
N.Sydney
Cable
Valentia
London
7400 Miles
⊗ Regenerative Repeaters
o Ordinary do
2600 Miles

Fig. 115.—Western Union Co.'s regenerative repeater circuit.

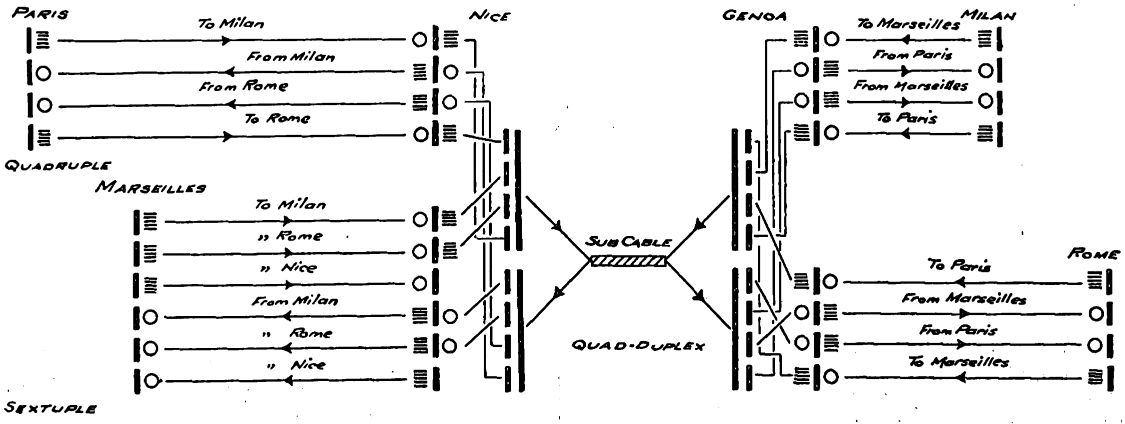

Paris
To Milan
From Milan
From Rome
To Rome
Nice
Quadruple
Marseilles
To Milan
" Rome
" Nice
From Milan
" Rome
" Nice
Sextuple
Sub Cable
Quad-Duplex
Genoa
To Marseilles
Milan
From Paris
From Marseilles
To Paris
Rome
To Paris
From Marseilles
From Paris
To Marseilles

Fig. 116.—French international regenerative repeater circuit.

The stator of the phonic-wheel motor can be displaced with respect to the rotor by means of the tangent screw TS. This enables the best part of the received signals (i.e. near the middle of a pulse where distortion due to bounce, etc., has vanished) to be selected. This orientation adjustment is effected by the passing of working signals, the stator being moved in one direction until the signals fail, then moved through the correct position in the contrary direction until failure again occurs. The middle of the two extreme adjustments is the correct position for S.

If the intermediate station has traffic for any other or for the terminal station, the IQ switch is turned to the right and the transmitter operated by perforated tape. It then controls the selector magnets of the interpolator mechanism and signals pass out to line L_2 in the standard manner. The perfect system of synchronism employed by the Eastern Telegraph Co. has been described previously.

Fig. 114 is a map of the cable route from London to Cape Town. Intermediate regenerator-repeaters are inserted at Porthcurnow, Fayal (Azores), St. Vincent, Ascension and St. Helena. At Cape Town the signals are recorded on a perforated tape and passed through a cable-code printer. This route commenced operating on the regenerator system on the 19th. January, 1927. Routes with as many as 11 relays are now in operation.

Signals have been transmitted from London to Penang (Straits Settlements) and back, employing 21 relays. Prior to the introduction of the regenerator no more than two relays of the then existing type could be employed.

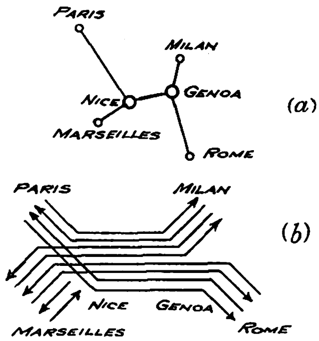


Fig. 117.—Line plant and channel arrangements of French international regenerative repeater circuit.

As a further example of the advantages of the regenerative repeater in building up long circuits, the circuit between San Francisco and London (Fig. 115) may be cited. There are 20 repeaters in circuit, 13 of the ordinary and 7 of the regenerative type. The length of the circuit is 7 400 miles, of which 2 600 miles consist of submarine cable.

Interworking of Circuits with Different Numbers of Channels.—When using the 5-unit code, a whole letter may be set up, stored and retransmitted at a later part of distributor revolution. This requires 5 relays per channel because the operation is not now pulse by pulse but letter by letter. All the advantages of regeneration are retained but the phase of the setting and retransmitting cycles may now be so adjusted as to permit of channels from 4 channel (quadruple) being worked through to 3 channel (triple) or two channel (double) or any of these types working through a duplex multi-channel system.

The utility of this is very clearly shown by Figs. 116 and 117. Here a quadruple at Paris has two channels to Milan and two to Rome. At Marseilles a sextuple furnishes two channels to Milan, two to Rome and two to Nice. The circuit between Nice and Genoa is furnished by a submarine cable worked on the quadruple-duplex-system.

Fig. 118 is the arrangement of the German-American cable worked at 250 words per minute by five channels of 50 words per minute each. A regenerative repeater is provided at the Azores. New York and Emden have one channel each to the Azores. Channels 2 and 3 are used by the Western Union Co. for Emden–New York traffic, and channels 4 and 5 are leased to the Commercial Cable Co. also for Emden–New York traffic. The British Post Office and Continental Administrations share channels of a single link in the same way.

Regenerative Repeaters Combined with Voice-frequency Transmission.—If to the principle of division of line time a plurality of voice frequencies are added as a further means of selection, channel repeating by regenerative repeaters may be considerably extended. Fig. 119 shows these combined features. London works to Paris quadruple-duplex, using d.c. transmission. Two duplex channels serve for London-Paris traffic, the other two being extended to Zurich. The number and arrangement of the channels are set out in the diagram.

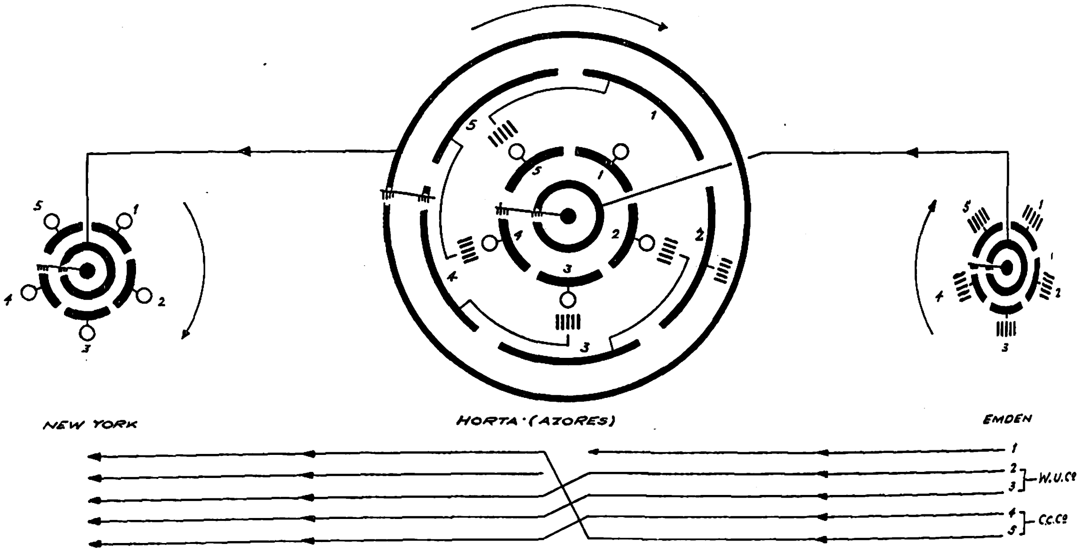


Fig. 118.—German–American regenerative repeater.

The a.c. voice-frequency signals pass through two repeater stations *en route*, these being of the standard telephone type, and the lines consist of two pairs in a telephone cable.

When the League of Nations is sitting at Geneva an additional frequency is employed, giving 8 or 4 duplex channels between Geneva and Paris.

Effects of Bias.—In the case of a long link with several regenerative repeaters at intermediate points, the accumulation of bias must be guarded against. Bias can arise from a variety of causes, such as inequalities of spacing and marking batteries, earth currents, defective relay or transmitter adjustments, and so on. Stoppages to locate the point at which the bias originates are costly, and hence careful scrutiny of the outgoing signals at all repeating points is necessary. Slow changes of phase due to inaccuracies in synchronism will produce the same effects as bias. The continuous operation of a long and costly circuit depends upon careful observations directed to the detection of tendencies harmful to accurate transmission, and the "automatic scrutineer," the invention of Mr. K. L. Wood and employed on the Eastern Telegraph cable system, detects a tendency to bias and draws attention to this.

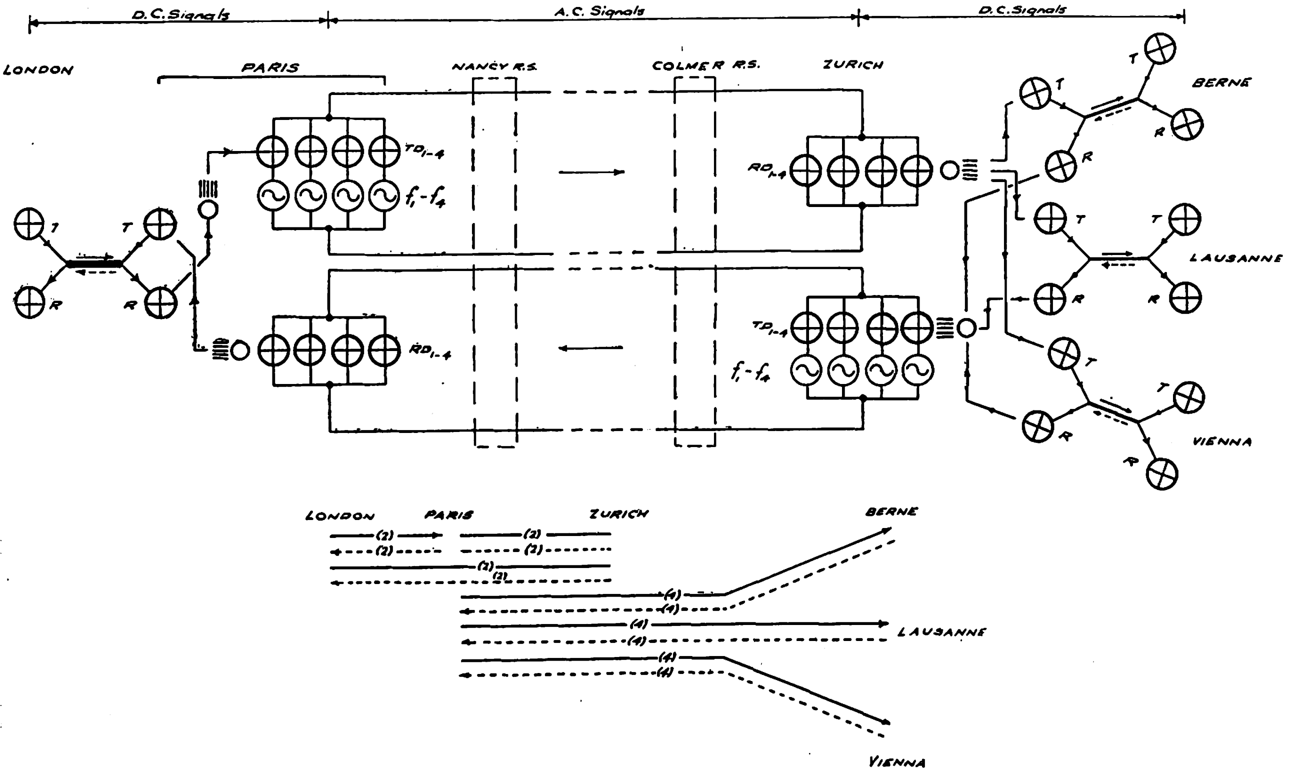


FIG. 119.—English–French international regenerative repeater arrangements.

Automatic Scrutineer.—Fig. 120(*a*) shows reversals with a spacing bias and the effect on the receiving relay is shown in Fig. 120 (*b*), where the marking pulses are seen to be shortened while the spacing pulses are lengthened. The points at which changes of sign take place are shifted to the right, changes from positive and negative being characterized by a smaller shift than those from negative to positive. Fig. 120(*c*) shows the same signals with a marking bias, and Fig. 120(*d*) represents the effect on the receiving relay. The effects here are exactly the opposite of those occurring in the previous case. The changes of sign are again shifted to the right but the greater shift takes place on a change from positive to negative. Fig. 120(*e*) shows the usual ring of shortened receiving segments, from which it will be seen that the maximum shifts are effected when the brushes are about to sweep over these segments. Even with this amount of distortion, signals will not fail and will be regenerated correctly, but the system is on the verge of failure and should have been readjusted before the conditions in (*b*) and (*d*) had been reached. Fig. 120(*f*) shows an arrangement by which the introduction of bias, however caused, is indicated visually and audibly. An additional ring of shortened segments, with their accompanying solid ring and bridging brushes, is provided and the whole ring is capable of slight displacement in either direction. The additional ring is fed with incoming spacing and marking pulses in the same manner as the usual shortened receiving segments, and at each change of sign in the signalling currents relay R_1, also controlled by the line signals, removes a short-circuit on relay R_2. If brush b_2 is on a bias segment when this occurs, relay R_2 momentarily operates the bell B and one or other of the bias indicating lamps. R_2 is of the centre-zero type.

It will be seen that, if a spacing bias exists, changes of sign when a segment is traversed will be from negative to positive, and relay R_2 will therefore be operated to flash spacing-bias lamp SBL. If there is a marking bias changes of sign occur on the segment from positive to negative and R_2 will light lamp MBL.

Fig. 120 merely illustrates the broad principles of the scrutineer and it is obvious that many modifications may be made to the indicating arrangement.

In practice the bias-indicating segments would be set backwards (to the left) to give an alarm before the conditions of either (*b*) or (*d*) had been reached. The scrutineer will also give an alarm if phase-creep sets in.

Regenerative Operation of Cable Networks.—France, the home of the regenerative repeater, is in direct communication with her Asiatic and African Colonies from Paris.

Synchronous Gulstad operation, together with a regenerator, secures higher speeds than would be possible with either alone, and this combination is employed on the German-American cable referred to above.

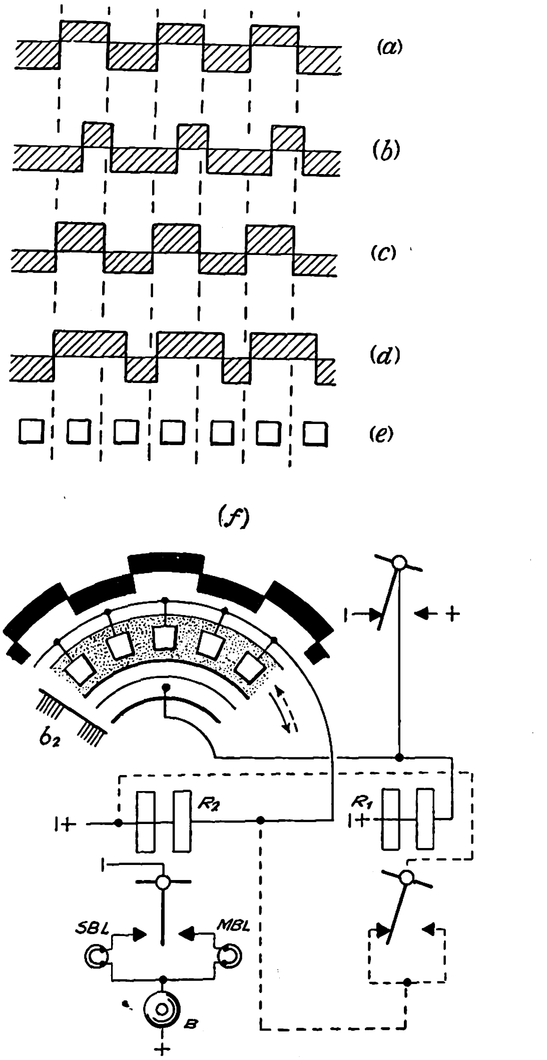


FIG. 120.—Eastern Telegraph Co.'s automatic scrutineer.

The introduction of the regenerator in the case of a large cable network effects considerable economies in staff by reason of the avoidance of retransmission, while it obviates delay and risk of errors in transmission.

Section (6). METHODS OF OPERATION OF LINE PLANT.

Methods of operation of line plant take the form of increased utilization of the line by such means as obtaining several channels by the use of a number of audio frequencies, by superposition, and by dual utilization for telephony and telegraphy.

Composite Working.—Audio-frequency systems have been previously dealt with before this Insitution and there is no need to treat them in this paper. The superimposition of telegraph on telephone circuits is also well understood, and Fig. 121 is given merely to indicate the possibilities of such means.

In June 1918 the American Army equipped a circuit such as that shown in Fig. 121 between Tours and Chaumont, a distance of 306 miles, with a repeater at Autun.

In addition to the three telephone channels the capacity of the 12 both-way telegraph channels was 704 words per minute.

Sub-Audio Telegraphy on Telephone Pairs.—The application of earthed telegraph circuits to telephone pairs in the manner indicated in Fig. 121 is limited. The present-day high-efficiency telephone circuits including loading coils and amplifiers operating with large gains are seriously interfered with by the telegraph currents. This interference is due to the effect of the comparatively large telegraph currents on the permeability of the iron cores of the loading coils, which leads to transient changes in their effective resistance and inductance to telephone currents. The higher harmonics of the telegraph signals are magnified by the amplifiers and furnish another source of interference. These diffi-

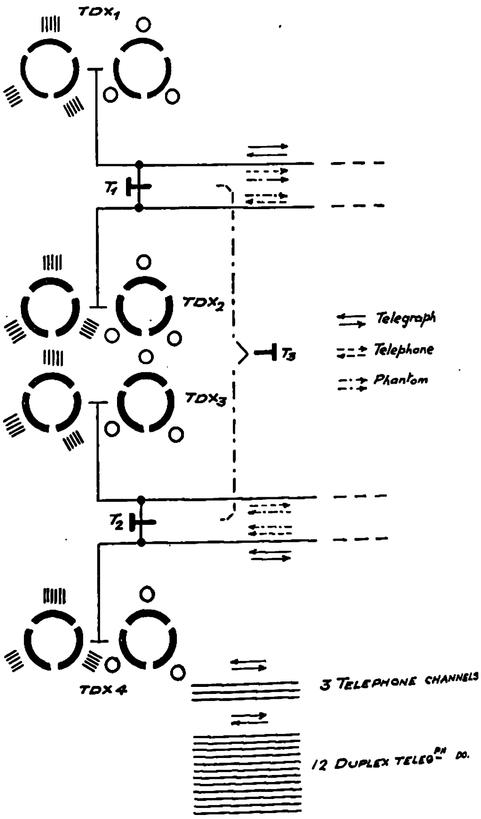


FIG. 121.—Simultaneous telegraphy and telephony on a telephone quad.

culties are overcome by reducing the telegraph currents to a magnitude of the same order as the telephone currents and by employing a complete metallic circuit for the telegraph channel.

Using a metallic circuit for the two channels and operating the telegraph with weak currents, the interference with the telephone by high-frequency components of the telegraph signals is so reduced that it is possible to dispense with much of the " noise-killing " apparatus of the older composite system and greater telegraph speeds are thereby possible. An incidental advantage arises also from the fact that the telegraph currents pass through both windings of the loading coils instead of one coil as in Fig. 121, and the coils thus help telegraph transmission instead of hindering it as previously.

In Fig. 122, L$_1$ and L$_2$ are the two wires forming a coil-loaded telephone pair. At the terminal the line forks, one branch going to the usual telephone apparatus (not shown) and the other to the telegraph apparatus. At the fork, the telephone branch is bridged by series condensers and a shunt inductance—while the telegraph branch is provided with series inductances and a shunt condenser. These are equivalent to high-pass and low-pass filters and when suitably designed effect separation between speech frequencies and the lower band of frequencies forming the components of the telegraph signals. The receiving relay R is double-wound and duplex operation is secured in the usual way by a balancing network BN. The series inductances and shunt capacities in the sending circuit controlled by TL partially suppress the high-frequency components of the telegraph signals. With the arrangement described, the " flutter effect " shown in the inset, which results when the system of Fig. 121 is employed, becomes negligible.

This system is finding considerable application in Germany and it is probable that it will, to a very great extent, supplant the voice-frequency multiple system so widely used in that country.

The system can operate on 2 to 3 mA at 24 volts down to 1 mA at 6 volts, and when applied to cable pairs can be permanently duplexed and will work at a speed of 600 letters per minute (5-unit code) over a distance of 95 miles.

Two-power Multiplex Operation.—The 2-power method of signalling, which has very serious objections when applied in the usual way to morse signalling, can be made much more effective when machine methods of sending are employed.

Fig. 123 (*a*) shows the letters F and L sent by hand on the polarized and non-polarized sides of a diplex or 2-power transmission circuit. Except for any imperfections in the formation of the A-side signals due to manual operation, these will be correctly transmitted and received. The B-side signals are, however, badly distorted. The dash of the letter L is split twice, due to reversals of polarity occurring, and the final dot will probably be clipped at the end. If the two sets of signals are transmitted by two automatic transmitters geared together so that the marking and spacing pulses are of equal duration, as shown in Fig. 123 (*b*), then splits will not occur with B-side dot signals at all, and will only occur at dot intervals during a B-side dash. The tendency to clip the initial or terminal portions of B-side signals has disappeared. It has been found possible in this way to work a 2-power circuit between London and Manchester at 200 words per minute—100 words per minute each side—a hitherto unattainable speed of operation for the B side. The fact that the B-side pulses are always at least of dot signal duration enables the B-side voltage to be reduced as the B-side relay gets more time to act. This fact removes very largely another defect of 2-power duplex operation. Out-of-balance currents are more serious when the B side is in operation, and tend to interfere with the satisfactory operation of the A side. It is possible with the new method to work satisfactorily with a power ratio of 1·5:1

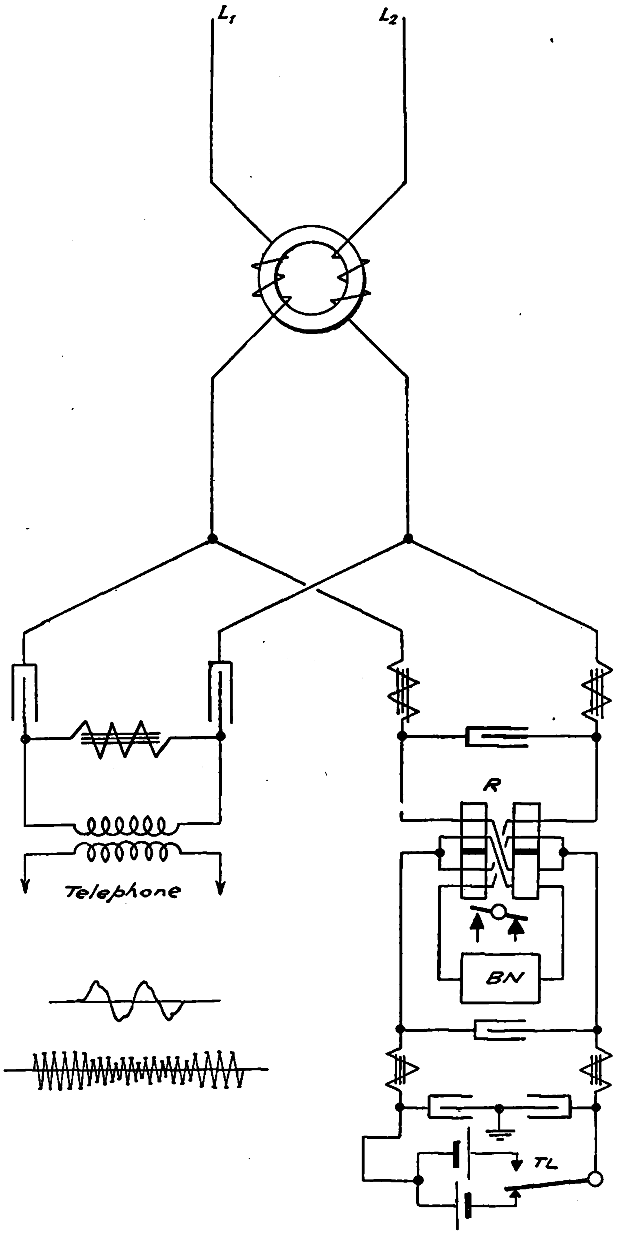


FIG. 122.—Sub-audio telegraphy.

instead of the more usual 3:1, and with a reasonably good balance the operating margin of the circuit is considerably extended.

The idea of timing the two sets of signals so that they originate and terminate together occurred independently and simultaneously to Mr. F. G. Creed and the author* and was applied by Mr. Creed to morse and by the author to 5-unit code operation.

Five-unit code represents the more perfect application of the principle, since the signal pulses of both sets of signals are identical in length and the splitting of signals still present in the improved morse method cannot take place.

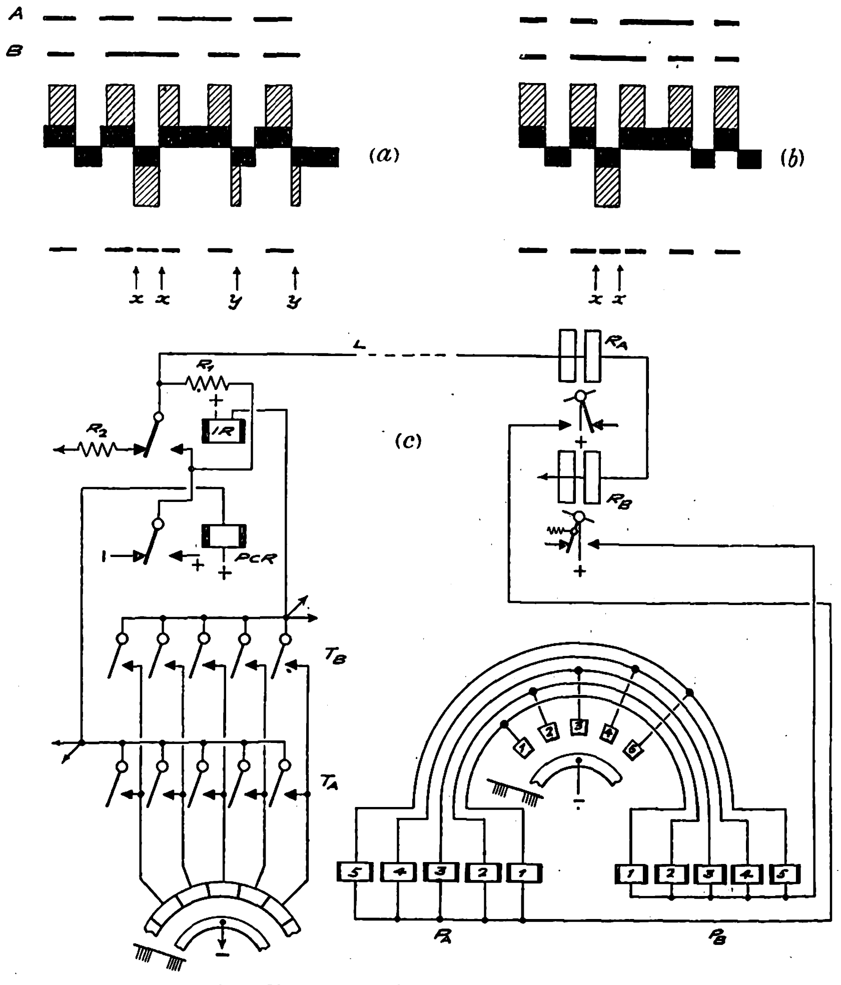


FIG. 123.—Two-power diplex signalling with 5-unit code.

Fig. 123 represents the 5-unit code method applied to diplex operation while quadruplex working is obtained, as will be understood, by employing the duplex balance. Two transmitters, T_A and T_B, are connected in multiple to one channel of a multiplex distributor and are operated independently by perforated tape transmitters, or manually in the usual way by observing a cadence signal. T_A operates a pole-changing relay PCR, and marking and spacing currents are sent out to line in accordance with the combination set up in the transmitter. T_B operates an incrementing relay IR which removes a series resistance R_1 and a shunt resistance R_2 from the line L. This is a well-known 2-power signalling method which needs no description.

At the receiving end the two sets of signals are sorted out by a polarized relay RA responding to the positive and negative currents from the distant A transmitter, while the non-polarized relay RB responds to the incremented positive or negative signals from transmitter B. Such a system, while perhaps not to be recommended for general application, could probably be used to advantage under special circumstances.

Temporary increases of traffic for which no extra line plant is available might be met by the application of this scheme. Also, if the speed of the line is uneconomical for a given required number of channels, the system presents an opportunity of increasing the number of channels to the extent desired.

Temporary communication between a station A and another C forking from a station B could also be obtained.

Morse Multiplex Telegraphy by Division of Line Time.—The application of machine sending to the multiplexing

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* [British Specifications 221556 and 222616.]

of circuits worked with the morse double-current land-line code provides a solution of this problem free from the defects of the hand-worked Delany multiplex. Here, again, the transmitters must be geared together so that the signal elements originate and terminate simultaneously. Fig. 124 shows the arrangement. T_1 and T_2 are the two transmitters which are geared together and to the brush arm of a sending distributor, so that the uneven-numbered segments are connected to the sending relay R_1 controlled by transmitter T_1, while the even-numbered segments are connected to relay R_2 of transmitter T_2.

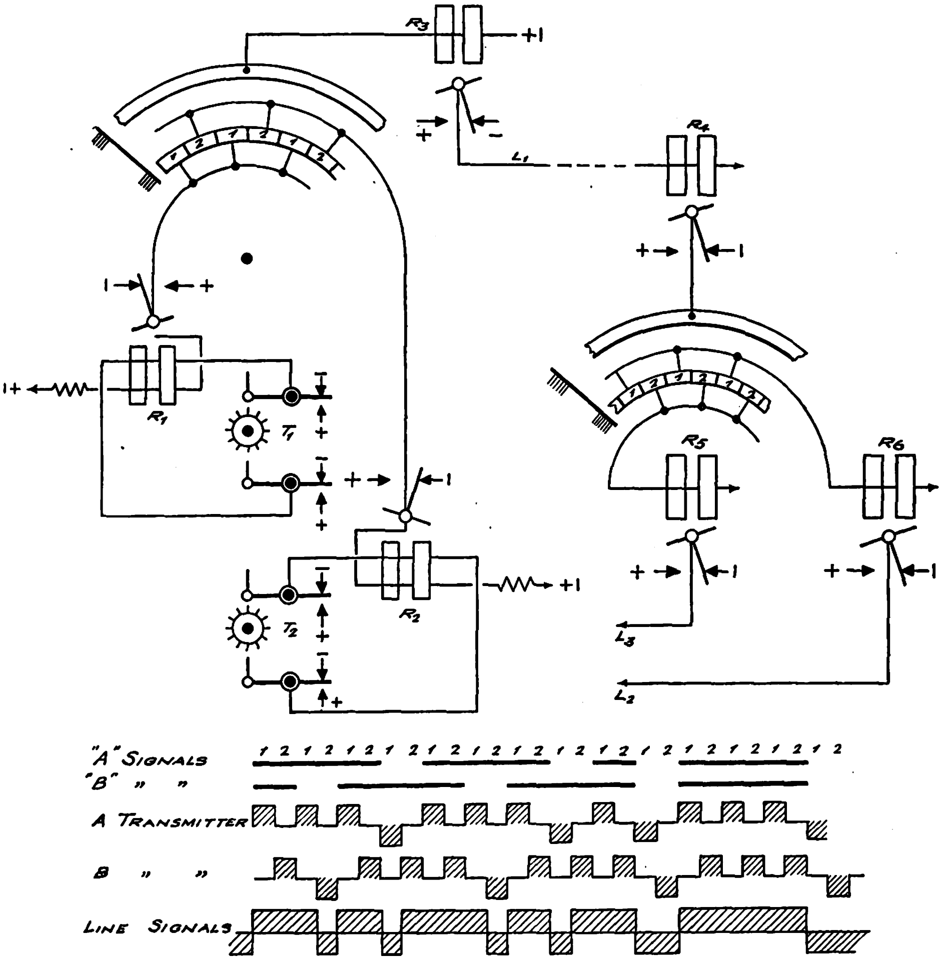

FIG. 124.—Morse multiplex system.

From the current/time chart appended it will be seen that each transmitter is connected through the relays and distributor segments to a third relay R_3, which actually sends the two sets of line signals for a period equal to half only of a signal pulse. T_1 sends during the first half of a signal pulse and T_2 during the second half. The two sets of signals are thus half a signal pulse apart from each other. The combined signals sent out to line are unreadable and the system may be claimed to be partially secret, as the line signals would be difficult to decipher.

At the receiving end the signals are distributed to the two receiving means, which may be two lines L_2 and L_3, or, of course, the signals may be terminated without repetition to distant stations. The receiving distributor is, of course, synchronized, by methods not shown.

Two-channel operation is shown in which the doubled capacity is obtained by halving the length of the signal pulses in the line. For triple or quadruple operation the pulses would be one-third or one-quarter of the signal pulse per channel. The storage feature of polarized relays, neutrally adjusted, is relied on to bring the signal pulses and spaces up to their correct length. Relays R_5 and R_6 may be provided with locking windings to hold the tongues firmly on whatever contact they are set.

With satisfactory synchronism a 2-channel set has worked at 150 words per minute per channel.

Transposition of Land-Line Morse Code.—It has been proposed to operate ocean cables with the Wheatstone-Morse Code at a rate giving a speed in words per minute comparable with the shorter cable code. A method of doing this is to speed up so that Morse Code reversals do not get through, these being interpolated by means of the Gulstad relay or similar device. The disadvantage of this arrangement is that the higher rate of transmission increases the difficulty of obtaining a satisfactory duplex balance. A method has been worked out by the Western Union Cable Co., by which Wheatstone Code may be employed in a cable code transmitter, transmitted to the cable, converted into a code consisting of positive, negative and zero units, and transposed at the receiving end into the original Wheatstone-Morse Code.

The Wheatstone-Morse Code may be resolved into three combinations, each containing two signal impulse units. Thus the letter "1" and its succeeding space is made up as follows:— (+ −) (+ +) (+ −) (+ −) (+ −) (− −).

If it is possible to substitute for the (+ −) type (which is a reversal) a positive pulse of the same time length, for the (+ +) combination a negative pulse and for the (− −) combination a zero unit, the Wheatstone-Morse is then converted into another code of the cable-code type. Further, the individual signal elements are of doubled length and the new code can be transmitted at a rate exactly double that of the original Wheatstone-Morse, while the speed in centre holes is only the same as it would be if the cable code morse were used. In this way it is possible to link, by means of a submarine cable, two land lines working Wheatstone without the sacrifice of overall speed which would be entailed by employing the Wheatstone Code throughout. At the sending end the conversion is attained without any alteration whatever to the standard cable-code transmitter.

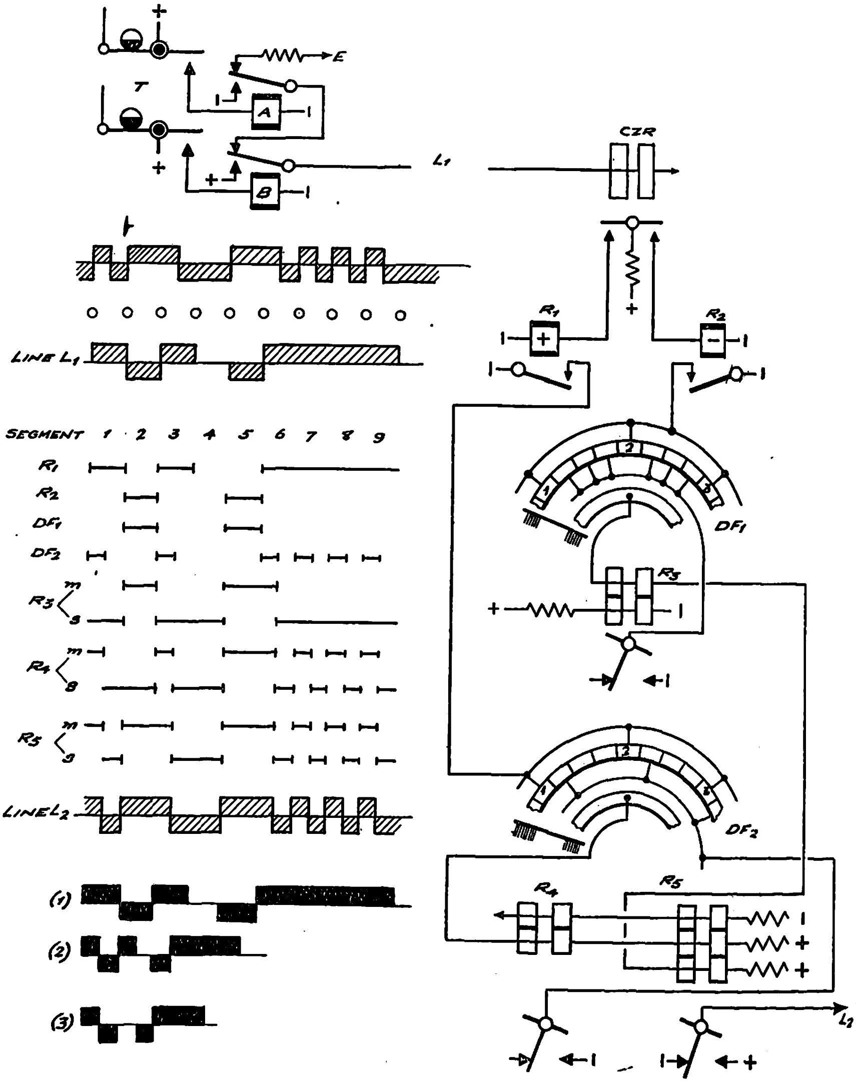

FIG. 125.—Western Union Co.'s transposing system.

Fig. 125 describes the sending- and receiving-end arrangements. The dot pecker enters the upper row of holes, and the dash pecker the lower row. Two relays, A and B, are controlled by the peckers, so that when relay A is operated a negative signal pulse is applied to the cable, while relay B when operated applies a positive pulse with both relays in their normal unoperated position. The cable is earthed when both peckers enter holes in the tape simultaneously (a Wheatstone dot) and both relays operate, but only relay B is effective and a positive signal pulse is transmitted for a time corresponding to the passage of the tape through a distance equal to the pitch of the tape-feed centre holes. When the dot pecker enters the upper hole, initiating a dash signal, a negative pulse of equal length is applied. At the lower hole terminating the dash, relay B applies a positive pulse, and when a space occurs between letters neither pecker operates and an interval of no current occurs of time value equal to that of either positive or negative signal pulses. The Wheatstone letter " A " is thus sent out as (+ +) (− −) (+ +) (0 0).

At the receiving end, the positive, negative and zero units are received on a cable relay CZR of the Brown type in which zero signal intervals have no effect, while positive or negative pulses operate relays R_1 and R_2.

A synchronous distributor is employed having faces DF_1 and DF_2 by means of which the hybrid code is transposed back into standard Wheatstone-Morse.

Relay R_3, operated from DF_1, is in series with one operating winding of R_5, and both are energized by R_2 when a negative pulse is received.

Relay R_4 is operated in series with a second operating winding of R_5 and both are energized by R_1 when a positive pulse is received.

Relays R_3, R_4 and R_5 are normally held in the spacing position by biasing windings in which a current, lower than the operating currents, permanently circulates.

If a negative pulse is received, R_2 operates and completes a circuit via its armature from negative to, say, segment No. 1 and solid ring of DF_1, operating windings of relays R_3 and R_5 to positive. R_3 operates and maintains both itself and R_5 energized over the three segments of DF_1, which follow segment No. 1 until segment No. 2 is reached. R_5 has reversed its armature and is sending out a positive signal pulse to the land line L_2. If, when segment 2 is reached, the same condition prevails, everything is as previously described, and so on.

If a positive pulse is received, R_1 operates and energizes relays R_4 and R_5. R_4 applies negative current via DF_2 and the segment adjacent to, say, segment No. 1, the solid ring of DF_2, its own operated winding and that of R_5. When, however, the next two segments between Nos. 1 and 2 of DF_2 are reached, they are insulated and the biasing windings of R_4 and R_5 operate, the circuit from the armatures of R_1 and R_4 now being broken. R_5 now reverses, and the long positive pulse has thus been transposed into a Wheatstone reversal.

The operation of the entire system is shown by the current/time chart given, in which (1) represents the signals sent into the cable, (2) the signals speeded up to the rate at which dot pulses can be sent through the cable, and (3) the same letters " a," " b," sent in cable code.

It will be seen that the resultant code given by this transposing method is only slightly inferior to the cable code, while the advantage of being able to link the two land lines up via the cable and to employ standard apparatus such as the Wheatstone-Creed more than outweighs the slight loss of speed which results.

Duplex Operation of Long Cables.—Duplex operation of long cables is especially difficult when delicate amplifiers are employed in the receiving branch of the circuit. This arises from imperfections in the duplex balance, which result in outgoing signal pulses entering the receiving branch and not only swamping the weak signals incoming from the distant station but producing false signals in the receiver. The magnitude of this disturbance depends upon the out-of-balance quantity which exists, while it is only transient in character and is at a maximum when a voltage is impressed on the cable at the sending end or a reversal of voltage is effected.

It occurred to the author some years ago that if the receiving apparatus could be cut off from the line during the transient outgoing disturbance, duplex operation could be improved. This involves synchronous distributors and also an adjustment of signalling speeds so that incoming and outgoing pulses are in phase with one another. The arrangement worked out and submitted to the Western Union Co. is shown in Fig. 126. Incoming signal pulses are received alternately on two relays A and B, which are intermittently connected in the receiving branch of the bridge circuit through the shortened segments of the receiving face RF_1 of a distributor.

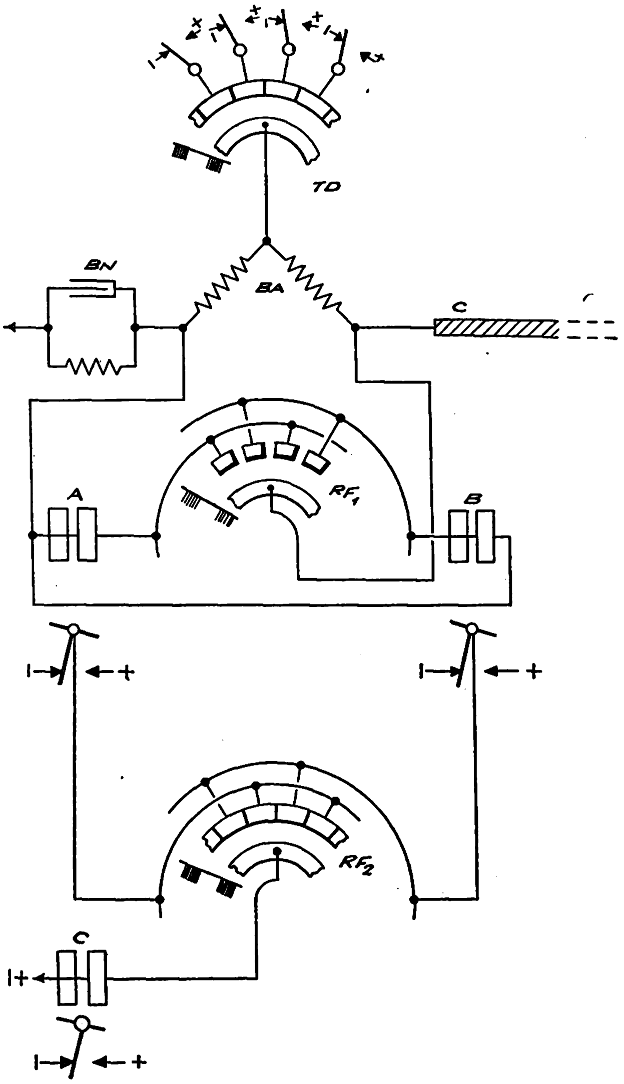

FIG. 126.—Method of eliminating " jar " on duplex circuits.

The receiving circuit is open at the times of greatest disturbance from the transmitter, provided the "in-phase" adjustment, previously mentioned, is secured. The received signals are regenerated by means of the second receiving face RF_2 and relay C. If the line lag is not equal in each direction, speeds must be so adjusted that it is represented by one or more complete segments of the distributors. The same idea subsequently occurred to the Western Electric Co.*

Two-way Working on Loaded Cables.—On long ocean cables of the loaded type the transmission is of the wave propagation character as distinct from the diffusion process in the unloaded cable. In the case of the loaded cable, the received current is zero from $t = 0$ to $t = T$, where $T = L\sqrt{(CL)}$. At this moment the current

$$i = 2E\sqrt{\left(\frac{C}{L}\right)}\epsilon^{-\frac{1}{2}LR\sqrt{(C/L)}}$$

suddenly rises to i and then increases gradually to its steady-state value in accordance with the equation. Such an arrival curve is shown in Fig. 127(*a*).

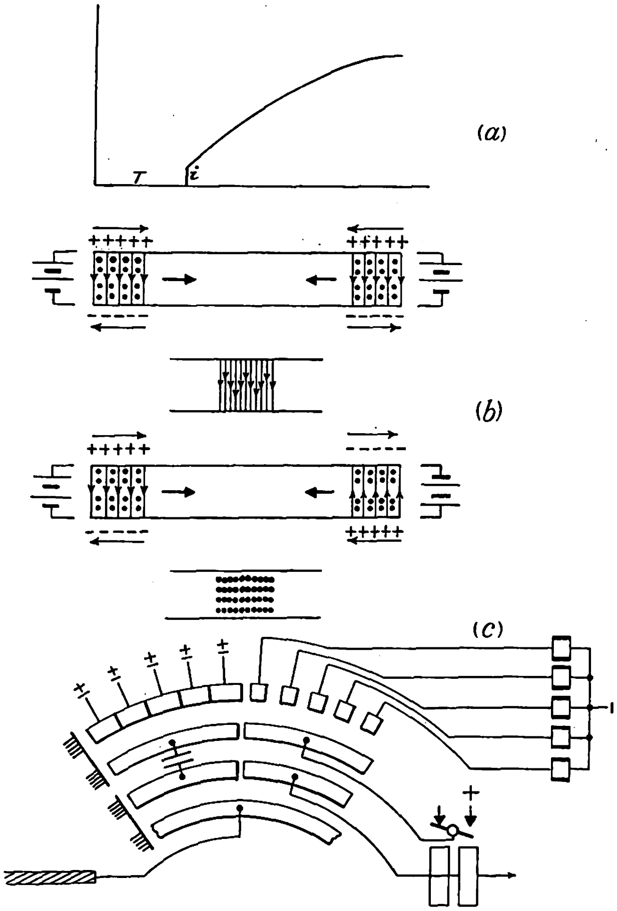

FIG. 127.—Two-way working on loaded conductors.

If wave pulses are sent from both ends simultaneously the electromagnetic pulses meet somewhere in the cable and two cases arise, as shown in Fig. 127(*b*). At coalescence either a doubled electric field or a doubled magnetic field is produced, and this breaks up into two pure waves proceeding to the two terminals of the cable. Thus it is possible to send pulses simultaneously from both ends of the cable and they will pass each other *en route* without interference. Based on these principles the Western Electric Co. have designed a method of 2-way working without the duplex balance in which the usual propagation contacts are not required.

In Fig. 127 the arrangement is shown in which the speed of the distributors is such that the time occupied by the brush arm in passing over one set of 5 segments is equal to the propagation time. The distributors merely switch over from sending to receiving simultaneously and the transmission and reception of one letter requires a time equal to $2T$. T may have varying values and this can be met either by alteration of distributor speeds or by using lengthening networks, or both. It is obviously possible for T to be great enough for more than one 2-way channel to be provided. Figs. 128(*a*) and (*b*) constitute a comparison of two cables, one, (*a*) loaded, the other (*b*) unloaded, in which the times of propagation are assumed equal. In the latter case it will be seen that "propagation contacts" representing a time $2T$ are required to secure both-way operation and the capacity for traffic is reduced by one-half.

Distortion Correction on Long Cables.—The voltage received on a long submarine cable at the ordinary signalling frequency is of the order of 2 to 5 mV. The power available is of the order of 2×10^{-8} watt, and no recorder is known which will operate on such power except at extremely low speeds. Magnifiers of the Cox, Heurtley and electrolytic tape types are well known, but their power output is so small that they can only operate a siphon recorder or an extremely sensitive moving-coil relay. Step-up arrangements may, of course, be employed by which a robust relay is finally operated and a considerable power output obtained. The maximum speed of operation of such devices is about 15 cycles per second.

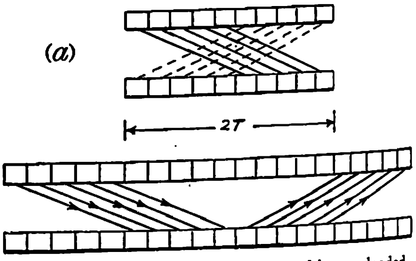

FIG. 128.—Comparison of 2-way working on loaded and unloaded conductors.

The vacuum-tube amplifier contains no delicate parts and maintains its adjustment indefinitely. It has no distorting effects on the signals and it permits distortion-correcting circuits to be readily applied.

The principle on which the vacuum-tube amplifier employed on submarine cables rests is that of producing the various derivatives of the arrival curve, amplifying them and superposing them on the primitive curve. This is already done approximately by the well-known reading condenser which gives a resultant current in the receiver approximately equal to the primitive and its first derivative. The vacuum-tube amplifier allows this process to be carried very much farther.

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* British Patent No. 228211.

The principal work on this subject has been done by Carson, Mathes, K. W. Wagner and others.

Austin M. Curtis lays down the requirements of such an amplifier to be as follows:—It must take an input signal having components as low as 0·5 mV and as high as 10 volts in amplitude and correct the distortion by amplifying the weaker components much more than the stronger, at the same time making any necessary phase corrections. It must operate satisfactorily with signals having weaker components as strong as 100 mV. An output of about 15 mA at 15 volts should be available, adjustable by small steps. It must be capable of handling currents containing frequencies between a small fraction of a cycle and about 180 cycles, the particular part of this band of frequencies which is to be utilized depending on the cable and the speed at which it is operated.

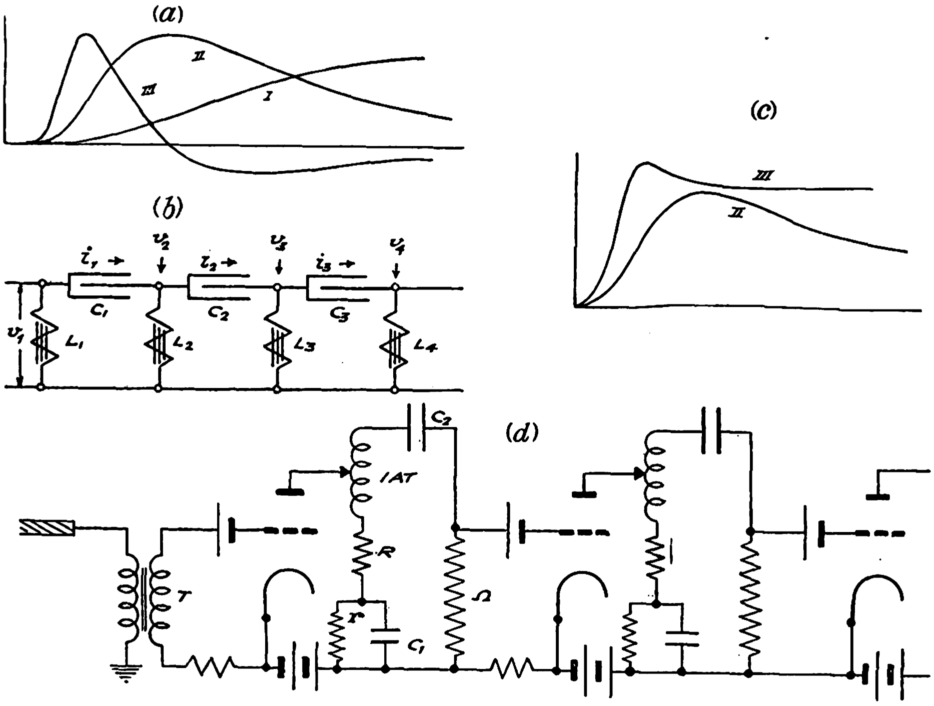

FIG. 129.—Valve amplifier with means for correcting distortion.

The amplification should increase to a maximum at about 1·5 times the signalling frequency, falling to zero at about twice this frequency. This eliminates the higher frequencies and results in suppressing the interfering currents lying above the band of frequencies required to form the signal.

An amplifier designed on these lines permits speeds up to 90 cycles per second, which equals, in cable code, 2 800 letters per minute. It is not entirely suitable for multiplex printing telegraph, as the longer pulses occurring in the 5-unit code necessitate the addition of apparatus to prevent " zero wander."

The conditions to be met in an amplifier of this type will be understood by consideration of the curves in Fig. 129(*a*). Curve 1 represents the arrival current at the receiving end of an ocean cable. Due to its low rate of building-up, rapid signalling is impossible. If a current of this form flows through an inductance, the voltage developed in this will be $L\,.\,di/dt$ as shown in curve II, Fig. 129(*a*), which represents to some scale the time rate of change of the arrival curve. If the current according to curve II is caused to flow through a second inductance, then the voltage across this will be $L\,.\,d^2i/dt^2$ or proportional to the second derivative (III) of the arrival curve. Proceeding in this way the third, fourth and higher derivatives may be obtained.

The amplitude of the derivatives is, of course, much less than that shown, the ordinates having been increased for convenience. It will be seen that successive derivates have a progressively sharper rise which is the required property for a received signal, but on the other hand have no tail, which is disadvantageous, as the signal is not sufficiently sustained. To get both features, viz. sharp rise and sustained amplitude or tail, the network must be arranged to combine all the derivatives in a single circuit.

Successive differentiation can be carried out by a network of shunt and series impedance, and one example is shown in Fig. 129(*b*). The voltage across inductance L_1 is $v_1 = L\,.\,di/dt$, where i is the arriving current. This voltage applied to condenser C_1 produces a current $i_1 = C_1\,.\,dv_1/dt = C_1\,.\,d^2i/dt^2$. The voltage v_2 across L_2 is thus $L\,.\,d^3i/dt^3$ and the current in $C_2 = i_2 = L\,.\,d^4i/dt^4$, and so on. With n meshes, the network will yield the nth derivative. If series resistances " r " are applied to the shunt and shunt resistances R to the series impedances, differentiation proceeds as before but all the derivates are then combined and appear as components in the output wave. Fig. 129 (*d*) shows a combined amplifier and distortion correction network due to Carson. The cable is coupled to the receiving network by a transformer T. The effect of the transformer is to deliver to the amplifier circuit a current approximating the first derivative of the arrival current. This is amplified by the first valve and delivered to the primary of an intermediate auto-transformer IAT. The secondary output from IAT will be proportional to the second derivative, but the resistance R maintains the first derivative. The condenser C_1, having the voltage dv_1/dt impressed on it, passes the current i which is approximately the arrival curve, the condenser exercising an integrating effect. Thus the arrival curve and its first and second derivatives appear at the output of the first-stage amplifier, which is coupled to the second by the large capacity C_2 and high resistance Ω.

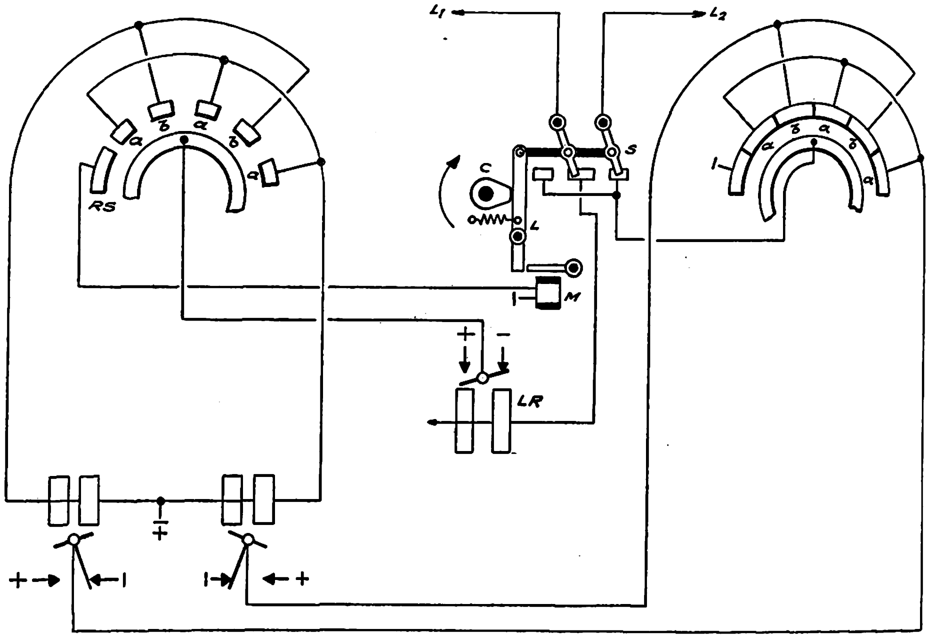

FIG. 130.—Channel reversal method.

Curve II [Fig. 129(*c*)] represents the type of signal obtained with two stages, and curve III that with three stages of amplification and distortion correction.

Channel Reversing.—On a long circuit working through regenerative repeaters in which both-way working does not depend upon the duplex balance, it is sometimes desirable to reverse the direction of operation of one or more channels to accommodate the traffic, which may be heavier in the direction BA than in the direction AB. Usually such both-way circuits are worked two channels AB and two channels BA (in the case of a quadruple), and the reversal of one channel will give a traffic capacity of 1·5:1 as against 1:1. Fig. 130 represents an arrangement which has been employed by the French Administration for a number of years. The diagram is drawn for a repeater station, but either line L_1 or L_2 may be considered as a terminal.

S is a switch which, in the position shown, connects up L_1 to line relay LR, so that signals are repeated, on the sector shown, from L_1 to L_2. The switch is controlled by a lever L controlled by a cam C on the distributor shaft, and a magnet M. If magnet M is operated when the low side of cam C is presented to L, the upper end of L moves to the left under the action of a coiled spring and reverses the position of switch S. Normally this operation is prevented by the fact that, in the de-energized condition of M, its armature abuts against the lower end of L and prevents its movement.

If now station B at the end of L_2 requires an additional channel, the operator at A applies a positive pulse by means of a switch to a special segment preceding the 5 transmitting segments of the sector to be reversed. This pulse is received at the repeater station by line relay LR and a local current sent via segment RS to magnet M, which reverses switch S in the manner previously described. The control of this sector has now passed to B and the normal condition can only again be realized by a special switching pulse from this station.

The necessity for direction control of the type just described is necessitated where long loaded ocean cables furnish several channels on the principle of division of line time.

It is extremely difficult to obtain a working duplex balance at high speeds on such cables, and they are at present operated in one direction for a predetermined period of time and then switched over by automatically operated direction-control apparatus at each terminal station. The direction of operation is governed by switches at each station.

Automatic Direction Control.—Fig. 131 illustrates the principles on which automatic direction control is applied to the 1926 North Atlantic loaded cable. Motor M_1 drives, through gearing, the brush arms over the various faces of the distributors. By means of step-down gears it also rotates at different rates a series of cams C_a, C_b and C_c. After the lapse of a certain time the closure of the contact springs of each cam will coincide, and when this coincidence takes place a circuit is completed for motor M_2 via the springs of C_c and C_b. Motor M_2 tends to drive through a friction clutch FC and second series of cams C_1 to C_4, but these are restrained by electromagnetic escapement E. Shortly afterwards the magnet of E receives a stepping pulse via the three control cams of the first group, and the second group of cams are stepped forward. When the shaft carrying cams C_1 to C_4 is stepped-off normal, the springs of cam C_4 establish a circuit for the magnet of E via the fifth distributor face in the lower part of the diagram. The shaft controlled by the escapement is now intermittently stepped on automatically until the group of cams it controls have made half a revolution. 120 teeth are provided on the escapement wheel and when it has made 60 steps the position of cams C_1 to C_4 is such that their springs are reversed and the system changes over from receiving to transmitting or vice versa. The change-over takes 6 seconds to effect, once the necessary conditions are set up, but the frequency of change-over is determined by the gears and cams controlled by motor M_1 and can of course be set for any desired period. The feature of this arrangement is that the direction control is automatic and starts simultaneously at both terminals.

The correction devices have to be modified, one to step back the brushes on correction and the other to step them forward. The reason for this lies in the fact that one distributor runs slightly faster than the other and is corrected by stepping the brushes back. When the direction of transmission is changed, the receiving station, which is also the corrected station, has now to transmit and the other distributor, which is now the corrected station, runs at a slightly lower speed and therefore must be stepped forward on correction. If this were not done the speeds would have to be adjusted each time a change of direction took place.

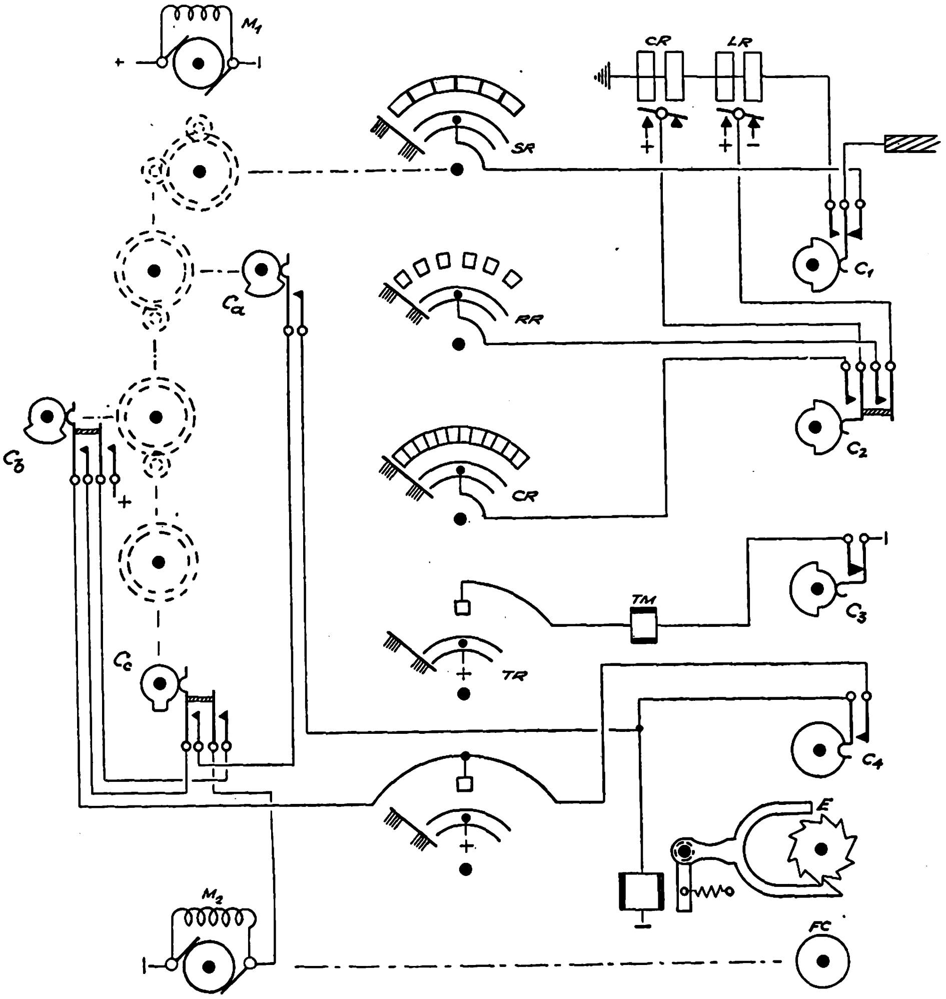

FIG. 131.—Automatic direction control on Atlantic cable.

Section (7). START-STOP MACHINE TELEGRAPH OPERATION.

General.—Start-stop operation of machine telegraphs is invariably of the single-channel type, although this is not a fundamental condition. Its characteristic feature is that all rotary mechanisms, distributors, printers, or a battery of cams determining printer operation, complete one cycle for each letter transmitted.

The synchronism required is relatively coarse and easily attained and maintained. Duplex operation is, of course, possible, and, on circuits where the traffic is not too heavy, transmission and reception can proceed simultaneously with one operator, as reception only amounts to gumming a tape on a message blank. This "one man" system of duplex operation is becoming general. Speeds of 40 to 65 words per minute are possible, and, where line plant between towns is adequate, start-stop channels are more economical than multiplex since they will carry more traffic with less staff. It can be superposed on telephone pairs, interlinked with main-line multiplex systems, and lends itself admirably to any scheme of exchange switching. There is no limitation to the length of line over which it may be operated, and start-stop regenerative repeaters can be applied wherever necessary. For very long links, however, multiplex operation will be retained—the start-stop system finding its sphere of application to inland traffic—while the multiplex will cater for costly international circuits. The early start-stop systems may be described as all-electric, but these are being almost completely superseded by those systems in which the mechanical distributor of Baudot is employed.

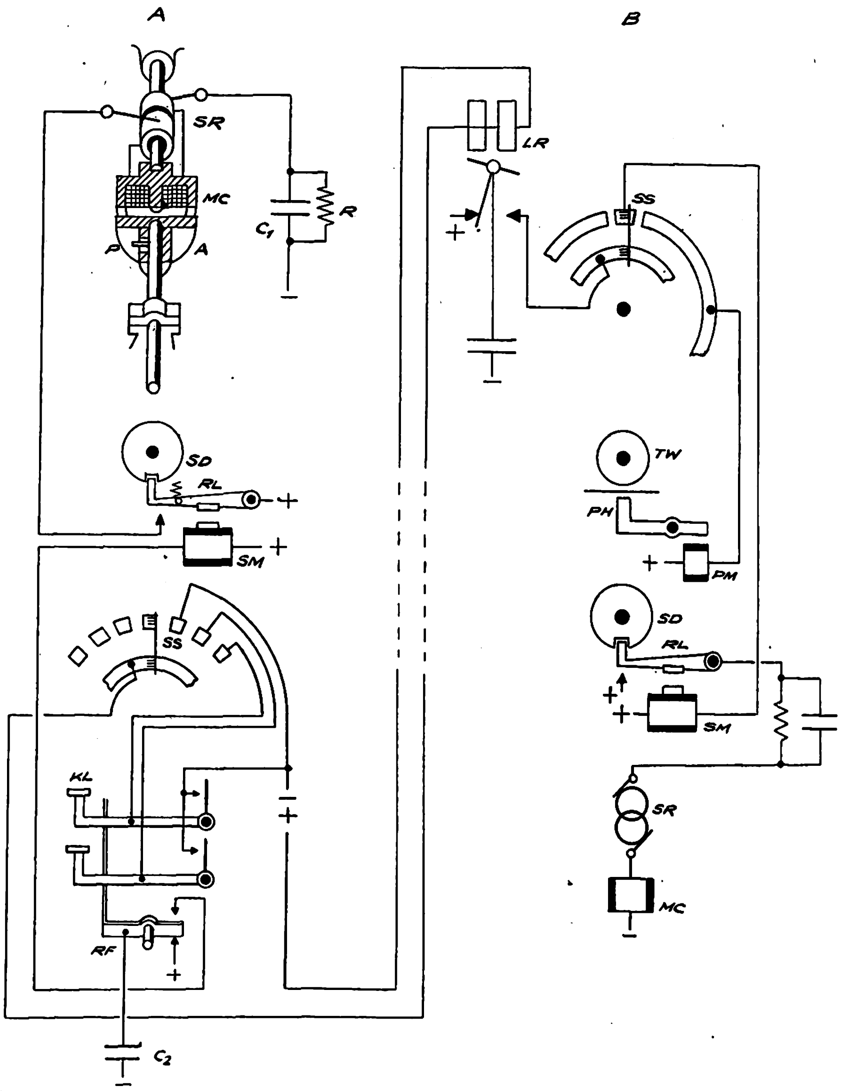

FIG. 132.—Siemens and Halske's start-stop Hughes system.

All-electric Systems.—Two examples of the all-electric type are dealt with. Fig. 132, an arrangement due to Siemens and Halske, may be described as a start-stop Hughes system, in which, however, only one letter is sent per revolution of the apparatus. At station A the sending arrangements are disclosed. A continuously rotating motor (not shown) drives a shaft carrying the exciting coil of a magnetic clutch MC. This portion of the clutch is rigid on the shaft and is fed by slip-rings SR on which brushes rest. In line with the first shaft is a second one which carries an iron armature A rotating with this shaft but capable of sliding along it within certain limits determined by a slot and pin P. The second shaft is normally restrained from rotation by the stop disc SD in a slot of which the pointed end of a release lever RL enters. RL can be withdrawn by a start magnet SM. The second shaft, when released, makes one revolution sweeping over a start segment SS and a number of segments, one for each character. A number of key levers KL are provided, each adapted to apply the negative pole of a battery to its corresponding segment, the positive pole being connected to earth or a second line. When any key lever is operated it rocks a frame RF which completes the circuit for the start magnet SM. The operation is as follows:—

When KL is operated it causes the normally-charged condenser C_2 to discharge via the upper contact of RF through SM. SM operates and frees the secondary shaft and closes a circuit from positive via its armature and lower contact slip-rings SR and clutch magnet winding to negative through a condenser C_1 shunted by a resistance R. C_1 allows of a powerful initial current in the coils of MC, while the resistance R cuts this down to a sufficient strength to exert a good holding effect. The armature A on the second is pulled towards the other half of the magnetic clutch and the two shafts are coupled together. This condition is maintained for a whole revolution as the release lever RL is held on its circuit by the stop disc SD. At the end of the revolution, RL snaps up into the slot in SD, disconnecting the clutch circuit and positively stopping the second shaft.

When the distributor brush-arm moves from normal it first sends out a start pulse from negative, start segment SS, solid ring line L_2, line relay LR at station B, line L_1 to positive. As it continues rotating, the brush arm encounters the segment corresponding to the operated key lever KL and another pulse is sent over the line. Each letter thus consists of a start pulse and a letter-signal pulse, and the various letters are differentiated from one another by the interval between start and signal pulses.

At the receiving end, station B, the start pulse moves line relay on to its operating contact and a normally-charged condenser is discharged via the relay tongue segment SS of the distributor through the windings of start magnet SM. The distributor shaft carries a type wheel TW against which a paper tape is forced by a printing hammer PH operated by a printing magnet PM. Since both distributors are in phase and as the type on the type face of TW occupies the same positions assigned to the letter-signal segments, it follows that the letter printed will correspond to the key lever operated at station A.

This system operates extremely well and at speeds higher than either the Hughes or the ordinary stock ticker. Its disadvantage is that it cannot be interlinked with a circuit using 5-unit code, unless costly transposing arrangements are provided.

Tape Control of Transmission.—Tape transmission is applicable to start-stop operation and is specially advantageous in the case of news distribution from a central news agency to a number of subscribers. In this case it is usual to run the sending distributor constantly while arranging for it to send out a start pulse once per revolution to maintain the necessary degree of synchronism at the receiving station or stations.

Fig. 133 shows an arrangement of this character employed by the Morkrum Co.—now the Teletype Corporation—of America. T is a tape-controlled transmitter of the type in which the tape is stepped forward by a pawl-and-ratchet mechanism letter by letter by a stepping magnet TM. The stepping of the transmitter is accomplished by a cam TC which, at the right moment and once per revolution, closes the circuit from an earthed battery to the magnet TM. This circuit passes differentially through the two windings of a relay SR via its armature back contact and via a contact of a tape control rod TCR. Relay SR does not operate under these conditions and TM is regularly stepped on once per revolution. The tape is fed directly from a per-

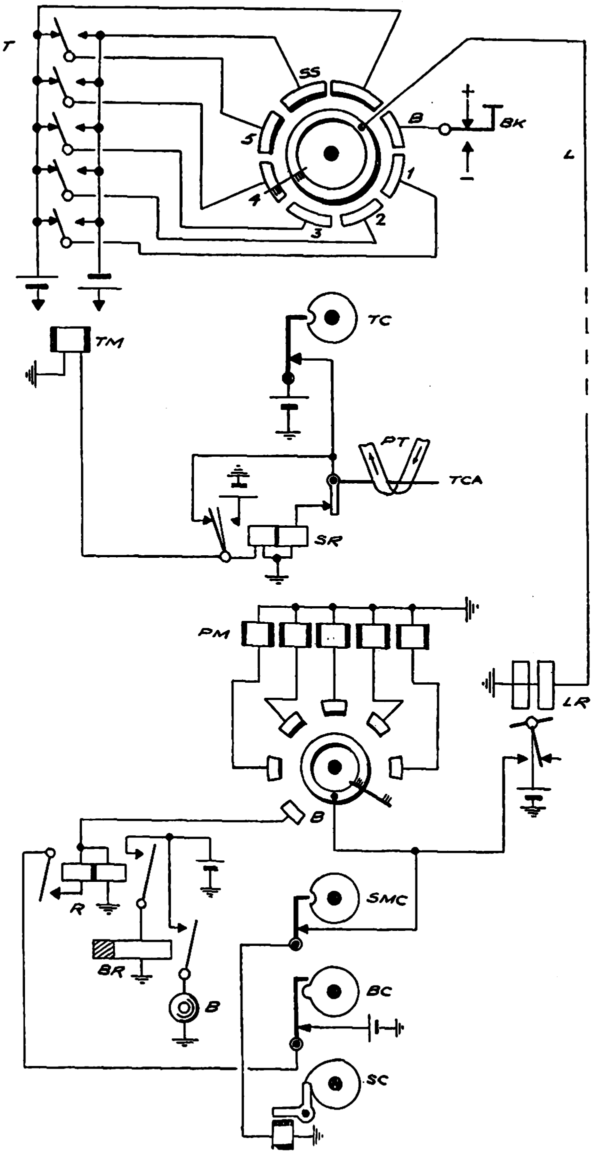

FIG. 133.—Automatic start-stop system for 5-unit code.

forator to the transmitter and forms a loop of varying length. If perforation stops or if the rate of perforation is lower than that of transmission, the tape loop shortens and ultimately lifts the long arm of TCR, breaking the circuit of one winding of relay SR. On the next stepping pulse from TC, only one winding of SR is effective and SR operates, locking itself up and permanently energizing TM. TM withdraws the transmitter peckers from the tape and prepares the feeding action for the next letter, but since feeding takes place when TM is de-energized it does not occur. The transmitter levers all go to spacing and no letter signals are sent out.

When the loop of tape lengthens again, TCR falls, connects up the opposing winding of SR and on the next stepping pulse this relay is released and the transmitter functions regularly. This automatic control of a tape-operated transmitter so that it stops when the tape is not supplied regularly and stops between the last letter sent and the next about to be sent, is due to Mr. Donald Murray.

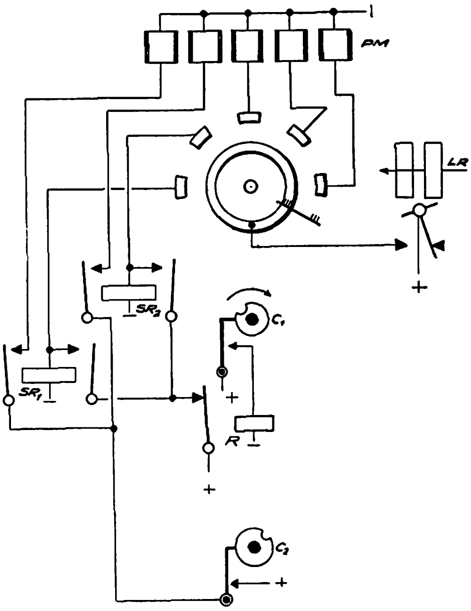

FIG. 134.—Receiving overlap arrangement for start-stop system.

Automatic Transmitter Control.—The stop-start control of the receiving distributor by the continuously-running sending distributor is effected as follows:—As the brush arm revolves at the sending station it sends out to line a negative pulse from start segment SS. This operates the distant line relay LR, and a local circuit is closed via the start magnet cam SMC and its springs to the start magnet SM. SM energizes and releases a shaft driven by a yielding clutch (not shown), and the distributor brushes make one revolution. At the sending end the negative starting pulse is succeeded by a positive spacing pulse, and positive pulse from segment B (the function of which is explained later), and then the 5 transmitting segments which will have positive (spacing) or negative (marking) battery applied to them in accordance with the setting of the transmitter levers of T. These letter signals are received at the distant end and distributed to the 5 printer magnets PM from the line relay via the receiving distributor.

Bell Signalling.—Arrangements are provided by which a code of bell signals can be sent out without interfering with the passage of traffic. This is the object of the segments marked B on each distributor. When the bell key BK is operated at the sending end, it applies negative battery to segment B and this operates signal relay R at the receiving station. R locks up from an earthed battery via the springs of bell cam BC. R operates in turn a slow-to-release relay BR which closes a local circuit for the single-stroke bell B.

When the brush arm comes round again, and before it reaches segment B, the locking circuit of R is broken at cam BC. BR holds up, and, if the distant bell key is still operated, relay R is again energized and maintains BR in the operated condition. Thus only one stroke of the bell is effected for one depression of the distant bell key, regardless of the length of time the key is operated, and there is no need for timing either the moment of operation of BK or the length of its operation.

Overlap at Receiving End.—There are two functions in the start-stop cycle where as much time as possible is required without gaining this at the expense of line time. One of these is at the printer and involves the printing and paper-feeding operations; the other is at the transmitter and refers to the tape-stepping action of the transmitter magnet and the settlement of the transmitter levers against their contacts after the subsidence of all "bounce."

In both cases the necessary time can be obtained by allowing the latter portion of one cycle corresponding to one letter partially to overlap the first portion of the succeeding cycle. Fig. 134 shows such an arrangement for securing overlap at the printer. The first two signal elements of a letter signal are set up on two storage relays SR_1 and SR_2 via the first two contacts of the distributor. They are both locked up through their right-hand contacts from the back contact of relay R, but the signals stored in them are not immediately transferred to the first and second printing magnets. This transfer is accomplished when the third signal element is received, when cam C_2 closes a circuit from positive through the left-hand contacts of SR_1 and SR_2 through the windings of the first and second printer magnets to negative. The remaining three printer magnets are set directly in the usual way. Shortly afterwards the transfer relay R is operated by cam C_1 and opens the locking circuit for relays SR_1 and SR_2, which return to normal. The time represented by two signal elements is thus added to the ordinary printing time by the use of an overlap period.

Overlap at Transmitting End.—The same principle applied to the transmitter is shown in Fig. 135. The distributor here is continuously rotated and sends out start pulses, one per revolution, to control the distant receiving distributor. The first two transmitter levers are directly connected to the distributor, but the third, fourth and fifth of these levers operate three storing relays SR_1 to SR_3. These lock up through their left-hand contacts in an obvious way, while their right-hand contacts repeat the setting of the last three transmitter levers to the distributor.

When this storage has been effected and the signal elements of the first two transmitter levers have been sent to line, the transmitter magnet TM can be operated by cam TC to feed the tape forward. Transmitter levers 3, 4 and 5 must be rendered inoperative at this stage so that they do not interfere in any way with the previous setting of the storage relays, and they are therefore disconnected by cam DC while the three last signal elements of the previous letter are being transmitted. When a letter signal has been completely transmitted, reset cam RC opens the locking circuit for the three storage relays, which release and are immediately ready to be reset. By this overlap arrangement all transmitter levers are at rest firmly on their contacts before the transmission of a letter signal commences.

main office or be extended to start-stop local circuits. Two relay groups are provided, one (RRG) for receiving signals from the main line destined for the local office, and one sending group (SRG) which receives signals from the local office for transmission over the main line to the distant station.

In addition to these, the equipment at the head office embraces a sending start-stop distributor SSD and a receiving start-stop distributor SRD.

Control is effected as follows:—Once per revolution the local ring of the receiving distributor closes a circuit from positive through start magnet SM_1 of SSD, which is thus kept continuously revolving, and sends out a start pulse to start relay SR controlling over line L_2 the receiving start-stop distributor at the branch office. The latter starts up and in doing so also starts up the sending distributor there, which sends a start pulse over line L_1 (a disconnection), and the release of relay RR closes a circuit for start magnet SM_2 and distributor SRD is started up. Thus the start-stop circuit is kept at correct speed and phase with respect to the main-line distributor.

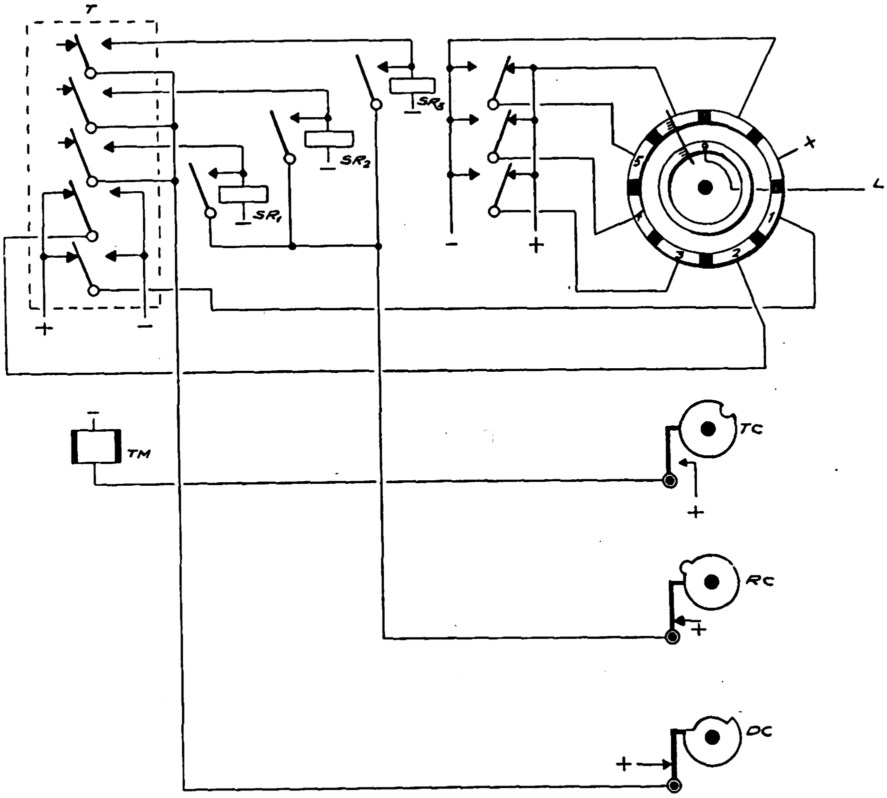

FIG. 135.—Transmitting overlap arrangement for start-stop system.

Interlinking of Start-Stop System with Duplex-Multiplex Circuits.—In Fig. 136 the arrangements at a main office are shown by which a local start-stop circuit may be interlinked over one duplex channel on a multiplex system connected to a main line. The local office is connected to the main office by two lines, one for transmitting and the other for receiving, although, of course, one line could be used by adopting the duplex balance. The local lines are worked on the closed-circuit principle.

The control exercised by the main office on the apparatus at the local office will be more readily understood by assuming that there is no traffic passing from main to local. The equipment at the main office consists of a distributor having a receiving face RDF and a sending face SDF. There are two local rings for control purposes, while other channels (not shown) may terminate at the

The distant transmitter at the branch office is preferably of the tape-controlled type, as, if a keyboard transmitter is employed, this must be normally locked and only unlocked at appropriate times. This, although not an impossible arrangement, is not desirable.

Signals from the branch office pass via SRD to the 5 storage relays SRG, but this does not occur until the main-line sector has been passed over, and the combination set up is not transmitted until the next revolution. Signals from the main line to the branch office are stored in RRG and are retransmitted immediately the sector on RDF has been traversed by the brush arm, and the relay group RRG is reset to normal by cam C after retransmission is completed.

The reciprocal or " flip-flap " control of the stop-start distributor can be dispensed with by increasing the number of relay storage groups, but the most convenient way is to use perforated strip recorders at the main-line station, a perforated tape representing the cheapest form of storage when several letter signals are to be stored.

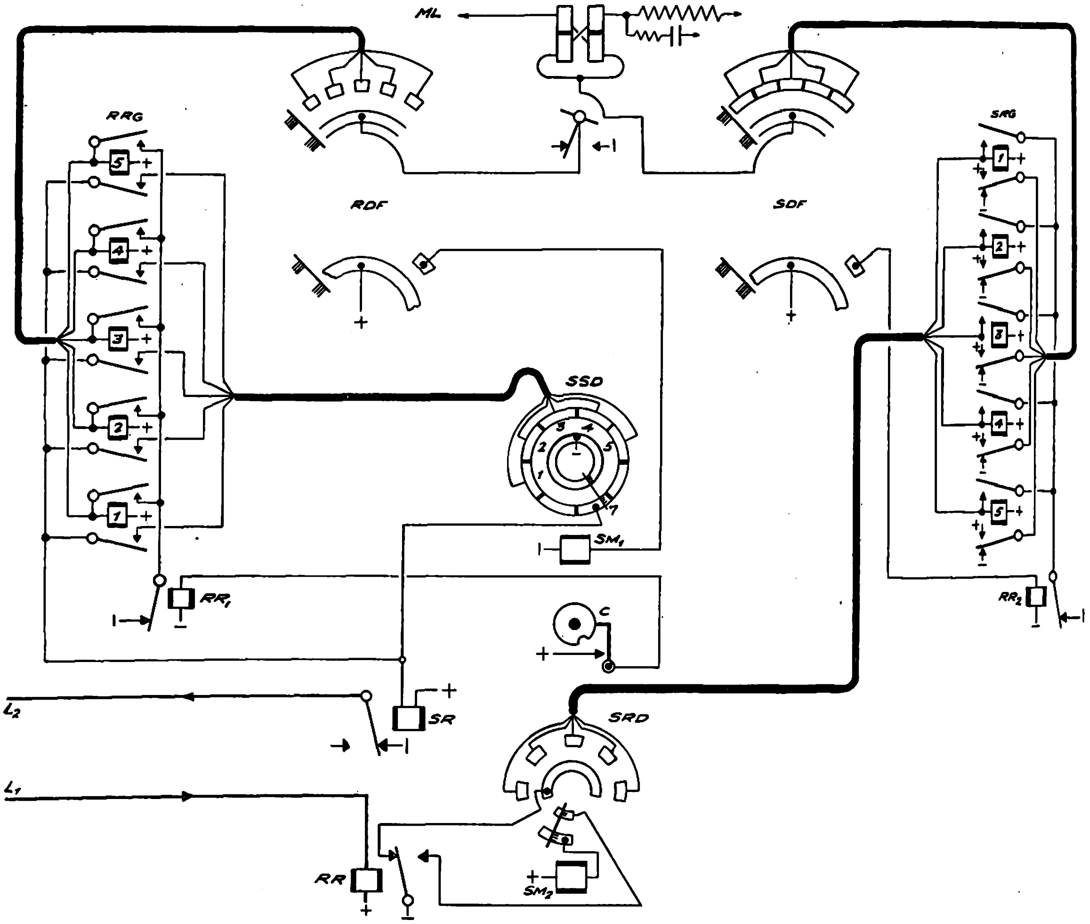

FIG. 136.—Interlinking of start-stop system with high-speed duplex-multiplex system.

Mechanical Distributors.—A comparison of start-stop systems using mechanical distributors involving a single transmitting lever at the sending end and a single magnet in the printer at the receiving end is possible by reference to Fig. 137. The reduction in the number of contacts, circuits, magnets and relays is all in the direction of simplification of maintenance, while the printer operations are all carried out by power drive, electricity only acting as a trigger.

Both the transmitter and receiver have certain common features. In the transmitter the movement of one of a number of levers (the character key lever of the letter to be transmitted) is translated into the current permutations of the letter to be printed at the receiving end. The key lever KL sets a number of combination bars so that they interfere or do not interfere with the movement of a number of levers adapted to oscillate in succession under the control of spiral springs. These levers are arranged to operate in succession on a common bar which oscillates a transmitter lever. Such mechanisms have already been described in Section (2). The start impulse is generated by a sixth lever, which operates invariably when the cam shaft starts into operation, no combination bar being provided to interfere with this. The key lever operates a clutch (not shown) to start the cam shaft and allow it to make one revolution.

At the receiving end the inverse function has to be performed. The same cam-controlled levers are either interfered with or not by a common bar which, in this case, is remotely controlled and therefore operated by a single magnet M. The sixth or start lever does not depend upon the joint action of a cam and the common bar but is released by the action of the bar only, the armature of magnet M. When it operates upon receipt of the start pulse, it trips a mechanism (not shown) which clutches the cam shaft to a power drive for one revolution. Under the interfering action of the common bar A, combination bars are arranged exactly as those of the distant keyboard, a row of slots alined, and one only of a number of selector bars drops into the slots and determines the printing. Bar SB could, of course, control the key lever of a typewriter by intermediate power mechanism, as described in Section (3).

Start-stop mechanism of the type described will represent the type printer of the future until such time as it is replaced, perhaps, by the transmission of a telegram as a picture—not an impossibility.

Section (8). The Future of Machine Telegraphy.

Telegraphy and telephony are nowadays comparable in so far as it may be said of both that they can bridge the distances between any two points on the earth's surface. What the valve amplifier combined with loaded conductors has done for telephony, the regenerative repeater, loaded conductors and the valve have also accomplished for telegraphy.

International telegraphy is remunerative; inland telegraphy, at least in Europe, is in a bad way financially. Inland telegraphy in America is successfully conducted by two privately-owned companies, while telegraphy in Europe is controlled by Government Administrations. The difference in the nature of the control does not, however, account for the degree of success achieved in the one case and the invariable failure in the other. America is a land of long distances, and between two centres with a community of interest the journey by train can easily occupy at least 24 hours. This geographical feature is, naturally, a stimulant to the use of the telegraph, and question, answer, or instruction can readily be handled by telegram where a telephone call would be a needless extravagance.

Long distances operate in favour of the telegraph and against the telephone, and the length and importance of the communication determines which form shall be used. The net effect is that while telephony in America is in a flourishing condition, economic factors enable the telegraph not only to survive but to attain a healthy, strong position alongside its rival.

International telegraphy will always be prosperous because it has a natural aid in the fact that as we move eastward or westward there is a difference of time of 1 hour for each 15 degrees of longitude—a difference which has to be *added* for eastward and *subtracted* for westward progression. This difference of time has no influence on telegraphy but operates against world-wide telephony, due to the fact that in the latter case the overlap of the working day becomes shorter and shorter eastward or westward of Greenwich.

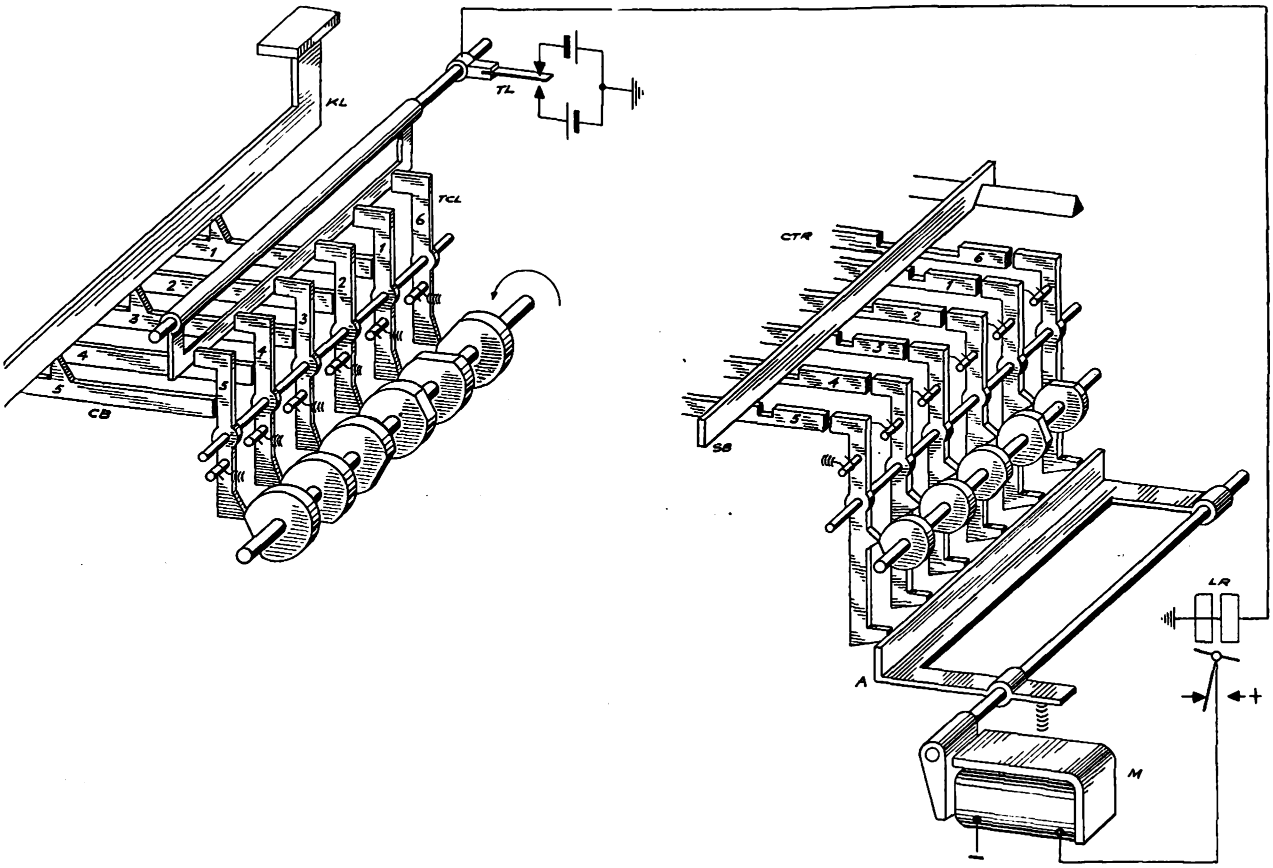

Fig. 137.—Transmitting and receiving arrangements of start-stop system with mechanical distributors.

Neglecting variations due to Summer Time Regulations, the time chart of Fig. 138 is drawn for a total difference of 5 hours westward and 12 hours eastward. The vertical divisions are spaced 15 degrees apart, representing 1 hour of time. The horizontal lines, a distance apart of 1 hour, divide the ordinates into 24 hours or 1 day. The sloping chain-dotted lines are spaced apart by an amount representing 8 hours and cut the Greenwich longitude at 9.0 a.m. and 5.0 p.m., considered to represent that part of the working day at which telegraphing would be effected and telephony normally carried out.

It will be seen that it is possible to telephone westwards (assuming normal business hours) only between 2 and 5 p.m. Talking eastwards must proceed in the morning and, commencing at 9.0 a.m., cannot be carried out further east than China. These differences of time constitute the only factor operating against world-wide telephony. Their sole effect on telegraphy is to cause a change in the direction of traffic, which flows eastward and westward alternately except for short periods where the working day overlaps. So far as Europe is concerned, difference of time has little influence on either inland or international telegraphy.

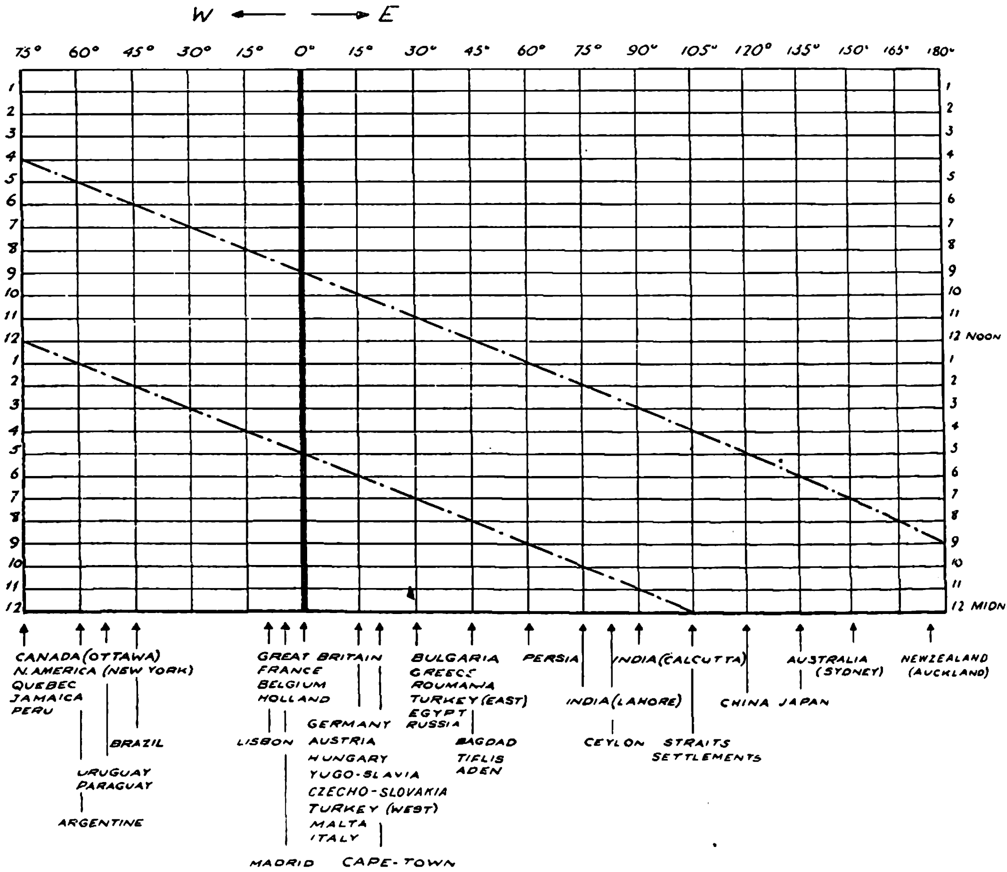

FIG. 138.—Chart indicating time simultaneously prevailing at different world centres.

From the foregoing it is clear that telegraphy (either radio or wired) will survive, and the only problem which has to be solved is the very serious one of making inland telegraphs pay in countries where distances are comparatively short. It has been clearly established in this country that of all the factors contributing to the cost of a telegram—supervision, line plant, office provision and apparatus, engineering and operating cost—the last-named is higher than all the rest put together and that the telegraphs cannot be made to pay until this cost is very considerably lowered.

The fact that joint use may be made of the telephone network for both telegraphy and telephony by methods set out in Section (5) of this paper, and that in this way many more telegraph channels are available than would be needed to carry a much greater traffic than is at present available, suggests one change which might be made.

Securing several channels on one line by the principle of division of line time is costly from a staff point of view. The synchronism which has to be observed requires the careful adjustment of apparatus and constant supervision to secure stable working.

It is only in the case of long, costly links of the transoceanic or transcontinental types that the multiplex method of operation will be justified.

The new factors which have arisen to make the utility of the multiplex for inland working of doubtful value are (1) the perfection of the single-channel start-stop machine telegraph, and (2) the co-ordination of line plant. But even if all the inland multiplex apparatus were scrapped to-morrow and equivalent channels obtained by single-channel start-stop apparatus, the problem of making the telegraphs pay would still persist. The principal factor in the operating cost is the retransmission necessitated by the fact that the originating office and the destined office between which a telegram has to pass are, in a great number of cases, not in direct communication with each other, and the message may have to pass from A to B, B to C and C to D instead of A to D directly. If we allow only 1 minute for such a message, there are 6 operators involved, 3 transmitting and 3 receiving, and 0·1 man-hour is absorbed, whereas if the transmission were direct between A and D the figure would be one-third of this. In this rough calculation no allowance has been made for the time required to collect and distribute the message at the intermediate offices B and C.

The problem to be solved is the abolition of retransmission. There is only one way—it may be called the last phase of machine telegraphy—in which this can be accomplished, and that is by the adoption of machine switching. A theoretical "trunking scheme" for an inland machine telegraph system, in which intercommunication is effected by switching processes well tried out in automatic telephony, is set out in Fig. 139. A main switching centre is shown at M, which would be located at or near to the centre of the network. Lines extend from M to 4 sub-switching centres in the centres of the northern, eastern, western and southern areas, and lines would radiate from these to other smaller centres which would either represent terminal offices or would be subordinate switching centres to the regional sub-centres. A free, through route from an office in any region to one in the same or any other region could be set up by dialling in the manner standard to automatic telephone systems, and the route set up could be held during signalling, without premature release of the switches, by means which have been worked out, while the release condition could be effected by known methods.

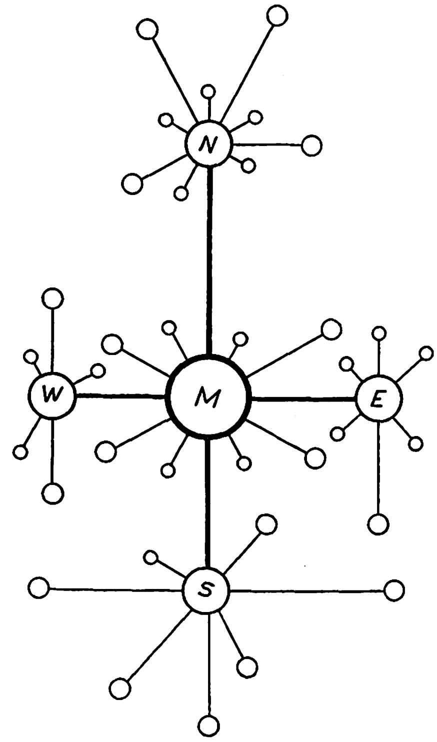

FIG. 139.—Theoretical telegraph network arranged for automatic through-switching.

Where the number of outlets from a switching centre is insufficient to accommodate a rush of traffic at any time, the messages may be stored on perforator-transmitters and stepped off in turn as outlets become available.

The system becomes feasible by reason of the number of telegraph channels rendered available through the combined use of the telephone line plant for both telephony and telegraphy. Such a system can be developed only by the co-operation of the administration, as data are necessary in order to determine the numbering scheme which will route the traffic in the best way. Moreover, such a scheme would certainly have to be applied gradually over a number of years, but yet must be designed from the start to be satisfactory when completed. The telegraph apparatus should be exclusively of the start-stop type.

Such a system as outlined would seem to have the following advantages:—

Considerable saving of operating, collecting and distributing staff.

Speeding-up of the telegraph service by saving the delay arising at retransmitting points.

Making the teletype exchange idea feasible.

The saving of operating staff is a net gain, as they would be replaced by a maintenance staff at the switching centres. The speeding-up of the service would certainly have a stimulating influence on telegraph users, and the larger revenue, with the assumed lower operating costs, would perhaps make it possible to reduce charges.

The regenerative repeater is one example of the reduction of operating costs by substitution of automatic processes for manual, it being well known that the cable companies have been able to make substantial reductions in the staffing at their foreign stations, and in many of these the present staff is a maintenance staff only.

With such a system of automatic through-switching provided on a nation-wide basis it might become practicable, if thought desirable, to institute a zone system of tariffs for telegraph traffic.

Fixed time rates for through-connections of $\frac{1}{2}$ to 1 hour's duration might become possible, the users at the two ends of the connection having their own teletype apparatus and thus relieving the administration of all operating work. Certain exchanges, such as those of the coal, cotton and metal trades could at fixed times in the day simultaneously advise their subscribers of market changes. They would all be provided with teletypes leased or bought outright from the administration, and the extra demand for these would enable the manufacturers to work on the basis of thousands, instead of hundreds as at present.

It is perhaps too much to prophesy the dawn of a Golden Age for telegraphy, but by the adoption of methods outlined above the amount of operative work by the administration would be reduced, firstly by the abolition of retransmission and secondly by the throwing of some operative work on the user himself. If this occurred the telegraph would more closely approach the conditions under which the telephone operates to-day. There are difficulties in the way, but it is the function and the privilege of the engineer to surmount these.

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DISCUSSION BEFORE THE INSTITUTION, 27TH MARCH, 1930.

Mr. T. E. Herbert: It is noteworthy that the period of adversity through which telegraphs have been passing has coincided with an amount of progress unparalleled during any corresponding period of the history of the art. Precision methods of speed and phase control are essential on transoceanic cables, but I think that these methods would result in greater stability of working if applied to inland circuits. From this point of view, I consider that the future line of progress will be in the direction of gang control of all multiplex circuits. In general, it is noteworthy that many of the methods described involve interference with the normal rate of vibration of the reed. This plan was given an extensive trial by the Post Office on inland Baudot circuits, but it was found to be less stable than the epicyclic-gear correction. There was some evidence of "jar" when the corrected magnet was energized. I therefore suggest that the correct method of attacking the problem is to decide precisely what amount of deviation from absolute accuracy is permissible without adverse interference with the signals. Having decided upon this value, the correction applied should be purely mechanical—and should not interfere with the normal vibration rate of the resonant system. The Mendonca governor, as described in the paper, is in use by the Post Office and is giving fairly satisfactory results. It has the advantage that the speed control may be varied at the table, whereas in the case of ordinary reed-driven distributors the adjustment has to be made some distance away, as the reed is usually fixed on the wall of the building in order to avoid vibration. On the other hand there is some indication that any variation (due to minor causes) in the load on the driven side of the Mendonca governor produces a definite alteration in speed. The suggestion of inter-office control of all multiplex circuits is particularly attractive, and I think that anything which tends in the direction of greater stability is very valuable, since the crux of the economic problem of telegraphs lies solely in economy of human effort. Considerable capital expenditure is, therefore, amply justified where labour savings can be effected. It should be realized that if the whole of the plant costs were eliminated the problem of the telegraphs would still remain. So far as I am aware, the first example of correction from the signals received is represented by the Hughes apparatus, and the devices employed by Creed are applications of the same basic principle. The various methods of obtaining phase correction of a distributor from the signals themselves are a natural development likely to be universally adopted. Gang driving of all start-stop machines in a large office has many advantages. By the use of synchronous motors all speed adjustments would be rendered unnecessary, and it would be possible to devise some form of concentrator for less busy circuits, thus reducing the total amount of apparatus which it would be necessary to provide. If the public supply of alternating current were accurate enough in periodicity to drive clocks through the medium of a synchronous motor, this problem would clearly be solved in the simplest and most economical manner. The second section of the paper, dealing with transmitters, is particularly interesting in that it brings out the fact that the basic principle of Kleinschmidt, Morkrum and Creed keyboard transmitters was definitely anticipated by Baudot. The elimination of chattering on transmitting contacts is a valuable modern improvement, and in this connection it may be stated that the latest form of Post Office standard relay with cores annealed in an inert gas, and with spring contacts, constitutes a definite improvement on the older form. The suggestion made by the author, that the typewriter form of keyboard should be modified, greatly appeals to me. The original motor-car bodies were designed on the lines of the horse-drawn carriage, and it is only necessary to compare the four-wheeler with a modern motor-car in order to realize how greatly the difference in the method of propulsion has altered the design. In the same way there is a fundamental difference between a keyboard transmitter and a typewriter, in the fact that the energy for printing the character has to be provided by the typist, whereas the keyboard transmitter key has merely to direct certain operations. I hope that the author will design a keyboard on the lines which he has suggested. With regard to the receiving mechanism, it is gratifying to be able to state that a British machine has been adopted by the Post Office, and is giving admirable results in practice. Some essential parts of the mechanism common to all successful machines were invented by Baudot. The Grünenwald plan [section (4)] is interesting but unlikely to be of service in this country, since the 5-key method of sending may be regarded as obsolescent owing to the fact that its speed is definitely less than that of a tape-controlled transmitter. The regenerative repeater, which we owe to the genius of Baudot, constitutes a notable advance, and a combination of the regenerative repeater with the Gulstad relay enables large economies in staff to be effected. It increases the working speed and stability of the circuits whilst giving remarkable flexibility in the extension of the various channels. Multiplex and voice-frequency systems consist merely in methods of economizing line plant, and it is only over very long distances that the cost and complexity of such methods can be justified. It has been demonstrated that an infra-acoustic circuit can be added to any telephone circuit without appreciable reduction in the telephone speaking efficiency. This means that a comparatively indefinite number of telegraph channels are available and the obvious development of the future seems to lie with these circuits, to which will be added some method of automatic switching so that retransmission of messages is entirely avoided. It is only when the source of supply of such channels has been exhausted that methods of multiplex operation of circuits can have any field for application. This excludes the case of the transoceanic cables, where the annual charges on the cable form the bulk of the cost incurred in the transmission of a message. The Creed quadruplex and the author's Morse multiplex are interesting examples of what can be done by the mechanical connection of two transmitters, but it is difficult to see that this method can at present be utilized in practice. The method of eliminating the "jar" on duplex circuits should go a long way towards solving the problem of duplexing loaded cables, and I should be glad to learn whether experiments are now in progress to exploit this suggestion. The interlinking of start-stop systems with duplex multiplex circuits is interesting, and may conceivably have considerable application when the possibilities of infra-acoustic circuits have been fully exploited. I am driven to the conclusion that the future of inland telegraphy will be bound up with the question of the transmission of communications direct from subscriber's office to subscriber's office. It may be that this development will take place by a comparatively gradual process, and that we shall first have a large number of leased infra-acoustic channels connecting firms having large amounts of business to transact together. The advantages of rapidity having been appreciated, the next stage in the development would be an automatic form of switching from any subscriber to any other subscriber furnished with suitable apparatus. The dawn of this era depends not on engineering advances, but solely on what is generally called "salesmanship" in the commercial world. In view of the difficulties which the manufacturers of calculating machines must have had to overcome in order to persuade the ordinary conservative business man to adopt their methods, it is clear how difficult a problem will be involved in making that same business man realize the advantages which will result from greater rapidity in his work. I should like to emphasize the point that the advantage of the direct telegraphy method over the telephone call lies in the fact that the written telegraph message can be dealt with in a routine manner in the office of the recipient, whereas a telephone call is frequently made either to the wrong department or to a person to whom the detailed knowledge necessary for an instant reply is not available. I think that the telephone should be used where discussion is necessary, and that for a vast volume of business at present conducted through the medium of the post the greater celerity of direct written communication would be of definite economic advantage.

Mr. F. G. Creed: I am glad that the author refers to the difference between the conditions which obtain in this country and those in the United States, and to the reason why the telegraph has a greater vogue over there than here. In favour of the Post Office it must be admitted that conditions which do not exist in America have to be faced in this country. With regard to the Mendonca governor, it seems to me that this is a British invention, as I believe that one of these devices was used on the Evershed and Vignoles megger many years ago. I invented it myself independently, but when about to use it I discovered that it had been anticipated. I think, therefore, that this governor should be given another name. The conflict between the Morse Code and the 5-unit Code is not yet settled, but it has come to be recognized, I think, that for the bulk of inland traffic and for a great deal of international traffic the 5-unit Code is the more generally useful, because it is so adaptable. Morse, however, will still be widely used on account of its remarkable flexibility. A Morse or a Wheatstone apparatus is ready to work as soon as it is placed on the table, and no adjustment of any kind is necessary. This cannot be said of the 5-unit multiplex apparatus, but 5-unit equipment of the start-stop type more closely approaches the Morse system in flexibility and reliability. The 5-unit system has made numerous advances which have made it easier for this system to become successful. There has been great improvement in lines in the principal countries of the world, battery conditions have improved and there has been a still bigger advance in apparatus—especially in relays and apparatus connected with synchronism. Practically perfect synchronism can now be obtained without any difficulty, and there is a choice of half a dozen pieces of apparatus to provide synchronism for the purposes of start-stop. As the author points out, regeneration has made another surprising advance, and a message can now come to London in two jumps from Rio de Janeiro. It comes through by regenerative repeaters across the Andes and up the west coast of South America to New York in one jump, and it reaches New York a fraction of a second after leaving Rio de Janeiro. The next jump is through several repeaters to London, and this takes place with equal rapidity. The present-day achievements of the telegraph are remarkable. When in India two years ago I arranged to have telegrams sent to me from distant places, one from Vladivostock in Siberia, another from Copenhagen and others from London, New York, San Francisco, Buenos Aires, Sydney (Australia) and Hong Kong. I asked that the telegrams should be dispatched to reach me in Bombay at 9.30 on a certain morning. They arrived with an average delay of half an hour, and I do not suppose that any particular care was taken to hurry them along. Unfortunately, however, the telegrams took an hour and a half to get from Bombay to Delhi, where I was demonstrating. This was all done by morse. Except for cable and radio services, the great bulk of telegraph work will, I think, in the future be handled (until something better is produced) by the 5-unit or 6-unit Code and especially by the start-stop apparatus, along the lines suggested in the paper. In my opinion, however, the telegraph engineer will have to consider more carefully the question of a 6-unit as against a 5-unit Code. The 5-unit Code only gives 32 combinations and of these a great many have to be used for shift, line change, column feed, etc., so that it is as much as one can do to obtain 26 useful combinations. Only about 45 letters and signals are commonly necessary in ordinary telegraphy in most countries, but with the 6-unit Code a total of 64 combinations is always available without any loss of time in shift. I think that it would pay even now to adopt the 6-unit system instead of the 5-unit, in view of the enormous development which in the future is bound to take place in connection with printing telegraphs. The author regards distance and time difference as the principal factors governing the use of the telephone in preference to the telegraph, but I would suggest that there are other factors of equal importance. As Mr. Herbert has already pointed out, people's time is valuable, and every year the value of time is growing, the cost of living is rising and we have to increase wages and salaries. Business men who have important engagements all day long do not wish to be interrupted by the telephone, and it would therefore be much better to have something that will produce a printed message. The question of language is also of some importance. In my own case, for example, while I cannot speak French fluently enough to hold a conversation over the telephone, I can write it sufficiently well for the average Frenchman to grasp my meaning. Tele-writing would facilitate the communication in both directions.

Lieut.-Col. A. G. Lee : With regard to the remarks on page 1376 concerning the control of tuning forks, the author attributes the invention of the valve-maintained tuning fork to the Western Electric Co., but I believe that it was invented by Eccles and Jordan, who took out a patent for it during the War. The valve-maintained tuning fork has been investigated by Dr. Dye at the National Physical Laboratory, as well as by others, and a considerable amount of work has been done on the subject. We employ a valve-maintained elinvar tuning fork at the Post Office Rugby Wireless Station, for developing the frequency used in the transmissions. We start with the valve-maintained fork oscillating at about 2 000 cycles per second and take harmonics from that to produce the frequency required. The advantage of the elinvar fork is that the temperature coefficient is practically nil. One of the factors which determine the constant frequency of the valve-maintained tuning fork is the same as that which gives constant frequency in a valve oscillating circuit, i.e., the grid and plate voltages must be as nearly as possible 180° out of phase. This condition is obtained by a suitable arrangement of the circuit, and since the tuning fork is then independent of any other factor such as the battery voltage the system oscillates at the frequency of the fork itself. By due consideration of factors of this type and by the use of thermostatic regulation, the Marconi Co. have produced a steel tuning fork which has maintained a constancy of frequency of 1 part in 100 000 for 7 months without any synchronizing whatever. The B.B.C. also use steel tuning forks at some of their small stations from which the harmonics are obtained in a way similar to that in use at Rugby. By this method the frequency of the wireless transmitter is maintained constant, it being necessary that these stations should keep within 5 cycles of each other and at a frequency of the order of 1 million cycles per second. The B.B.C. have, I understand, maintained this frequency within 5 cycles throughout the last two years. The steel tuning-forks both of the B.B.C. and of the Marconi Co. have a thermostatic control which regulates to within ± 0·05 deg. C. I think that such arrangements, although perhaps rather elaborate for an ordinary telegraph office, might, as the author suggests, be justified for those of the largest type. On page 1381 it is stated that the speed control of a number of synchronous motors in one office is quite practicable and that its advantages require no emphasis. I agree with the author that the advantages are considerable, but where the out-stations are in different countries and in different hands I think one control for the whole office is likely to give some difficulty. With reference to the Verdan system described on page 1423, this is the modified Baudot apparatus which, it is claimed, will remove to a large extent the effect of atmospherics in radio circuits. The arrangement was invented some time ago, but its use has not become widespread for a reason which is evident from the table on page 1423, in which the method of operation of the circuit is clearly set out. From this table it would appear to be only necessary to go on repeating a signal a sufficient number of times in order to eliminate the atmospheric disturbances. This supposition, however, overlooks one fundamental point with regard to atmospherics—they do not always reinforce the signal, as suggested in the first column of page 1423. When an atmospheric causes a free oscillation in a radio circuit the oscillation lasts a considerable time—of the order of a dot or a dash and sometimes longer. If the atmospheric disturbance occurs at such a time as to produce a phase difference in opposition to the signal element in the circuit, the effect of the latter is completely swamped, as is borne out by practical experience. Also on short-wave circuits there is fading or partial disappearance of a signal, a phenomenon which occurs probably to an extent equal to that of the atmospherics. I would estimate disturbances due to fading at 50 per cent, and disturbances due to atmospherics at 50 per cent, but the Verdan system will not deal with fading. With regard to phantom working, we have in this country a large number of telephone wires and we are at present experimenting with double phantom working: this is sometimes known as "ghost working," and is referred to in the paper. It makes use of a circuit which is superimposed upon telephone phantom circuits, and by its aid we hope to obtain for telegraphic use a large number of circuits which cannot be used for telephonic purposes, thus allowing teleprinters to be installed in place of the Baudot system. Experiments have recently been carried out in connection with the loading of double phantom circuits. It was evident that since the circuits were being used for telephone purposes, loading coils for telegraphs could not be inserted directly in the lines. At points 50 miles apart where these circuits entered telephone repeater stations a loading coil was introduced, and it was found that by concentrating the loading at these points it was possible to work the teleprinter apparatus on such underground telephone circuits. With loading we have worked over a distance of 600 miles without a telegraph repeater in circuit, whereas when the loading is omitted we can only work over 200 miles without a repeater. Regarding a telegraph current as being of the alternating type, it can be represented by a low-frequency current of 25 cycles per second together with an allowance for the higher harmonics, say, up to 60 or 70 cycles per second. It has been found by experience that an allowance of this kind enables a received current which approximates to a square-topped wave to be obtained. The highest frequency—60 or 70 cycles per second—is comparatively low, and the spacing of the loading coils 50 miles apart enables us to obtain about $2\frac{1}{2}$ to 3 coils per wavelength. A value of between 3 and 4 coils per wavelength is usually necessary for telephonic frequencies.

Mr. K. L. Wood : The paper will be of great use in educating the young telegraph engineer and in broadening his outlook, which is liable to be restricted to the system with which he is particularly concerned. With reference to the first paragraph of page 1372, I should like to point out that the mechanical hit-or-miss method of selection (on the gas-engine governor principle), employed in the Heurtley and the Eastern Telegraph Co.'s systems of cable regenerators, appears to approach as closely as possible to the theoretical desideratum of an infinitely small receiving segment. I do not know whether a comparison has ever been made between the mechanical system and that in which picking-up and locking relays are controlled by a brush passing over a short segment on a distributor. It may be that, while the mechanical system is nearly perfect, the electrical one is so nearly as good that the difference is not apparent in practice. It would be interesting to know whether the method for overcoming possible distortion due to indefiniteness of the commencement of the regenerated signal owing to the breadth of the pick-up segment, which was the subject of a patent, has been found to be of any practical advantage. With regard to the correction of a reed or fork by reference to a clock (pages 1377 to 1380), it would appear at first sight that there is little difference in principle between the methods of Figs. 13 and 14. It will be noticed in Fig. 14, however, that when the correcting mechanism AM or RM rotates the shaft S in one direction or the other, and alters the speed of the reed R by an alteration in the angular relation of the magnet M to the armature at the end of R, then, since the commutator C is on the same shaft, its angular position in relation to the brush B at any time is altered. This phase alteration of the means of comparison is the principal feature of the invention, and it is very important in that it prevents hunting. This would inevitably occur with the arrangement shown in Fig. 13 unless the phases both of the commutator and the clock contact were correct and the reed had the right speed at the moment of starting. For example, suppose that one were timing a clock to a standard chronometer by making observations of the hands at intervals and altering the pendulum of the clock to be corrected only; if the hands showed a fast error a losing rate would be put on until the positions of the hands had been made to coincide. The chances are that when this occurred the rate would be too slow, the hands would fall behind those of the standard clock and an oscillation of the speed and hands would take place. Alteration of the commutator C in Fig. 14 is seen to be equivalent to making a step alteration of the hands every time a correction is made to the pendulum, and it is by this means that hunting is avoided. With reference to gang driving of motors (page 1380), the number (8) of motors controlled by one reed is small. We have found that each reed can control 4 relays, and since each relay normally operates 3 motors 12 of the latter can be run from one reed. This is a convenient number and the reed and relay contacts do not give any trouble in these conditions, it being possible to run 20 motors without evidence of undue sparking. Further, it is possible to control a second reed from the first by the simple expedient of connecting the driving magnet in series with that of the controlled reed, the reed being so adjusted that its natural period is nearly correct. In addition to the advantages mentioned in the paper it may be stated that, since at every station on a chain of regenerator stations the motors are running at the same speed within the accuracy of the various clocks, changes of speed can be made with little trouble. Each station is provided with numbered gears which are easily interchanged, and it is only necessary to change the gears on the transmitter and on the regenerators at intermediate stations in order to increase or decrease speed by a definite amount. All hand adjustment of the speeds of the various reeds is eliminated, and there is no need to wait for the stations nearer the terminal to synchronize before further stations are readjusted. Circuits can be, and often are, stopped at a given time, the speed is altered, and traffic is passed on again at the altered speed within half a minute with 4 synchronous stations on the line. The number of stations makes only a slight difference to the time taken to regain synchronism since the whole operation, beyond changing a pair of wheels, is automatic. It seems to me that methods which have been found to work so successfully as this could be applied to the stop-start system. It is interesting to know that both backward and forward corrections were used in the Baudot original method of correction. For submarine cable regenerator systems employing a number of linked sections this method is essential. The remarkable rapidity with which a series of 22 cable regenerator stations can come into synchronism after a change of speed, or on starting up, would not be possible on one-way correction; to those accustomed to the equal-speed 2-way correction system, it is a matter of surprise that a system demanding continual corrections to enable one station to keep phase with another whose speed is different, does not, even on landlines, produce disadvantages out of proportion to the simplification of the apparatus. Cable distortion due to balance and other factors causes the arrival time of the signals to differ considerably, and the greater the interval between the times of arrival the greater the phase shift must be in order to pick up sufficient corrections to compensate for a change of speed. In this respect there is a fundamental difference between synchronizing on submarine cables where distortion is present, and synchronizing on landlines where distortion is comparatively small. With reference to Fig. 30, I should like to mention that this apparently somewhat crude mechanism was devised in 1912 and there was a good deal more on the shaft behind the disc which carried the 4 rollers, than is shown on the diagram. I aimed at producing a sleeve capable of being easily corrected whilst rotating, but in which the corrected part would be rigidly attached to the shaft when the cams were called upon to do serious work. In addition to the phase correction, step-by-step speed correction acting on the governor adjustment shaft was used. The method of Fig. 37, for altering the rate of the reed itself in accordance with the impulses derived from the signals, is a good one, but it necessitates a separate reed for each regenerator set. The clock control method, therefore, is more economical.

With reference to the start-stop mechanism described on page 1393, the early cable clutch regenerators worked on this system, but it was soon realized that errors in starting (due to distortion) and in completion of a letter (due to speed) resulted in the mutilation of the space element, and that the latter was just as important as a signal element. A method for limiting the effect of distortion was devised, but it was found that each step in this direction necessitated a more and more accurate speed. The natural result was that in 1914 we turned our attention towards developing a continuous rotary system, but no progress could be made until after the War. With reference to speed and phase indicators (page 1397), close setting by the clock of the reeds at stations and the use of gearing from a constant-speed motor obviates the necessity for these devices on cable code working. With regard to phase orientation (pages 1397 and 1398), although the method due to Higgitt of rotating the stator of the motor is mentioned in another part of the paper, it might have been included in this section where such methods are classified. It is ingenious and has the great advantage of eliminating gears and their attendant backlash. No mention is made in the paper of converting transmitters, in which cable code is sent to line from Wheatstone slip, or of perforators, in which Wheatstone slip is produced from cable code signals. As regards clutches, no reference is made to that successful type in which there is very little friction when it is not operated but the operative member of which when released is clutched to the rotating shaft in such a way that increased work on the clutch gives increased frictional grip. Such clutches can work at high speeds and can grip with an accuracy of $1\frac{1}{2}$ per cent of a revolution at, say, 1 000 r.p.m. The description, on pages 1433 and 1434, of the automatic scrutinizing device employed by the Eastern Telegraph Co. deals chiefly with its use for indicating the introduction of bias, but this is only one of the useful features since it will indicate deterioration of the signals beyond a certain predetermined point, due to any cause whatever; this point is set so that warning may be given before such deterioration occurs as will give rise to occasional errors. The synchronizing system adopted by the same company, in which phase corrections may be applied in either direction, enables a bias-correcting system to be used which depends upon the early or late arrival of the signals due to bias. For instance, if in a cable code system the dots produce a greater number of early corrections than late and the dashes a greater number of late than early, it is obvious that the dots are thick and the dashes are thin, i.e. a dot bias exists, and vice versa for a dash bias. Since the correcting relays indicate early or late and the line relay shows dot or dash, it is possible to work a ratchet mechanism attached to the relay bias-adjustment so that it is operated in one direction or another until the bias is eliminated. This step-by-step system is found to be very reliable.

The transposing system of the Western Union Co. (Fig. 125) for passing double-current Wheatstone signals over a cable as positive, negative and zero signals is ingenious, but the speed loss would be about 30 per cent compared with ordinary cable code. What might be called a " contrary " transposing system was devised for the Eastern Telegraph Co. in 1925; it enables ordinary cable code signals to be relayed through a land line working double current, i.e. with positive or negative always on. This system, which has since been improved, shows on land lines a 30 per cent gain in speed possibilities as compared with Wheatstone working, although it is probable that in most cases such a gain would not be important. With regard to page 1439, I should like to know what results are obtained with the duplex " jar " eliminator. When a sending inductance is used we should not expect much, if any, benefit to be obtained. The inductance smooths off the rate of change of the sending current, and we therefore consider that in general the majority of the balance disturbance does not take place in a particular small part of the sending period. Unequal channel working receives no consideration in the paper, although it is coming into use to a certain extent where two cables of different *CR* values are linked up to a high-speed cable, the high-speed cable carrying two channels of different speeds, and the regenerator at the junction retransmitting the faster channel into the low *CR* cable and the slower channel into the high *CR* cable. This system involves the selection of signals from a regular-running instrument such as a transmitter, so that the signals can be selected regularly and sent irregularly on the transmitting side whilst on the receiving side they are selected irregularly and sent regularly. With regard to the saving of staff by the introduction of machine switching, this has been done as far as possible on cable networks by arranging selective switches at each intermediate station on a regenerator chain. These switches give great flexibility, enabling a terminal to drop messages automatically at any intermediate station in the form of perforated slip for use in a printer or for retransmission on branch lines. They also allow any station to transmit to any other station on the unoccupied part of the chain, or when the terminal is pausing. Owing to the smaller number of lines there is not nearly so much scope for economies of this kind on cables as there is on an inland network.

Mr. W. Cruickshank: In connection with 2-way working on loaded cables (pages 1440 and 1441), the author states: " If wave pulses are sent from both ends simultaneously, the electromagnetic pulses meet somewhere in the cable and two cases arise as shown in Fig. 127(*b*)." The first case is where two positive e.m.f.'s are applied, one at each ene of the line, and the second is where a positive e.m.f. is applied at one end and a negative at the other. It is further stated that "at coalescence either a doubled electric field or a doubled magnetic field is produced and this breaks up into two pure waves proceeding to the two terminals of the cable." I do not understand what is meant by pure waves, and with regard to the statement that pulses can be sent simultaneously from both ends of the cable and that "they will pass each other en route without interference," I think that the passing of two pulses on a cable is not possible without interference, if at all. In the case of two positive e.m.f.'s, fed one at each end of the line, it would seem that momentary currents or pulses start from both ends and that when such pulses meet at the centre the magnetic portion of the field disappears, its kinetic energy reappearing as potential energy at the end of the period. This may be the doubled electric field referred to by the author. The e.m.f.'s having been cut off and the receivers replaced at the end of the line, the two halves would discharge back through the receivers and give rise at each end to signals which are really produced by their own pulses, the phenomena being somewhat similar to particular cases in the ordinary differential duplex. In connection with Fig. 129(*b*), the author suggests that it is possible to use such an arrangement as a phase corrector, and on page 1441 he describes the same arrangement as an example of successive differentiation carried out on a network of shunt and series impedance. He states that the voltage across inductance L_1 is $v_1 = L.di/dt$, where i is the arriving current, and that this voltage applied to condenser C_1 produces a current $i_1 = C_1.dv_1/dt = C_1.d^2i/dt^2$. Although this may be mathematically correct the fact remains that the voltage v_1 is not the one which is applied to the condenser C_1. The circuit shown in Fig. 129(*b*) is merely a high-pass filter. I agree with the author as to the means which he has suggested for turning the loss on telegrams into a gain. The only hope of making inland telegraphs pay lies either in arranging for the public to send the telegrams themselves or in reducing the number of retransmissions. The former scheme could be put into practice (as in the case of telephony) by an operator at the sending station manipulating a dial for the purpose of selecting a distant office. The system of Fig. 139 would be suitable, and although a complicated machine telegraph and a rather complex telephone mechanism are involved both have been shown to be satisfactory, and it is only a question of applying the two together to make the scheme successful. It may be a paradox that in order to make the telegraphs pay the number of lines must be increased, but the line costs of the telegraph administration form only a small proportion of the total cost. The major item of cost of inland telegraph traffic is the operating expenditure and it is only by reducing the latter, even at the expense of increasing the size of the line plant and the number of channels, that a way out of the present position can be found. Colonel Lee has spoken of the method of working double phantom circuits, and Fig. 122 shows a German scheme for working telegraph circuits on telephone pairs. This diagram, however, does not give a full account of the system and one difficulty in connection with superimposing telegraphs on telephone pairs is the lack of space at the repeater stations. In order to send low-frequency telegraph signals and allow them to pass the telephone repeater, a low-frequency pass filter has to be adopted. This by-passes the telegraph currents round the telephone repeater, the current reappearing on the down side of the repeater. At a repeater station it is a very simple matter to by-pass the telephone repeaters, provided that a telegraph circuit is superimposed on the phantom telephone. As Colonel Lee has mentioned, we have been working London to Glasgow satisfactorily for 2 months with loading coils at the repeater stations only, and the teleprinter has been used without any trouble whatever. The currents on this line are of the order of 1 mA per wire and 4 mA per quad, their amplitude approaching that of telephone currents. It is possible to work the telephone circuits without noticing the telegraph signals at all.

Mr. H. Kitchen: Large telegraph offices are becoming more and more dependent upon a power supply, and any failure of this supply creates an abnormal amount of trouble and dislocation of service. For example, recently when a dense fog came over London all the lights were switched on and the voltage dropped appreciably, with the result that the Central Telegraph Office, so far as the motor-driven portion of it was concerned, came to a standstill. Now that the country's electricity supplies are being changed over to a.c. we are likely to experience more trouble than has been the case with d.c. motors, because a.c. motors capable of running at a constant speed do not seem to be freely available and when they are procured are not entirely free from trouble. I should like to ask the author whether in running a.c. motors with telegraph printing mechanisms he has experienced any trouble due to excessive heating. Mr. Cook of the Post Office has designed a governor for use with Baudot distributors and this is working very satisfactorily. This governor is more easily adjusted and handled than the standard Baudot governor. On page 1376 there is a list of external factors which cause variations in the rate of vibration of a fork or reed, and to this list I should like to add mechanical vibration. Care should be taken to select the most stable position possible for a tuning fork or reed. On page 1419 the author states: "The capacity of a duplexed line is only $1\frac{1}{2}$ times its simplex operating speed as a maximum"; this statement, I think, requires some qualification. The longest and most difficult Baudot circuit in this country is the underground line between London and Newcastle, which is working quadruple-duplex. If this circuit were worked simplex the capacity would be about 50 per cent of its present value, and I think that this percentage might be applied to the majority of hand-worked systems. On page 1451 the author gives his views on the problem of retransmission of messages and indicates that the solution lies in machine switching and machine telegraphy. Machine switching has been tried by the Post Office, but not precisely as suggested by the author. The experiment has not been very successful from the traffic point of view because, although fewer operators may be needed in transmitting telegrams from A to D, where there are two intermediate offices, so much time is lost in dialling and getting through to the particular station that the effective load of an operator drops from about 72 to 28, and therefore approximately 50 per cent more operators would be required to work such a system. Expensive machines such as teleprinters should not be supplied to offices where the load is comparatively light, and offices with heavy loads should not be joined to a concentrator or to a machine switching arrangement, if the maximum economical advantages are desired. Machine switching causes excessive delay, and as rapid despatch is the first essential of a telegraph service it is not clear how the proposal could be applied without considerable additional cost. I am afraid, therefore, that application of the author's ideas would not lead to a reduction of costs. Some other method, I think, will have to be devised and this is really not so much an engineer's as a traffic officer's problem.

(*Communicated*): At the author's suggestion I give below a brief description of the Cook type of Baudot governor (Fig. A). This modified form of the Baudot governor was devised to permit of speed alteration directly by means of a screw motion, and without the use of additional masses. It also gives a wide range of speeds without the necessity for experimental adjustment as regards initial spring tension. Adjustments for speed are effected by altering the length of spring in use, and the basic requirement of zero tension at zero amplitude is maintained automatically once the governor has been assembled correctly. The single mass of the Baudot governor is retained, but only one spring is employed, one end being anchored to the mass and the other supported by a blade passing between the spirals of the spring. The spring can be rotated at its point of anchorage in the mass in order to fix the correct tension at assembly and should not thenceforth be altered. The blade is a fixture at one end of a cylinder and corresponds in effect to the potence of the Baudot governor. The other end of the cylinder is threaded and screws into the frame of the governor, the pitch of the thread being the same as the spirals of the spring and both being right-handed. By turning the cylinder clockwise, the blade is advanced along the spirals of the spring, and, although the effective portion of the spring is shortened by the process, no additional initial tension is given because the blade and cylinder have together been moved across the centre of rotation by an exactly equivalent distance, the cylinder being screwed into the frame. The speed is now higher than before, but the balance of the governor as regards tension is undisturbed and is correct for the whole range of movement which the thread and spring permit. It is essential that the spring be so wound that it is without tension when fully collapsed, or alternatively that the pitch of the thread cut on the cylinder is proportionately reduced if such initial tension exists. The range of speed given is approximately 165–195 revolutions of the brush arm per minute, and the accuracy of the governor does not vary appreciably from that of the standard pattern.

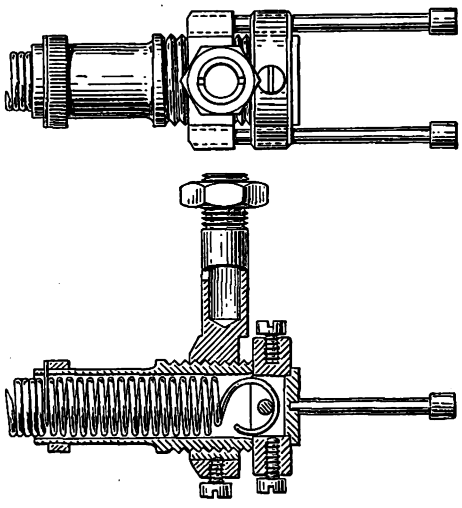

FIG. A.—Cook's Baudot distributor governor.

[The author's reply to this discussion will be found on page 1464.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 10TH MARCH, 1930.

Mr. F. G. C. Baldwin: It is pleasing to note the author's tribute to the work of Baudot, and although his system must eventually be abandoned, Baudot's work will stand as a monument for all time. The author gives sound reasons why the telegraph is more successful in America than in Europe. I think that similar reasons apply in regard to telephony. While I am hopeful of increased development in the use of the telephone in this country, and I agree that there is plenty of scope for further development, the fact cannot be disguised that comparisons between this country and America which do not take into consideration the geographical differences of the countries and the temperamental differences in the people, are futile. The author's suggestion for avoiding retransmission by the adoption of machine switching is interesting, and there may be places where such provision could be introduced. Reference is made to what, I think, would prove to be the chief difficulty, viz. the congestion arising in busy periods between places with one or only a few outlets. One station might call another unsuccessfully at intervals and still not dispose of traffic in a reasonable time during peak hours. Machine switching would not allow of code time working. Similar methods were tried by the Post Office and the results were not an unqualified success. It seems doubtful as to whether the automatic switching scheme suggested in the paper would be sufficiently flexible. The difficulty is that the telegraph is not developing in the same way even as the telephone. With regard to motor speed-control, it is agreed that constancy of speed is essential, and the Post Office has had little difficulty with d.c. motors. Alternating-current supply is now becoming common, and difficulty is being experienced in obtaining a.c. motors which run at a constant speed. Has this difficulty come to the author's notice, and does he know of a method whereby it can be overcome? Mr. Cook, of the Post Office Telegraph Department, has devised a governor which is functioning excellently on Baudot sets and which is simpler and more easily handled and adjusted than the standard Baudot governor. Regarding vibrating reeds or forks, the experience of the Post Office is that voltage variations and mechanical vibration are the cause of most of the trouble. An appreciable drop in the power supply to a large telegraph office is responsible for a general stoppage on all power-driven units, with consequent delay and confusion to traffic. After reading the paper, the power engineer will appreciate the difficulties of the telegraph engineer in maintaining synchronism. Vibration is difficult to avoid, and the utmost care should be exercised in choosing positions for forks and reeds. Twelve teeth are shown on the star wheel of Fig. 26; the Post Office uses a wheel with 15 teeth, and this reduces the amount of phase displacement.

Mr. J. W. Wilson: As a Press telegraphist I should like to give some account of the use of the telegraph so far as newspapers are concerned. The Press of this country is indebted to the telegraph, and also to the telephone, for the supply of more than 50 per cent of its news. Generally speaking, newspapers are purely business propositions and if they are to make a profit they must supply their readers with fresh news, in order to create and retain their circulations. As an example of the amount of news telegraphed in connection with an up-to-date provincial newspaper, I would mention that the *Newcastle Chronicle*, which was the first newspaper in the country to have its own private telegraph facilities, receives between 80 and 100 columns of news daily over its system of five wires, viz. from London, Glasgow, Manchester, Middlesbrough and the Press Association. Several columns are also transmitted from Newcastle to other offices in the Allied Press group, and the total traffic exceeds 100 000 words per day. Since all the newspapers throughout the country are collecting and transmitting news in this way, it can readily be seen that the telegraph system plays an important part in the organization of newspapers. Press telegraphists unfortunately have little opportunity for experimental research, as they have to concentrate on the practical side of their profession. Newspaper proprietors are not concerned with the advantages of one system of telegraphy over another. Their first consideration is economy, their second is efficiency and their third, and most important, is speed; the system which provides these three essentials is, to them, the ideal one. It was chiefly the question of speed which decided the very existence of newspaper private wires, and as soon as these had been introduced it was found that "copy" was being received much more speedily than before. Test messages were occasionally dispatched over both systems at identically the same instant, and in every case the newspaper private wire was found to be faster than the public service, even by such a margin as 2 hours between London and Newcastle. In view of present-day competition speed is more important than ever, and every second is of the utmost value. During the last decade the advance in Press telegraphy has been almost revolutionary. A little more than 10 years ago there was not a newspaper in Newcastle which possessed any mechanical means of telegraphic communication other than the Wheatstone apparatus, the key and the sounder. At the present time the entire Press of the city is mechanized, and the Creed system, which has completely justified itself for this class of work, is used—as it is in the case of the majority of newspapers throughout the country. The Baudot, I think, is to be preferred for commercial purposes, but for Press work it must be acknowledged that the Creed system with the column printer is the most economical of all systems of high-speed telegraphy. It is, in fact, the best one-man equipment in existence. Newspaper authorities are now realizing the vast importance of their telegraph systems, and are regarding them more and more as the pulse of the whole organization. Without an efficient system of high-speed telegraphy no newspaper can hope to exist, and a breakdown in the telegraph means chaos in every other department. During the last year or so the Allied Press have provided Messrs. Creed and Co. with opportunities for experimental work on their wires between London and Manchester, and as the outcome of these experiments the system at present used by the Allied Press group will doubtless undergo considerable change in the near future. I am unfortunately not at liberty at the moment to give any information as to the methods to be adopted, but some of the apparatus upon which the author has commented favourably will be used to speed-up the telegraphs of the Allied Press. The regenerative repeater is doing much to speed-up telegraph communication, but those responsible for Press telegraphs are slowly—though nevertheless surely—beginning to favour the use of the thermionic valve, with its untold possibilities. The Press is just beginning to feel the necessity for development in its telegraph service, and attention is being focused more and more every day on the possibility of development through the medium of the "picture" cable, the idea being that a perfect connecting link between two distant stations leads to considerable improvement in the speed and reliability of all systems. The introduction of phototelegraphy as a commercial proposition has provided a new field for research, and with such remarkably efficient cables as those now used for the purpose of transmitting pictures one is at a loss to imagine the future possibilities of telegraphy. At the moment, excellent pictures are being received from such distant centres as Brussels, Paris, Lugano and the Riviera. The results of these transmissions are quite as good as those from comparatively near centres such as Glasgow and Manchester, and it is in this direction that the Press expects future development to take place. The change-over to the "picture" cable may not come for some years, although we have been experimenting in this direction with some measure of success. In addition I understand that experiments conducted by the Post Office have been carried even further with equal success, and with the introduction of several different frequencies the old multiplex systems will have to be overhauled and brought up to date. The advance of telegraphy calls for an equal advance in technical knowledge on the part of all telegraphists, whether they be employed on a newspaper or elsewhere. The old-time key-and-sounder clerk is dead, and the operator-telegraphist of the future will have to be a more skilful as well as a more intelligent individual than his predecessor. In this connection I advocate compulsory training in technical and mechanical telegraphy for all young men and women who aspire to become telegraphists.

Mr. J. T. Bramwell: I was surprised to read on page 1419 that the traffic-carrying capacity of a Baudot circuit is not doubled where duplex working obtains. On making inquiries, I found that in one hour this morning 173 messages were forwarded and 222 received on a certain duplexed Baudot circuit; more messages could have been disposed of had they been available. Had this circuit been worked " up and down " or simplex less than 197 messages would probably have been transmitted, as time is lost in the gumming process. I suggest that in practice duplex working does double the traffic-carrying capacity of an inland Baudot circuit, and I should be glad if the author would verify the statement referred to. The evil effects of " bounce " and transit time are mentioned on page 1426, and on the following page the merits of the Gulstad relay are set forth. The line relay LR in Fig. 112 appears to be of the ordinary type, without any provision for counteracting these two unfavourable characteristics, and yet the combination of relays in Fig. 112 is described as a true regenerative repeater. As " bounce " and transit time are almost non-existent in the Gulstad relay I suggest that better results would have been obtained had one of these been used as a line relay. Will the author give his views regarding this suggestion? With reference to the financial loss on the inland telegraph system, I think that the extended use of teleprinter apparatus and the utilization of cable wires jointly for telephone and telegraph purposes will help to solve this problem. The author's forecast of automatic telegraph systems similar to present-day telephone systems will no doubt be partly, if not wholly, realized in the course of time. In the meanwhile, however, I consider that economies could be effected by introducing through switching facilities on telegraph concentrators at centres such as M in Fig. 139. With a view to reducing the number of retransmissions, circuits fitted with start-stop apparatus might be advantageously terminated on concentrators at large centres, and where phantom circuits can be formed they too might be terminated on concentrators as through switching outlets. Regenerative repeaters and cable-code calling and clearing signals would probably be found useful in the development of such a system.

Mr. G. F. Bellwood: In reading the paper I have been impressed with the following two definite features. First, that the electrical condition of the circuit must be perfectly stable in order that the printing mechanism may function correctly; secondly that, generally speaking, printing systems are comparatively slow, and where speed of transmission above a certain number of words per minute is obtained there is no individual printer which will work at the same rate. In support of the first statement, numerous examples are given in the paper relating to synchronism, corrections, governors, phonic wheels, speeds, etc., and the arrangements adopted to secure a satisfactory electrical condition are explained. With reference to my second comment, it is necessary to multiply the number of printers in order to deal with incoming traffic. For example, in the Creed system a speed of 200 words per minute may be obtained, but the printer can only work at about 90 words per minute, and hence at least two printers would be necessary to carry the traffic on a fully loaded circuit. As a further example to illustrate the slowness of the present printing systems, I would point out that some years ago it was usual to work a Wheatstone telegraph over a distance of approximately 200 miles of aerial line at an average speed of 550 words per minute. The transmitter and receiver both had specially weighted driving motors, and at the receiving end a polarized relay of 400 ohms resistance was placed directly in the line circuit, the Wheatstone receiver being worked from the relay local. The received tape slip was written up by hand, but if Creed printers had been available it would have been necessary to employ about 6 of these to keep pace with the Wheatstone transmitter. In the Baudot and stop-start systems transmission speed and printing speed are identical, and each channel clears its own traffic; the " Autoplex " also prints at the same speed as that at which the transmitter works, and this is an advantage. The process is thus carried out in one step and additional staff and instruments are not required. In order to make for economic efficiency each channel should clear its own traffic, but in all machine systems where each channel completes its own work speed is lacking. Our printers are not by any means high-speed instruments. The fastest and most modern which we have in use, the " Teleprinter 3A," is a start-stop instrument developed by Messrs. Creed and Co. This gives an actual speed of 60 words per minute, and each channel completes its own traffic. We must apparently remain satisfied with this speed, for the following reasons: (1) Operating costs are low, and a skilled Morse telegraphist is not required, although in this connection experience counts. (2) The speed is of the magnitude with which the average typist can deal and within which the existing staff may be trained to work. Fig. 122 shows a system of sub-audio telegraphy on a normal telephone loop, and it would be interesting to know whether the ordinary Post Office method of superposing a telegraph on a telephone loop, or even of superposing a loop telegraph on two telephone loops, could not be efficiently adopted. In theory, the telegraph signals sent over the loop should cancel out, and a speedier and more efficient circuit than that shown in the diagram should be provided. The 2-power diplex signalling system with 5-unit code, shown in Fig. 123, is interesting, but I think that the last paragraph on the first half of page 1436 needs amplification, as in my view a diplex is a circuit which works two ways out and one way in. It is, in fact, an ordinary quadruplex with the " B " apparatus removed at one end, and in the duplex condition. I should be in agreement with the principles of the system shown in Fig. 139 if the proposed system were on similar lines to that in an automatic telephone area, with manually worked junctions and trunks for long-distance communication and zone working generally. Unfortunately for the telegraphs, however, local traffic within a radius of 10 or 20 miles is practically negligible, and only long-distance telegraph traffic would have to be catered for, except in isolated cases. The following disadvantages occur to me: (1) For short-distance traffic it is cheaper to use the telephone with its combined question and answer. A 3-minute conversation is allowed, as against a 12-word telegram. (2) The traffic from one of the regional offices, connected to the north centre, for example, may have telegrams for places as far distant as between 200 and 300 miles. I do not know of any dialling arrangement which would permit of signalling over such distances, even if circuits were available. (3) It is stated that the system becomes feasible because of the number of telegraph channels rendered available through the combined use of telephone-line plant for telephone and telegraph purposes, but even so, quite apart from the interference with the trunk circuit so far as signalling is concerned, at least one-third of the cost of a pair of wires should be charged to telegraphs in each case. For long-distance telegraph calls this would be very costly. (4) The time occupied in switching, especially over long-distance connecting lines, would be appreciable; in fact it might easily be as great as that occupied in transmitting, and this assumes that a free outlet is available. (5) The cost of the apparatus and maintenance of such a system would be considerable. The author has given us the genesis of a scheme which, although it has been mentioned before by other telegraph engineers, has distinct possibilities, though these may be more limited in scope than those which obtain in a telephone system.

[The author's reply to this discussion will be found on page 1464.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, 17TH MARCH, 1930.

Prof. E. W. Marchant: I am sure that this paper will be a classic in the records of the Institution. The subject with which it deals is highly specialized, and it is difficult for anyone who is not engaged in telegraph work to discuss it. I should like to refer to the governor shown on page 1372. This has, I believe, been in use for a considerable number of years, but, in the form in which it is shown, it is almost identical with a governor used by Mr. J. F. Gill in a speed indicator invented by him in 1915. I have here his patent specification. I understand that the author knows of an even earlier governor of a similar type. I should like to mention, however, that in the governor shown in Fig. 3 there is a brush bearing on the cone C; since the brush is rubbing against a cone it is almost certain that there will be uneven wear on the former, because the velocity is greater on the outer edge than on the inner. There is likely to be more wear on the outer side, and therefore the line of contact between the cone and the brush face may change slightly. Mr. Gill has improved upon this by using a pivot on the brush holder. This ensures that the radius of action of the force on the rubbing surface in relation to the pivot of the arms A_1 and A_2 remains unaltered with wear of the brush. The main advantages of the telegraph are that it can be used for very long distances and that a better load factor is possible with it than with the telephone. In the case of the telephone both the subscriber and his correspondent have to wait until the line is free, whereas with a telegraph the load can be spread out and better use can be made of the line. It seems to me, therefore, that the cost of a telegram ought to be considerably less than that of a telephone message.

Mr. T. E. Herbert: Speed and phase control is generally denoted by the term "synchronism." This term is scarcely applicable, for when we talk of two clocks being in synchronism we mean that both move at a uniform speed and that at every instant they indicate the same time, whereas two distributors are said to be in synchronism when their speeds are equal with a constant phase difference. It is perhaps more nearly correct to say that the distributors are in "unison." The brushes used on distributors are by no means satisfactory. Copper-wire brushes have been used very extensively. In America a braided-copper brush is employed, while in France a carefully prepared wire brush is used, but neither of these seems to be altogether successful. I think that few of us realized, until we had read this and the previous paper by the author, how vast a contribution Baudot made to telegraph mechanisms. Practically every machine that we have at the moment can be traced back to fundamental designs due to Baudot. The objection to the ordinary reed and phonic-wheel drive lies chiefly in the fact that regulation is individual to each circuit, and I am forced to the conclusion that better results would be obtained by the use of precision apparatus common to all the circuits. This is definitely foreshadowed by the author. I also suggest that, in the method which will ultimately emerge, the rate of the resonant control will be kept constant, i.e. will not be varied to effect phase corrections at intervals under the influence of signals. The use of a Mendonca governor eliminates the reed and its adjustment. This is an excellent feature, since the reed is usually fixed on the wall of the instrument room to avoid effects of vibration, and so is often several feet from the set which it controls. The author states that the pressure of the brushes must be fairly heavy. Some irregularities have been noted in the results obtained, due to variation of the power required on the driving side, and, generally speaking, one doubts whether the method is quite so stable as the reed and phonic-wheel method. As the operating charges form the main part of the cost of a message, the expenditure of a large amount of money is justified if absolute stability of the circuits is secured. Apparatus failure is exceedingly costly and, in my opinion, apparatus stability is one of the most important points which have to be watched. Future progress will probably be made along the lines of distributing alternating current of unvarying frequency to all the circuits. Methods of frequency control were described in the recent paper on the Billingham power station,* but I doubt whether sufficient accuracy will be attained for their use in speed control. The author suggests that the "grid" should provide such current, and I hope that his suggestion may be realized. The infra-acoustic method is particularly interesting, as we have a vast network of telephone circuits to which telegraph channels could be added. Thus we can provide telegraph channels in sufficient number for any purpose.

Mr. J. Davey: Apparently the author is of the opinion that multiplex telegraphy is on the wane, and this certainly seems to be the case, as the present tendency is to introduce teleprinter working. Baudot distributors and retransmitters, however, are still in use at Liverpool Head Post Office. At present we have a line from Dublin to Liverpool, one from Liverpool to Manchester and one from Liverpool to Birmingham. These circuits provide the following type-printing channels, each having a speed of 30 words per minute. One channel from Dublin to Liverpool, one from Liverpool to Dublin, two from Dublin to Manchester, two from Manchester to Dublin, one from Dublin to Birmingham, one from Birmingham to Dublin, three from Liverpool to Birmingham, three from Birmingham to Liverpool, two from Liverpool to Manchester and two from Manchester to Liverpool—18 channels in all. The main distributor at Liverpool sends out correction current to Dublin, Manchester and to the distributor on the Birmingham Baudot at Liverpool. This in turn sends out correction current to Birmingham, and thus these distributors are all held in check by one in Liverpool. The system works well when the lines are free from trouble, and it is one example of what multiplex telegraphy can do. We have a somewhat similar arrangement of circuits between London and Cork, but in this case we are using automatic keyboard perforators with automatic transmitters. Two 2-way channels are being provided between London and Cork, and two each are in existence between Liverpool and London and between Liverpool and Cork.

Mr. A. Munck: The author refers to the difference between telegraphy and telephony; the main difference is, I think, that in telephony the public do the work whilst in telegraphy we do it for them, even as regards the spelling in some cases. The ideal plan is to compromise and make the public do part of the work. This has in part been done by the short-distance typewriter, which has replaced many of our telephone circuits. The most equitable way of charging would be for each customer to pay for the time which he occupies or, in other words, per yard of slip. With regard to errors, the operator has to cope with many difficulties that he should not be charged with, such as bad handwriting, atrocious code words, etc. In spite of this, our periodical examinations show that the average operating errors amount to less than 1 word in 17 000. With regard to the maintenance of cable apparatus, this does not present great difficulty to us, as a previous speaker has pointed out; and at my own station (Liverpool) the time during which the cable has been out of commission due to any plant failure has averaged 1·54 minutes per week during the last 12 months. It is difficult to obtain complete flexibility of the system. We have full flexibility in one direction, as the incoming signals can be forked out and made to serve many cities; Liverpool may share a cable with London or Paris, for instance, in the homeward direction. The difficulty occurs when two stations are required to send into the same cable. This can only be done by letting one fork drive both phonic wheels and then stepping them into phase.

Mr. C. E. Reeve: Telegraphs present quite a different problem from that of an ordinary business proposition which is earning money. The rural telegraph lines, which run through sparsely populated outlying areas where relatively costly plant has to be maintained irrespective of revenue, are often run at a loss—never at a profit. On the other hand, an analysis of the revenue earned by main lines would, I think, disclose a profit. This system is a legacy of a generation other than our own, and, while we may reasonably be expected to find correctives, the responsibility for finding a cure should not be thrust upon the present-day administration. I should like to know what the author visualizes as the design of a machine which would work economically in rural districts. In 1914 a Committee of Inquiry was held with the idea of deciding upon a standard keyboard, but I have not heard of any definite result. Although after reading the author's two papers one would get the idea that we had greatly progressed, I think that we have advanced very slowly. Expenditure on telegraphs might be cut down by providing pure phantom circuits over every telephone cable; the capital and running charges would be extremely small with low voltages in use. Further, the human element seems to be in process of elimination. I believe that the Eastern Telegraph Co. have reduced a large operating staff to what is practically a skeleton maintenance staff, by installing relays mentioned by the author. This is a step on the path of progress, but it is taken at the expense of the craftsman. With regard to the question of brushes, a brush was invented by Halske in 1913 for working the first Siemens-Halske duplex system. This brush was not produced again after the War had broken out and stocks had become exhausted. We could not find out the composition of the metal used in it. It was, I believe, a combination of silver and phosphor-bronze. Whilst it worked on the distributor face, it produced very little attrition. It secured a perfect contact, perfect transmission and apparently eliminated self-inductive discharges when the brush passed from one segment to the other. At the present time we have a good system of teletype, and I should like to know what the author visualizes as the future development of this apparatus. Is the teletype exchange with selective dialling and automatic switching a practical possibility? Would there be need for synchronization of the motor speeds from a universal predetermined centrally controlled rate, or would gang control at the particular office be necessary?

Mr. J. C. Prescott: I should like to ask the author how far it is possible to eliminate phase-swinging in phonic-wheel apparatus, and what is considered to be a reasonable angular deviation due to hunting. I should be glad if he would give me some information as to the methods used for reducing the swing, and as to whether electromagnetic damping is employed to any extent.

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* See page 1233.

On page 1381 of the paper it is stated that a phonic-wheel motor is polarized from an external source of direct current when it is to be used for operation with alternating currents. What advantage is gained in this way? Polarization is not resorted to in the small phonic-wheel motors used on the Duddell oscillograph; these are operated from the alternating-current supply and they seem to run satisfactorily.

Dr. T. H. Turney: I am particularly interested in the author's description of the methods of overcoming distortion. I had always looked upon signal distortion from Fourier's point of view, that is to say, I regarded it as due to the unequal attenuation and phase shift of the component frequencies in the original signal. It is in the nature of a revelation to me to regard distortion as an unequal attenuation of the differential coefficients of the sent signal. This conception of distortion seems to be similar to that of McLaurin.

Mr. A. J. Pratt (*communicated*): The reference to composited or simultaneous telegraph and telephone working is interesting. Perhaps the author is of opinion that the difficulties mentioned on page 1434, and others of which he is no doubt well aware—with regard to interference to telephone circuits produced by the large telegraph currents—are sufficiently serious to impose practical limitations to the extended commercial use of the composited system of telephone and telegraph working. Simultaneous telephone and telegraph working has always presented some difficulties, and with the introduction of the loaded underground circuit the difficulties have been considerably enhanced. Low-pass and high-pass filters are necessary to block out telegraph frequencies, and, on the other hand, sparking at the relay contacts, for instance, is caused by the use of low-pass filters. Line conditions are varying and unstable and many types of loading coils and degrees of spacing are in use to-day. The interference (mentioned on page 1434) from iron-cored loading coils is not very serious in view of the present-day practice of using loading coils of the dust-core type. Notwithstanding these difficulties with a frequency band for high-grade telephone transmission of 200 to 3 000 cycles per second, the lower range from 0 to 200 cycles should be available for telegraph transmission so long as noise in the telephone circuit can be eliminated. I should like the author to expand his view as to the practical and commercial possibilities of the simultaneous telephone and telegraph system of working, particularly in this country, where the distances between the large industrial and telephone centres are relatively short and easy to negotiate from the point of view of telegraph and telephone cables. There is a further reference to the same subject on page 1450, where the joint use of the telephone network is suggested in order to reduce the cost of the telegram. As suggested in the paper, there would appear to be a greater prospect of success in this direction by reducing the operating costs, by the abolition of retransmission and by putting the burden of the operative work, or a large share of it, upon the shoulders of the user himself, rather than by eliminating a portion of the engineering costs through the introduction of ultra-scientific methods for working telephone and telegraph circuits.

THE AUTHOR'S REPLY TO THE DISCUSSIONS.

Mr. H. H. Harrison (*in reply*):—

London.

Replying to Mr. Herbert, I agree that precision methods of speed and phase control could probably be applied with advantage to inland circuits. This would lead to an increase in transmitting capacity, accompanied at the same time by a greater operating margin at the receiving end. This arises from the fact that, with the abolition of phase-swinging, the importance of shortened receiving segments is considerably reduced. At present only a fraction (about one-half) of a received signal pulse is effective due to the shortened segment. On the receiving face of a 20-segment distributor of the Baudot type each receiving segment occupies an angle of 9 degrees. At 3 revolutions per second of the brush arm the duration of a received pulse is just over 8 milli-seconds. If shortening is abolished, then with 25 segments an additional channel (the duration of a signal pulse is 13 milli-seconds approximately) could be obtained. Actually some shortening would be experienced, since adjacent segments are not in contact with one another, but these figures illustrate the possibilities. It is true that the Mendonca governor is sensitive to load variation and it is really only suitable where the load is very nearly constant, and very light, as it is with a distributor drive. If the public supply is not sufficiently constant with respect to frequency, then gang control in offices with inter-office speed control is the solution of the problem. Correction from the signals themselves is the best method to adopt where very fine divergences are to be obtained, and correction should be effected both ways. To obtain maximum margin, the receiving distributor should be continuously under the control of the master clock which is furnished by the timed signals from the sending end. It is not unreasonable, however, to expect that the a.c. supply of the near future will furnish a simple and direct means of phase and speed control for inland circuits, and the necessity for correction will disappear. The Warren system of frequency control enables public and private time systems to be driven from a.c. mains. The clock mechanisms are driven by a small shaded-pole synchronous motor. The Grünenwald system has been included in the paper because it represents a modern development in a system of machine telegraphy which is still largely used in Europe, South America and the British Dominions. The advantages of the improved form of quadruplex and the morse multiplex reside in the possibility of getting maximum speed out of the line while the channel speed is well within the economic limiting speed of a Morse Code printer. I am not aware of any application of the method described for eliminating duplex "jar." I agree with Mr. Herbert that the telegraph ideal is the possibility of transmission direct from user to user. A very striking example of the economies realized by through switching on a telegraph network is furnished in a paper by Mr. J. A. Webster.* This paper describes the arrangements in use on the Entre Rios and North East Argentine Railways. With the remainder of Mr. Herbert's remarks I am, of course, in thorough agreement.

Mr. Creed refers to the British origin of the Mendonca governor. It was, and is, in use on the Evershed megger, but its real inventor is an American named Duryea, who applied it to the maintenance of constant magneto speed with variable speed of a motor-car engine (see British Patent 26615/1896). Subsequently Lanchester independently invented it, and later Evershed, who did a considerable amount of research work on the best combination of materials for the friction disc and coupling pads, applied it to his well-known megger. It was tried later for train-lighting purposes, but was not a success as, owing to the load to be transmitted, the heat developed between pads and disc became excessive. I do not think that there can be said to be any conflict now between the Morse and 5-unit Codes, nor do I agree that morse will be retained on account of any supposed flexibility. Morse or Wheatstone apparatus, which is ready to work as soon as it is placed on the table, is almost obsolete and the present-day Morse apparatus is a machine telegraph system designed by Mr. Creed himself. Very nearly perfect as this apparatus is, it is not as flexible as the apparatus it replaced, nor can any machine telegraph system be absolutely flexible. Start-stop systems more nearly approach the ideal because their speed is such that they will work over any line from the short local line to the long-distance main line without any readjustment. Morse telegraphy will survive for ship-to-shore radio services where hand-speed operation is in force, because, in many cases, the volume of traffic would not justify the installation of machine telegraphs, while Morse signals can be read with a background of disturbance owing to the selective functions exercised by the human operator. The machine cannot discriminate against any irregularities of this character. Long-distance radio links carrying regular commercial traffic can be and are being operated by machine methods, and morse has no special advantages here. With regard to the substitution of a 6-unit for the 5-unit Code, I am in complete agreement with Mr. Creed. It is interesting to note that Baudot originally used a 6-unit Code in the early stages of the development of his system. Such a code makes it possible to dispense with inversion devices, thus simplifying printer mechanisms, and saves line time on secondary signals controlling the operation of the printer mechanism. So far as the text of a message is concerned, there is no saving of line time, as the inversion signals take the place of the word-spacing signals which would, otherwise, have to be used. The increase of 20 per cent in the length of a letter signal is only of theoretical importance. The difficulty in the way of this change lies in the capital sunk already in 5-unit apparatus by different administrations who would probably be reluctant to move. Telegraphy nowadays has to be considered from the international point of view, and the contemplated change would have to be agreed to by all before it became possible. Mr. Creed has reversed my views on the influence of distance and time on the relative use of telephony and telegraphy. I pointed out that differences of time operate in favour of the telegraph and against the telephone. I agree that, except in special cases, the printed is superior to the spoken word. Especially is this so, as Mr. Creed points out, where difference of language arises.

Lieut-Col. Lee points out that the valve-maintained tuning fork was invented by Eccles and Jordan. I regret that I have given the impression that it was the invention of the Western Electric Co. Sketch (*c*) in Fig. 10 shows one of their methods of controlling a tuning fork driving a phonic-wheel motor, and it should have been stated that this was an application of a well-known method of tuning-fork control. I am glad to have an opportunity of setting this right. The performance data quoted by Colonel Lee form a valuable addition to my paper from the point of view of speed-control possibilities. With accurately controlled forks at two stations, speed differences can become so fine that a difference of phase of 1 degree between the two distributors would require several hours to accumulate. Correction can be entirely dispensed with and phase adjustments made by hand once or twice per day by means of mechanism disclosed in Figs. 53 and 54. Dispensing with the need for correction and, thereby, for correcting mechanism, is only of secondary importance. When constant speed and minute speed difference are simultaneously attained one source of signal distortion is removed and higher speed per channel or, alternatively, more channels may be secured. Where telegraph offices are in different countries some difficulties might at first arise with the control of synchronous motors in each office, but I look to the C.C.I. to formulate standards which would keep matters right. With regard to the Verdan apparatus, it is true that the atmospherics in Table 1 (page 1423), are shown as giving rise to " extras " only, but it is stated that it is found in practice that the majority of disturbances are in this direction and it is a fact that the Verdan system gives good service at times when Morse working has been found impracticable. The figures given by Colonel Lee as to the operating results on " ghost " circuits are most interesting to me as I am sure they will be to other telegraph engineers.

Mr. Wood raises the question of the indefiniteness of the commencement of the regenerated signal owing to the breadth of the " pick-up " segment. Provided that the signalling speed is such that the receiving relay will operate reliably with the breadth assigned to the segments in question, and provided also that there is complete absence of overlap between receiving cycle and retransmitting cycle, the regenerated signals will be true copies of the originals. Where partial overlap takes place, however, distortion can be set up, especially if a run of positive signals is succeeded by a solitary negative pulse. If maximum speed with nearest possible approach to true regeneration is required under these conditions, thermionic valves must be applied between the segments and the first relay in the chain. The only work then for the received signals is to vary the potential of the valve grids, the valves acting as triggers to operate subsequent relays. I agree with Mr. Wood that the arrangement of Fig. 14 is superior to that of Fig. 13. The latter figure was inserted as a record of the inception of the idea of clock control of a vibrating reed. The phase shift of brush B (Fig. 14) is, as Mr. Wood explains, of the utmost importance. The interchangeable gears at each station of a chain of regenerator stations is, as pointed out by him, an important and valuable feature of the Eastern Telegraph Co.'s system. One-way correction on land lines is good enough because of the comparatively low speed of Baudot circuits and the relatively high margin. This is American as well as European experience, but on long and difficult cable circuits 2-way correction is absolutely necessary. I have been experimenting for some time with a system requiring very precise synchronism and have used not only both-way correction but both primary and secondary synchronism on the lines of that discussed in the last paragraph of page 1371. I regret that Higgitt's method of orientation shown in Fig. 113 was not included in the section on speed and phase control, and I agree that it is both ingenious and simple and possesses the same advantages as do those methods shown in Figs. 53, 54 and 58. I am not aware that the duplex "jar" arrangement has been tried. A smoothing inductance in the transmitter lead has been used for many years when superposing a telegraph circuit on a telephone loop, and for precisely the same object as that mentioned by Mr. Wood. I am aware of proposals for unequal channel working but did not know that such were actually in use. The introduction of automatic switching, as described by Mr. Wood, is an interesting example of what I believe will be the trend of telegraph development within the next few years, but, as Mr. Wood says, it is to the inland network that we must look for spectacular economies.

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* "Intercommunication Telegraph Working," *Proceedings of the Institution of Railway Signal Engineers*, 1929, Part 1.

In answer to Mr. Cruickshank, I mean by the expression "pure wave" a wave in which the electromagnetic and electrostatic energies are equal to each other. The explanation I have given is based on the treatment to be found in Franklin's "Electric Waves," and as the two sets of signals do reach their receivers, under the conditions laid down, the use of the word "interference" is justified whatever the exact transmission process may be. Mr. Cruikshank is correct with respect to Fig. 129(*b*). I overlooked the fact that for the various equations to apply correctly the meshes must be separated from one another by the arrangement of valves shown in Fig. 129(*b*).

In answer to Mr. Kitchen, I have had no experience of running printing telegraph mechanisms with a.c. motors. I should have stated that forks or reeds should be protected from mechanical disturbances. Mr. Kitchen's description of the Cook governor is interesting, and, since the relationship between amplitude and spring tension is secured once and for all at the factory, it represents an improvement in the right direction. The correct adjustment of spring tension by running and observation is a time-wasting process. My remark as to duplex and simplex speeds seems to have been misunderstood. This is no doubt due to my not having stated the case with sufficient definiteness. What is meant by the statement is the following: If S is the *maximum* simplex speed on any given circuit, then, due to inherent out-of-balance quantities in any artificial line formed of a finite number of meshes of capacity and resistance, the combined duplex speed is $1\frac{1}{3}S$. I feel that with the present state of affairs where more lines are available than the traffic requires, multiplex circuits could be given greater stability by using separate lines for up-and-down working and abolishing the extra complication of duplex apparatus and the additional adjustment. I agree, of course, that a duplexed Baudot circuit is superior to a simplexed circuit from the point of view of output, so long as the channel speeds are the same in the two cases. Mr. Kitchen does not describe the method of automatic switching which the Post Office has tried and so I cannot comment on it. I agree that teleprinters should not be placed in small offices where telephone communication to the nearest telegraph office can be economically effected. I cannot see on what grounds Mr. Kitchen bases his very definite statement that machine switching causes excessive delay. First of all, I know of no machine-switching telegraph system in use, and I cannot understand how a properly designed machine telegraph system could give rise to such a condition as he postulates. Machine switching by means of which a circuit can be set up via two or more intermediate switching centres requires, as is known, a few seconds only, and, provided the number of channels (channels which can be obtained from the existing telephone network) are proportioned to the volume of traffic along the route, there should be no delay which would justify the term "excessive." Considerable delay arises at times with the present system of inland telegraphy, and even America provides regional traffic controllers to counteract it [see Bibliography (38)]. I quite agree with Mr. Kitchen that the provision of machine switching cannot be effected without considerable cost, but if inland telegraphy is to be prevented from sinking lower and lower financially, heavy capital expenditure will have to be incurred. The new teletype exchange facilities offered to the public by Mr. Kitchen's department will involve additional cost. The system that will ultimately be developed will certainly require the co-operation of traffic officers, but it is primarily an engineering problem.

Newcastle.

Mr. Baldwin appears to fear that congestion would ensue if machine switching were adopted. I do not think this would arise if the system were designed after a full investigation of the traffic conditions. So far as the number of channels are concerned, it would appear that if dual use is made of the telephone network, more channels would be available than would be required. For example, on the London-Manchester telephone cable some 300 telegraph channels could be formed by merely adding terminal equipment. This would allow, taking an extreme case which would scarcely arise in practice, 300 offices to be simultaneously in connection with Manchester. Terminal equipment would only be added to such channels when actually seized for telegraph traffic. With reference to the speed control of alternating-current motors, if an ordinary synchronous motor is used the speed of this is dependent upon the constancy of the supply frequency. Supply companies are commencing to install systems of frequency control to permit of interconnection, and when this is general an improvement may be expected in the running of small a.c. motors. If an induction type of motor is used, it is possible to control this by introducing a governor which will vary the slip. Of the two causes of trouble with reeds or forks mentioned, the more serious is mechanical vibration. Over a limited range of voltage variation, the change of fork frequency is very slight.

Mr. Wilson's contribution to the discussion is very interesting as it gives us a picture of one branch of machine telegraphy about which very little is known. The craft of the hand-worker is, as Mr. Wilson states, fast vanishing and is being replaced by another craft making much higher demands on the individual.

In reply to Mr. Bramwell, my statement as to the capacity of a circuit when duplexed as compared with its simplex capacity refers to the condition when maximum speed is being sought for. A hand-worked circuit if duplexed certainly has a doubled traffic-carrying capacity, but this may be very much below its maximum capacity and as the speed is raised step by step it will be found that the both-way capacity becomes less than 2 : 1, for reasons which I have given in reply to another speaker. Mr. Bramwell has overlooked the fact that in Fig. 112 the transmitting time does not overlap the receiving time, so that either relay " A " or " B " when about to send out a signal is already on its contact—marking or spacing—" bounce " has subsided and the period of transit time is over. I agree with Mr. Bramwell's final remarks.

The speed of 550 words per minute mentioned by Mr. Bellwood is not a practical one. A Wheatstone transmitter will not work day-by-day continuously at this speed, and at the receiving end the handling of the " slip " would be a stupendous task. As a " stunt " it is all very well, but it is not practical politics. I have seen similar performances when some distinguished visitor has to be impressed, but the transmitter had to be adjusted by skilled mechanics and the adjustments could not be maintained permanently. It is quite true, as Mr. Bellwood points out, that printer speeds are low, but low speeds mean easy maintenance, and, provided the unitary speed is not below skilled typist speed, there seems no reason to attempt anything higher. High-speed printers have been manufactured but they knock themselves to pieces. Optical printers involving photography with developing, fixing and drying processes can operate at extremely high speeds but are complicated and not suitable for employment under conditions to be met with in a telegraph office. Mr. Bellwood asks whether the Post Office method of superposing a telegraph on a telephone loop or superposing a telegraph loop on two telephone loops could be efficiently adopted. I see no reason to doubt this. The sub-audio method only absorbs one telephone pair as against two in Mr. Bellwood's alternative, and as start-stop methods of operation are assumed to be becoming the universal method for inland telegraphs the question of speed does not apply. The word " diplex" must, I think, be taken to mean the transmission of two sets of signals simultaneously in one direction over one wire. The addition of the duplex balance and transmitter and receiver at the other end of the line is necessary where traffic is to be 2-way, but it is conceivable that a newspaper wire, where transmission is all one-way, except for acknowledgments and corrections or other service purposes, would not need these additions. Mr. Bellwood need have no fear as to the possibility of dialling any desired distance. Dial pulses are merely signal pulses and wherever telegraph signals can be sent so also can dial pulses. It does not appear to me to be necessary to load the telegraphs with one-third the cost of any telephone loop used for the dual purposes of telegraphy and telephony. Where such use involves additional equipment which would not be required if the wires were used solely for telephony, the telegraph side would naturally be debited with the cost. The telephone side are entitled to some credit allowance for the use of their line plant, but such charges would surely be such as to encourage the telegraph side of the business. It is impossible to discuss automatic switching adequately without complete traffic data, and I think that the matter must be left there. I cannot see that the switching time over an inland telegraph network should be any greater than in a telephone network such as London. The apparatus will cost a considerable amount, but, as I have stated in answer to another speaker, the telegraphs can only become a healthy, vigorous activity if a considerable capital outlay is incurred.

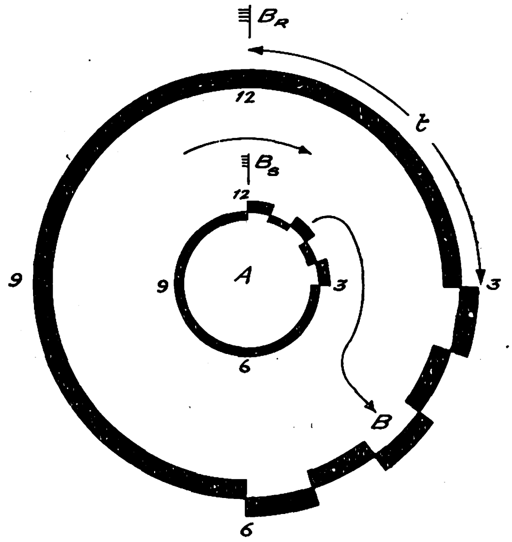

Fig. B.

Liverpool.

Prof. Marchant is right in pointing out that the line of contact between the friction pad and the cone of the Mendonca governor is apt to change slightly, but this has no noticeable effect in practice. Mr. Gill's modification is interesting but it does not seem worth while to complicate the Mendonca governor by introducing it.

Mr. Herbert is in error in stating that there is a difference of phase between the distributors on a machine telegraph circuit. Where line lag exists, it is the *signals* which are out of phase. This is perhaps more clearly seen by reference to Fig. B. Here a quadruple circuit is assumed and the inner circle represents the positive and marking currents sent out from Station A, a letter signal being transmitted on the first quadrant or during the passage over the 12 to 3 o'clock interval. The line lag is assumed to be equal to the time taken to sweep over 90 degrees or one quadrant of the distributor faces. Reception commences at the second station B when the receiving brush B_R reaches the 3 o'clock position, by which time the sending brush B_S will also be at 3 o'clock, having just finished the transmission of the letter signal as reception commences. Thus, except for slight differences of phase due to speed variations, the sending and receiving brushes are always very nearly in phase. I agree with Mr. Herbert's remarks as to the substitution of precision apparatus common to all circuits in place of the present individual regulation. The remarkable results achieved by the Eastern Telegraph Co. confirm this conclusion.

The Mendonca governor ceases to be efficient when the load varies.

I think the alternating-current public supply of the near future will be of a sufficiently satisfactory character to serve groups of a.c. motors in a large telegraph office.

Mr. Davey's remarks illustrate the remarkable flexibility of the multiplex system. With the use of telephone pairs to furnish the channels, interlinking of the character described will be much more simply and efficiently secured, using teleprinters and, where necessary, simple forms of repeater.

Mr. Munck's facts with respect to cable operation are interesting and I agree with him that we should make the public do as much of the work as we can. Large numbers of them do their own telephone operating and I look to the future when they will do their own telegraph operating also.

I agree with Mr. Reeve that we are suffering from the actions of those who have gone before us. Too much was paid for the telegraphs in the first instance, and the concessions granted to bribe the Press of the day to regard with a friendly eye the acquisition of the telegraphs by the State applied a load which should never have been borne. Mr. Reeve asks whether the teletype exchange with selective dialling and automatic switching is a practical possibility. The answer is in the affirmative. Gang control of the motors in a large office would be an advantage and it might be practicable here to provide one motor per instrument table, controlled as to speed, and transmit from this by bevel gears and Bowden wires to four or six teletype machines on the same table, thus saving individual motors.

In answer to Mr. Prescott, various types of viscous damper are applied to phonic-wheel motors to reduce phase-swing, and such dampers usually take the form of a hollow flywheel loaded with mercury. The eddy-current brake has also been employed. It depends entirely upon the form of motor and arrangement of pole-pieces as to whether polarization is necessary. The motor in Fig. 17 would not run without the polarizing windings.

In reply to Mr. Pratt, the short distances prevailing in this country negative the value of dual use of telephone pairs, but as the multiplex is replaced by start-stop apparatus, and if and when machine switching is introduced, the necessary multiplication of telegraph channels will put another complexion on the matter.

THE TWENTY-FIRST KELVIN LECTURE.

"SOME RECENT ADVANCES IN THE ELECTRON THEORY OF METALS."

By R. H. Fowler, F.R.S.

(*Lecture delivered before* The Institution 1*st May, and before the* Scottish Centre 16*th May*, 1930.)

(1) Introduction.

In acknowledging the great honour you have done me in asking me to deliver the Twenty-First Kelvin Lecture, I must offer some preliminary words of explanation and apology. No apology is needed for speaking to you on the electric and magnetic properties of metals. I imagine nothing could be more appropriate or more in sympathy with the interests of that great pioneer whose memory this Lecture annually perpetuates. Nor, I take it, is any apology needed for speaking about abstract theory, as yet of little or no practical importance. We can all agree with the President of the Royal Society in his last anniversary address, that it is by the reciprocal interactions of theory and practice or experiment that knowledge and power advance. This point need not be laboured here. But I do feel rather apologetic for inflicting on you, after so short an interval, the new quantum mechanics or wave mechanics—these are merely two names for the same thing, though apparently not everyone is yet aware of this identity. But my best excuse (and an amply sufficient one) is that quantum mechanics has come to stay and that no real progress in the theory of metals (or, for the matter of that, of other forms of matter) is possible without it.

I shall be concerned in this Lecture with particular applications and results of quantum mechanics rather than with first principles. But still I cannot avoid some attempts to give a simple physical meaning to some parts of the general theory. This is a difficult task at the present time. For the situation is that within a quite definite field, equivalent to non-relativistic particle mechanics, quantum mechanics is, I am confident, in its final form, though its ideas are still so novel that we do not often (if ever) talk about them intelligibly. We may still need a new Einstein to make our theorems more perfectly relativistic; we certainly need a new Lagrange to deepen our powers over complicated problems. But these are details compared with the appalling fact that we have already at our disposal "Newtonian" quantum mechanics which we can use with complete confidence, yet hardly ever talk about in a satisfactory physical way.

My object is to give you now a rough survey of the electron theory of metals—good solid conductors of electricity—as it stands at present. I most emphatically do not guarantee that what I say is up to date on every point, but if I can convey to you the standing of the theory, as re-established by quantum mechanics, I shall be more than satisfied.

(2) The Nature of a Metal and Classical Theory.

I suppose that the electron theory of metals effectively began with Drude. At any rate the triumphant explanation by his theory of the relationship between electrical and thermal conductivities gave it its first real start. The theory, of course, was based, and is still based, on the simplifying approximation, now fairly well justified, that a metal consists of a number of positive ions—atoms that have lost one or more electrons—more or less permanently resident at the positions required by the lattice structure of the metal crystal, together with the lost electrons free to move about among the ions. The simplest assumption of all, which should be correct for monovalent metals like the noble metals and the alkalis, is that each atom sets loose exactly one electron. The electrons and ions act on one another with the usual Coulomb forces, but to the first approximation the effect of these from the point of view of an electron is to make the interior of the metal an electrically neutral region of roughly constant *positive* potential, such that work must be done to extract an electron and leave it at rest outside in free space at zero potential. Inside the metal, then, to this approximation the free electrons will behave like a perfect gas of uncharged partilesc of mass m, the mass of the electron. In the next approximation we must recognize that there are regularly arranged spots (the ions) where there is a more or less violent deviation from uniformity; classically a moving electron will suffer collisions at these spots. The electrical resistance of a metal is determined by the rate at which these collisions dissipate the directed momentum in a beam of moving electrons. The mean space rate of dissipation of this momentum, p, involves a length which one calls the mean free path, λ,

$$\frac{dp}{dx} = -\frac{p}{\lambda}$$

The classical theory included in its initial successes even the prediction of conductivities of the right order for not unreasonable values of λ. But it was ruled out of court by at least one outstanding difficulty, that a perfect gas of one free electron per atom would necessarily contribute $\frac{3}{2}R$ to the specific heat of the metal, that is, 3 calories per gramme-atom per degree Kelvin, whereas no comparable contribution is allowable. The vibrations of the massive ions satisfactorily account for the whole, and there were other related difficulties. The main difficulties could have been turned by supposing that there were only a few free electrons doing all the work; they would then require to have correspondingly long free paths. The surprising effect of small traces of impurity upon conductivity requires these long free paths to be real. But classically it was quite impossible that the free path should be much longer than the atomic spacing in the lattice.

(3) The Quantum Mechanical Revision.

All these and similar difficulties have been entirely removed by the quantum mechanics working on Drude's model of a metal quite unaltered. In fact, it was the dynamics of electrons, not the physical model of a metal, which was wrong and impeding progress. A recognition of some of the more subtle features of quantum mechanics is required to put us on the right track. Let us now approach the problem of metals afresh, starting with the quantum mechanical behaviour of a single electron in the approximate potential field provided by our model of a metal. Quantum mechanics assigns to any such system a certain number of possible stationary states whose energies are fixed by the condition that solutions of a certain linear differential equation (Schrödinger's) shall exist, satisfying certain obvious physical requirements. If V is the potential energy of an electron, h Planck's constant, and ∇^2 the familiar operator of Laplace, then this equation is

$$-\frac{h^2}{8\pi^2 m}\nabla^2\psi + (V - W)\psi = 0$$

and the possible values of W are the possible *total* energies of the electron. Now our picture requires that V shall vary rapidly near the metal boundary, and otherwise be either 0 or $-C$, according to whether we are outside or inside. The transitional region in Fig. 1 is probably fairly thin, but we need not at this stage worry about it, for it can be shown that it makes no difference if we take it instead as a sudden step. Again as this step is fairly high (10 volts or so would be high for present purposes) it makes little difference if we take it infinite. We have then to solve the wave equation

$$-\frac{h^2}{8\pi^2 m}\nabla^2\psi - E\psi = 0$$

where E is *kinetic* energy, subject to the condition that $\psi = 0$ on the boundary and outside, where V becomes infinite.*

It is easy to solve this equation if the region within which the electrons are confined is a rectangular box, of edges a, b, c. The shape of the box can be shown not to matter for practical applications. For this simple shape the possible kinetic energies are given by

$$E = \frac{h^2}{8m}\left(\frac{r^2}{a^2} + \frac{s^2}{b^2} + \frac{t^2}{c^2}\right)$$

where r, s, t are positive integers and the corresponding function ψ is

$$\psi = \sin\frac{\pi r x}{a}\sin\frac{\pi s y}{b}\sin\frac{\pi t z}{c}$$

We now find, on account of the smallness of h and in spite of the smallness of m, that if we take a box of any ordinarily small size, let us say 1 mm^3 or even a cube of edge $\frac{1}{2} \times 10^{-4}$ cm, a wavelength of visible light, the energies of the possible stationary states lie so close together that we cannot distinguish them for practical purposes from the continuous distribution allowed by classical mechanics. If we then packed into such a box a number of electrons comparable with the number of atoms in the same volume of metal, *and if they did not interfere with one another in any way*, we should get a distribution of free electrons indistinguishable from the classical (Maxwellian) distribution of Drude's theory—with the same properties and the same failure as a representation of an actual metal. But here quantum mechanics makes its first really fundamental contribution in this field, as was first pointed out *for metal theory* by Sommerfeld. It is that one can never, even in zero-order approximation, as it were—even in the limit of vanishingly small interactions of the particles' mutual potential energy—treat a composite assembly of two or more electrons by simple combinations of the states possible to one electron. To the present depth of our analysis, at least, this is not because of the Coulomb repulsion between the electrons. It applies equally in the limit when this may be supposed to be neutralized. It is not because of other forces which might be regarded as giving the electron *a size*. It is something far more fundamental, entering into the quantum dynamics because its equations are all *linear* in the fundamental wave-function ψ, and entirely foreign to classical particle dynamics because its equations are essentially non-linear, for example in the momenta. It is mathematically like a species of interference due to the superposition of wave systems, with which you will all be familiar in ordinary oscillating systems, though this analogy must be used with extreme caution. One is apt to think of the de Broglie wave systems associated with particles by the quantum mechanics as wave systems like electromagnetic waves in the ordinary space-time of physics. But the wave system of a pair of electrons, for example, is, so far as it is anything describable, strictly a wave system in a six-dimensional space, and so on for more electrons. Electromagnetic or optical analogies are invaluable, but when we wish to use our results by interpreting them in physical space-time, the greatest caution may be necessary. Well, whatever may be the correct physical description, the theory is certainly of such a form that possible states of two or more electrons present in a single box together are confined to a selection only of all the states that can be built up by repetition from the states of a single electron. The proper selection can be simply described by saying that *no two electrons can ever be simultaneously in the same stationary state*—a saying which holds for all assemblies

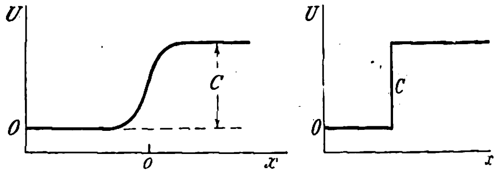

Fig. 1.

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* This is the form to which our physical requirements reduce in such a limiting case.

of electrons, e.g. for a single free atom, for which it was first detected semi-empirically by Pauli, being generally now known as *Pauli's principle*. The principle must be strictly interpreted. We shall have to admit later on that electrons have a spin of their own and an associated magnetic moment which is capable of exactly two orientations, along and against any magnetic field. These two orientations may be regarded as the two possible values of another quantum number which, with r, s and t, makes up four for each electron. The strict enunciation of Pauli's principle is, then, that in any assembly of electrons no two electrons may ever have the same *four* quantum numbers.

I have deliberately stressed the independence of Pauli's principle of any crude mutual potential energy between the electrons. This is the correct and only not-misleading attitude to adopt at the present development of the theory. But perhaps if the recent researches of Eddington [*] prove ultimately fruitful one may hope to fuse together Pauli's principle and Coulomb interactions as two manifestations of a single, more comprehensive, scheme.

As I have said, Pauli's principle is a direct consequence [†] of the laws of quantum mechanics, and it was its introduction into metal theory by Sommerfeld that gave metal theory its new start. Allowing for Pauli's principle, we find that the number of free electrons with kinetic energies between E and $E + dE$ in a unit volume of an idealized metal, instead of being given by the familiar distribution law of Maxwell

$$n(E)dE = A'e^{-E/kT}E^{\frac{1}{2}}\,dE \quad . \quad . \quad . \quad (1)$$

is given by the slightly different law of Fermi and Dirac

$$n(E)dE = \frac{4\pi(2m)^{\frac{3}{2}}}{h^2} \cdot \frac{E^{\frac{1}{2}}\,dE}{1 + e^{E/kT}/A} \quad . \quad . \quad (2)$$

A, A' are constants so adjusted that the total number of electrons of all energies is correct—say, the equivalent of one per atom for a monovalent metal. It will be noticed that equation (2) reduces to equation (1) when A is very small, but there is no resemblance when A is large. When A is large its value is given approximately by

$$A = e^{\bar{E}/kT}, \quad \bar{E} = \frac{h^2}{8m}\left(\frac{3n}{\pi}\right)^{\frac{2}{3}}$$

where n is the total density of the electrons.

Just here is where the very small mass of the electron takes effect. Obviously A depends on the mass, and turns out to be large for electron densities of the order of metallic ones, so large, in fact, that the distribution would be quite unclassical even, for example, for copper at 1 500° K. This is shown clearly by the actual distribution law sketched by Nordheim in Fig. 2. At ordinary room temperatures, and even well above, the distribution is such that, nearly enough,

$$n(E) \propto E^{\frac{1}{2}} \qquad [\bar{E} < \bar{E}]$$

$$n(E) \propto e^{-E/kT}E^{\frac{1}{2}} \qquad [\bar{E} > \bar{E}]$$

What happens is that at all such temperatures practically every possible electronic state for which $E < \bar{E}$ is occupied by its one electron, while for $E > \bar{E}$ practically all are empty. The very few electrons that are there are too few to worry each other, so that they can obey Maxwell's law.

We find at once that the specific heat difficulty melts away. One can see at a glance from Nordheim's figure that the change of energy content with change of temperature must be very small. Detailed calculation confirms this and gives the total kinetic energy, $E_{kin.}$,

$$E_{kin.} = \frac{\pi}{40} \cdot \frac{h^2}{m}\left(\frac{3n}{\pi}\right)^{\frac{5}{3}} + \frac{2\pi^3 mk^2T^2}{3h^2}\left(\frac{3n}{\pi}\right)^{\frac{1}{3}}$$

from which the specific heat contribution is utterly negligible. (It is in fact *too* small, and later more refined calculations by Bloch [*] make it rather larger generally and possibly much larger in a limited region, so that it is able to account in a most satisfactory way for certain interesting specific heat anomalies such as are found, for example, by Simon [†] at fairly low temperatures for grey tin and other metals.) The constant term, on the other hand, is large; the electrons have a large "zero point energy." But this is without importance for metallic phenomena.

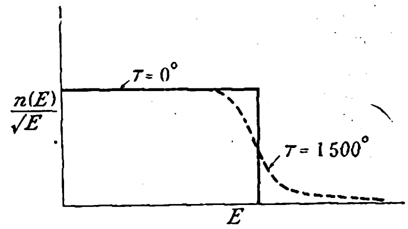

Fig. 2.

(4) The New Conduction Theory.

So far, so good—now comes the real crux. What happens in conduction problems, which are not equilibrium states but states of steady flow?

In a preliminary survey Sommerfeld revised Lorentz's calculations by using the new equilibrium $n(E)$ instead of Maxwell's, and showed that to give observed conductivities the mean free paths must be very long. This is all to the good, as we have seen for empirical reasons, but classically a free path in a metal of from 10 to 100 interatomic distances seems to be nonsense. Quantum mechanically, however, it is just what we must expect, as the work of Houston,[‡] Bloch [§] and Peierls [||] has shown us. For if one examines the behaviour of an electron now no longer in a region of uniform potential but in a potential with variations which are perfectly space-periodic, one finds that though these periodic variations alter the energies of the stationary states of an electron in our box yet they do not affect at all its power to move freely through the box in a given direction. Such perfectly periodic variations of potential can correspond only to a metal which is a perfectly pure, perfect single crystal at zero temperature, assuming that then all the ions are at rest relative to each other. But in such a substance the mean free path of an electron with a kinetic energy of a few volts should be infinitely long, and the substance should possess an infinite conductivity. One can give an analogy to these long or infinite free paths from physical optics. Light in passing through an optically homogeneous medium such as air or many crystals is to a first approximation not scattered or absorbed at all, though every molecule is a potential scattering centre. As was first shown by the late Lord Rayleigh, it is only local deviations from perfect uniformity that scatter the light; deviations which in a dust-free gas are probably fluctuations of concentration and in a crystal flaws and foreign bodies. Just so the de Broglie waves of the electron are not scattered by perfectly regular lattices but only by random deviations from perfect regularity, due to thermal agitation, to strains or to impurities.

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[*] *Proceedings of the Royal Society*, A, 1930, vol. 126, p. 696.

[†] This is not an entirely correct statement. Quantum mechanics cannot yet predict that electrons will in fact obey Pauli's principle; it can as yet only show that if initially all electrons obey this principle, they will continue to do so for ever.

[*] *Zeitschrift für Physik*, 1928–29, vol. 52, p. 555.

[†] *Berliner Berichte*, 1926, p. 477.

[‡] *Zeitschrift für Physik*, 1928, vol. 48, p. 449.

[§] *Loc. cit.*

[||] *Annalen der Physik*, 1929, vol. 3, p. 1055; and 1930, vol. 4, p. 121

This description, however, is still not entirely adequate. It is quite certain, both theoretically and from X-ray evidence, that at the absolute zero of temperature the ions of a metal crystal are not at rest in their positions of equilibrium but oscillating about them, the whole crystal containing a considerable irreducible zero point energy of oscillation. This fact, which at first sight appears destructive of the theory, urges a closer investigation, for conductivities certainly tend to infinity in favourable cases as the temperature tends to zero, even apart from questions of supra-conductivity. It is then found that one cannot properly discuss the mean free path without investigating in detail the exchange both of energy and momentum between an electron and the lattice, which must occur when a free path is terminated. One can analyse the motion of the ions in the lattice into elastic waves in the manner of Debye in his theory of specific heats. In order that a free path may be terminated it is necessary:—

(1) That an electron of energy E and momentum p shall be transferred to E', p', *which latter, by Pauli's principle, must be a vacant stationary state.*

(2) That the oscillatory state of the lattice shall change to a new state absorbing the energy and momentum differences $E - E'$, $p - p'$.

At high temperatures there is comparatively little difficulty in fulfilling these requirements, but at low temperatures Pauli's principle makes it difficult for an electron to do anything but gain energy, while the oscillations of the lattice, being almost entirely in their lowest state, find it almost impossible to lose energy. Thus the chance of exchanges (in spite of zero point energy), and with that the resistance, rapidly diminishes.

Quantitative investigation on these lines has been carried through exactly for high temperatures and yields an electrical resistance varying as T, in admirable agreement with experiment. At low temperatures the investigation is much more difficult, and theoretical resistances varying like T^3, T^4 or T^5 have been obtained. While any of these is, generally speaking, in fair agreement with experiment, it seems to me that the final investigation has yet to be made. We may, however, rest well content with what has been done until the next step can be taken in relating the theory to supraconductivity. This step has not yet been taken. It may be connected with the theory of magnetic effects, about which I shall say something later in connection with Kapitza's experiments.

(5) THERMO-ELECTRIC EFFECTS.

Before leaving the subject of conductivity I should record that the theory as so far developed gives an explanation of reversible thermo-electric phenomena, which in a general way is entirely satisfactory. The various thermodynamic relationships are of course preserved, and the Thomson and Peltier coefficients are given, even by Sommerfeld's version, values of the right general order of magnitude and type of variation with absolute temperature. The refinements introduced by Bloch and Peierls could no doubt be made to give a very satisfactory account for many metals. I should like to mention in conclusion a valuable critical article on these effects and their relationship to equilibrium states recently published by Stern.*

(6) EMISSION OF ELECTRONS.

We have so far tacitly assumed that all the electrons stay for ever in the metal, as of course they would have to do if the potential step at the surface were infinitely high. But if the step is finite no part of what precedes is effectively altered, except that formula (2) indicates that there are present in the metal at any time a certain number of electrons (depending on the temperature) with sufficient energy to escape. Since free paths are rather long, it is sufficient to ignore the periodic lattice structure in the potential and consider what happens when an electron of kinetic energy E falls on a potential step or hill, in which to a first approximation the potential is a function of the distance from the boundary alone. It is easy to show that in such a problem the motion of the electron parallel to the surface is unaffected, and the problem resolves itself into a one-dimensional one. We can now confine attention to a stream of electrons of energy W in its motion normal to the surface incident from inside the metal on potential hills of various shapes. Typical natural and idealized boundary hills are shown in Fig. 3.

Now the classical solution of this problem is rather hard-and-fast and gives no scope for the observed variety. The electron would then always come out if $W > B$, the summit height of the hill, and never if $W < B$. In the quantum mechanics, however, things are very different. The electron never comes out if $W < C$, the *final* height of the step, but always has a non-zero chance of coming out if $W > C$, even though $W < B$. If we call this chance of emergence $D(W)$ and $N(W)dW$ the number of electrons incident on unit area in unit time with normal energies between W and $(W + dW)$, the total saturated current I per unit area which the metal can emit (supposing it is all collected as in the usual thermionic measurements) is given by

$$I = e\int_0^\infty N(W)D(W)dW$$

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* *Proceedings of the Royal Society*, A, 1930, vol. 126, p. 570.

Now on Sommerfeld's theory we know $N(W)$, and this theory is amply accurate for the present application. We can calculate $D(W)$ and hence the thermionic current I. I think one may say that these calculations are successful, for they show that $D(W)$ is sensitive to the nature of the hill, *that is to the nature of the surface layer, which may often be a layer of impurity present by accident or design.* The theoretical current is given by the formula

$$I = AT^2e^{-\chi/kT}$$

where A and χ are constants characteristic of the emitter. This is of the well-known proper empirical form, but the theory further accounts correctly for the empirical correlation between A and χ (the work-function), by means of the effect of these potential hills. I do not want to spend more time on these points now. I dealt with them in detail in the Boyle lecture at Oxford this time last year. I think it is fair to say that, using perfectly natural assumptions as to the nature of the boundary hill, the usual phenomena of emission of electrons from hot metals, under very strong electric fields and under the influence of light, can to a first approximation be accounted for to our complete satisfaction. I think, however, it would interest you if I said a word or two more about how it is that an electron can go through a region in which its kinetic energy is apparently negative. Its chance of going through is large if the region is very thin, and dies away exponentially as the region widens. When we consider the wave nature of the electron, regarding it as a train of de Broglie waves, we see that this is closely analogous to a well-known phenomenon of physical optics. If light is incident on a plane interface at an angle greater than the critical angle, there is total internal reflection. But if the second medium is very thin, only a few wavelengths thick, and followed by a third medium the same as the first, there *is* a weak transmitted beam formed in the third medium after all.

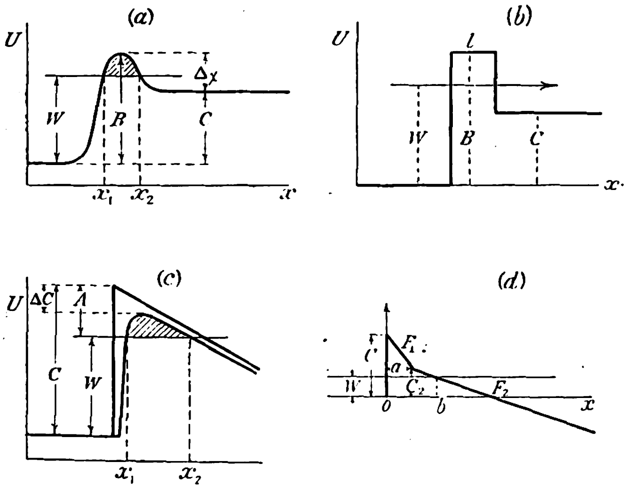

FIG. 3.—Typical natural and idealized boundary potential hills.

(*a*) A natural type of hill when an electro-positive mono-molecular layer is present and the image force is ignored; (*b*) The same, idealized for simplicity of calculation, but without loss of any essential feature; (*c*) An idealized hill (a precipice) with a strong external field of force helping to pull out the electrons, and the same hill modified by the image effect. (This modified type of hill explains the Schottky effect, and the unmodified the ordinary auto-electronic discharge); (*d*) A hill with two slopes, one intrinsic and the other that of the applied external field, explaining the combined effect of strong fields and mono-molecular surface layers.

(7) MAGNETISM AND FERROMAGNETISM.

We have been able to advance so far ignoring the specific interaction of the Coulomb forces between each pair of electrons or ions. But Heisenberg * has shown that when these are taken into account, and also the magnetic moments of the electrons themselves, the theory, though still in a larval stage, gives a beautiful account of ferromagnetic phenomena.

The first step in this part of the theory was really due to Pauli † and concerns the approximation in which we still neglect the Coulomb interactions. We infer from atomic spectra that every electron has a spin or moment of momentum of $h/(4\pi)$, that is, a one-half quantum according to ideas with which we have been familiarized long since by Bohr, and at the same time a magnetic moment of one Bohr magneton. The Bohr magneton is the magnetic moment of any electronic orbit in any atom in which the electron has just one unit, $h/(2\pi)$, of orbital angular momentum. Thus the ratio of magnetic moment to angular momentum for the intrinsic spin of the electron must be just double the ratio of these quantities for any electronic central orbit. (Incidentally, this fits beautifully into the later versions of relativistic quantum mechanics which we owe to Dirac.) If, then, our free metallic electrons carry each a Bohr magneton the axis of which can be turned along and against any imposed magnetic field, why are the alkalis and noble metals not strongly paramagnetic with a temperature-dependence similar to that of the classical gas-theory of Langevin? The answer is that once again Pauli's principle intervenes to prevent the accumulation of the electrons at any reasonable temperature into states in which an appreciable excess are orientated along the field. The susceptibility of our electron gas is not difficult to work out exactly, though I shall not attempt to do so here. It turns out that there is theoretically a slight residual temperature-independent paramagnetic susceptibility of the same order as the usual diamagnetic one, which, in combination with a normal diamagnetic effect from the ions, accounts very satisfactorily for such paramagnetic effects as are actually observed in the lighter alkalis. These effects are really extremely small, and from here on we shall ignore them and speak as if our idealized metals, neglecting specific interaction effects, are (as they should be) magnetically neutral. We have, of course, assumed here that the ions are inert, as they would be for the monovalent ions of the alkalis and the noble metals, which contain only completed groups of electrons.

In introducing his theory of ferromagnetism, Heisenberg points out that as a *formal* explanation of the whole body of ferromagnetic phenomena, Weiss's familiar theory is completely satisfactory. The essence of the theory is that there must be in the total internal energy of a ferromagnetic substance a rather large term which depends in a certain way on the magnetization. Granted the existence of this term, known as Weiss's molecular field, everything fits together as it should, but the difficulty has been to account rationally for its existence, since the actual magnetic energies involved are some 10 000 times too small. This defect quantum mechanics and Heisenberg have now removed.

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* *Zeitschrift für Physik*, 1928, vol. 49, p. 619.

† *Zeitschrift für Physik*, 1927, vol. 41, p. 81.

Heisenberg starts by directing attention to the *gyromagnetic anomaly*. You know that there is an effect, sometimes called the Richardson-Einstein-de Haas effect, in which when a bar of metal is magnetized it acquires simultaneously a proportional angular moment of momentum which can be actually measured if the suspension is sufficiently delicate. Since all atomic orbits of electrons have one constant ratio, $e/(2mc)$, for magnetic moment to mechanical moment of momentum,[*] one expects to observe a constant ratio between the magnetization and the angular momentum generated, from which e/m may be calculated. The constant ratio is found, but for all ferromagnetics, for which alone until quite recently experiments have been made, the value of e/m so observed has exactly twice its expected value. This is the so-called anomaly, but the observed value is exactly what one would expect if the magnetization were contributed entirely by the orientation of the intrinsic spins of electrons and not of their orbits at all. We assume, therefore, that the magnetism of a ferromagnetic is derived entirely from the orientation of the spins of its loosely bound or free electrons. Is it then possible to account for the energy of Weiss's molecular field by any obvious terms which we have hitherto disregarded in our simple metal theory?

Heisenberg's affirmative answer is delightfully simple. It is that the necessary terms are to be found in the effect of the Coulomb forces—the electrostatic repulsions and attractions—which must now be taken into account. In this step, however, we meet one of the most elegant subtleties of quantum mechanics, which I will try to explain by using the simplest possible example.

In order to get a feasible method of approach to the interaction problem, Heisenberg idealizes the metal in a different way from that which we have used hitherto. He imagines the crystal lattice to be composed of *atoms*, not ions, and expanded by continuous growth of the lattice constant until all the atoms are rather far apart. This looks so different a model as almost (if accepted) to deny the validity of our old one—but this inconsistency is only superficial, and it has in fact been shown by Bloch [†] (at least, I think his argument is valid) that one can get similar effects to Heisenberg's by putting the interactions into our original model; the necessary technique is, however, more complicated and we may follow Heisenberg, recognizing that there is nothing inconsistent with our previous model in his method of approximation, even if the magnetic and conduction electrons are the same, as recent experiments seem to establish. We must therefore discuss the possible stationary states and energies of a large number of regularly arranged similar atomic systems each containing one, two or a few electrons in similar orbits sufficiently loose for the interactions to matter. The large number, though essential to represent a metal, introduces merely complications of detail but none of kind: we can confine attention to *two*, and for purposes of illustration to two hydrogen atoms in their normal states.

Now here again the linearity of the wave functions comes in. It is impossible, when account is taken of the electrostatic interactions, for there to be a stationary state in which one electron is in one atom and the other in the other. If we could start with a particular assignment we should still find after a time, depending on the distance apart, that the electrons had changed places. When the atoms are fairly close together these exchanges become quite rapid and the corresponding energy term—the electrostatic interchange energy, as it is sometimes called—quite large and nearly comparable with the unperturbed energies. The system, of course, has actual stationary states (in fact two) of definite energies, which may be regarded as built up by superposition in definite ways out of the unperturbed solutions with the electrons in their separate atoms. The two states have quite different energies which vary differently with the distance apart of the atoms. In one of them the electron-spins and magnets balance each other out and the system has no magnetic moment. In the other the spins have to be parallel and the system has a magnetic moment of two Bohr magnetons. The energy difference of the two states, due to the electrostatic interchange term, is of altogether greater order, at least when the atoms are fairly close together, than the magnetic energy terms themselves. Now suppose we consider a number of such pairs set parallel, and far apart from each other in a magnetic field. The magnetic field will alter the distribution of all the electron magnets (to what exact amount, of course, it is part of Heisenberg's problem to calculate) and therefore the relative number of pairs which are neutralized or possess a magnetic moment, and of course the orientation of the latter. It will therefore have to alter the distribution of the pairs among their two stationary states, and therewith the energy content of the whole system, and that, too, by an amount depending on the magnetization, which is very large compared with the magnetic energies themselves. Here is the true origin of Weiss's molecular field! The atoms in a real metal lattice, each with an electron in a similar orbit, present a problem exactly similar in type, though it requires the help of abstract group theory conveniently to carry through the calculations. We can now safely proceed to the result of these calculations. Heisenberg finds, for a metal in which there is one "active" electron per atom, that in the equilibrium state the magnetization σ is given by a root of the following equations:—

$$\frac{\sigma}{\sigma_0} = \tanh x \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$2x = \frac{e}{mc} \cdot \frac{h}{2\pi} \cdot \frac{H}{kT} + \frac{\sigma}{\sigma_0}\left(\frac{zJ_0}{kT}\right)\left(1 - \frac{J_0}{kT}\right) + \frac{zJ_0^2}{2k^2T^2}\left(\frac{\sigma}{\sigma_0}\right)^3 \quad (4)$$

These equations are essentially the same as Weiss's. In them σ_0 is the maximum possible magnetization, σ the equilibrium magnetization at temperature T under a magnetic field H, k is the gas constant for one atom, z is the number of nearest neighbours to any given atom in the metal (Heisenberg neglects all interactions except between nearest neighbours), and J_0 is practically the interaction energy which gives the energy separation between the stationary states of a pair of neighbours. In order that the metal may be capable of ferromagnetism J_0 must be *positive*; in order that the Curie point may be at a reasonably high temperature J_0 must be rather large. Heisenberg can show in a general way that these conditions are rather difficult of fulfilment and that ferromagnetics might be expected to be rare and to be found only (as they are) among the metals of least atomic volume—a genuine triumph! *

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[*] Here c is the velocity of light, and e/m the ratio of charge to mass for the electron.

[†] *Zeitschrift für Physik*, 1929, vol. 57, p. 545.

(8) KAPITZA'S EXPERIMENTS ON CONDUCTIVITY IN STRONG MAGNETIC FIELDS.

We have now glanced cursorily over that part of the field in which quantum mechanics has consolidated the position of the theory, ignoring, for lack of time and space, many pretty corners. I would now direct your attention to most interesting results recently obtained by Kapitza, not yet accounted for by quantum mechanics but promising to throw much light on the theory of metals. It had been believed, on the evidence previously available, that the resistance of a metal was increased by a magnetic field H by an amount proportional to H^2. Kapitza has shown that for larger fields this is not true, but that the actual change of resistance can be very closely represented by a formula of the following type:—

$$\frac{\Delta R}{R} = \beta\frac{H^2}{3H_k} \qquad [H \leqslant H_k]$$

$$\frac{\Delta R}{R} = \beta\left(H - H_k + \frac{H_k^2}{3H}\right) \qquad [H \geqslant H_k]$$

This form has been confirmed by later experiments by Meissner. ΔR and H_k appear to be independent of the temperature for a given specimen, but H_k is violently sensitive to the mechanical treatment to which the specimen has been subjected, and also to its purity. Naturally this is not the only formula which would represent the facts, but it does represent them in what appears to be a significant way, and we shall accept it provisionally here. The form suggests that there are random disturbances in the metal which have the same effect as, and combine vectorially with the effect of, an externally applied magnetic field, and that the effect on the resistance of this composite magnetic field is directly proportional to its strength H and not to H^2. The above formulæ are derived on this hypothesis from the combined effect of an external field H and an internal field H_k, the latter averaged over all directions. It must be confessed that a large primary effect on the resistance proportional to $|H|$ is at present most surprising theoretically, but theory is not yet in a position to deny the possibility and the deductions from this interpretation are too interesting to be ignored. We are required and enabled by this theory to analyse the ordinary resistance of a metal into two parts—an ideal resistance R_i and an additional resistance ΔR_0 due to the H_k. The former depends only or mainly on the temperature and must be the resistance which we have been theoretically studying hitherto. The additional ΔR_0 is approximately temperature-independent, but depends on the mechanical state and treatment of the specimen and its content of impurities. Moreover, ΔR_0 as obtained in this way should be such that it is the same as the residual resistance observed by Kamerlingh Onnes at very low temperatures. This correlation appears to hold in fact. R_0 should also, when deducted from the actual resistance, leave behind an R_i the same for all specimens of a given metal. This also it appears to do. The hypothesis suggests, further, that perhaps the onset of supra-conductivity is concerned with the sudden disappearance of ΔR_0 rather than of R_i, and that perhaps R_i, if one could measure it properly, ultimately tends violently to zero, perhaps like $e^{-b/T}$. All this is still very speculative but should encourage further advances both in theory and experiment.

(9) CONCLUSION.

It must not be thought that I am too optimistic about the present position of the theory of metals. There is much still to be done. I am optimistic to this extent—that I think that quantum mechanics, as at our disposal to-day, is entirely adequate for a final electron theory of metals, or for any other physical theory which can treat the velocity of light as infinite. But metal theory is still far from adequate; we have still to select the proper model and still more to show that it *is* the proper model. By that I mean, of course, that part of the complete theory of metals is to deduce from the properties of atoms and the principles of quantum mechanics that a collection of, say, copper atoms with a reasonable energy content will form a metal and not, for example, a gas. Further, having formed the metal, the theory must specify what simplications may or may not be made in the further treatment of conduction. In the work I have described these more fundamental problems have not been touched, but I think that a very promising beginning has been made on them by Slater.* It appears likely that this work and the complete theory when it comes will very greatly modify the simple model which we have used hitherto. But part of my faith in quantum mechanics is derived from the fact that, give it any physically reasonable model, it provides results which are always in good sensible accord with the requirements of experience. Experimenters and theoreticians alike, we can all, I think, press forward with our work in the confident expectation that we are on the right lines and that progress will be sure and not particularly slow.

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* BLOCH (*Zeitschrift für Physik*, 1930, vol. 61, p. 206) has still further advanced the theory by improving it for low temperatures with the help of very important new methods developed by SLATER (*Physical Review*, March 1930).

* *Loc. cit.*

SURGE INVESTIGATIONS ON OVERHEAD LINES AND CABLE SYSTEMS.

By S. W. Melsom, Member, A. N. Arman, B.Sc., Associate Member, and W. Bibby, B.Sc., Associate Member.

[*Paper first received* 17*th December*, 1929, *and in final form* 20*th February*, 1930; *read before* The Institution 10*th April*, *and before the* West Wales (Swansea) Sub-Centre 25*th April*, 1930.]

Summary.

The paper describes measurements of surge voltages made under actual working conditions on 33-kV transmission lines both overhead, underground and composite.

The apparatus used for the measurements was the klydonograph, and the paper gives a description of this instrument in its final form and a discussion of its working principles. The specially designed auxiliary condensers required to subdivide the line voltage are also described.

Measurements on three important transmission systems covering a year or more of continuous recording are detailed. Generally there is a large amount of oscillatory surging set up by brushing at insulators when such insulators are in a dirty condition, the over-voltage being of very high frequency and of the order of three times the normal line voltage.

The atmospheric conditions under which salt is deposited on insulators are described, and some of the records show the effect on the line voltage of a salt-laden insulator up to the time at which flash-over occurred and the line was put out of operation.

The question of porcelain insulators to meet the prevailing foul conditions and to avoid surges due to brushing is discussed. It is shown that with proper attention to design the voltage at which brushing commences can be materially increased, and it is suggested that this factor is of even greater importance than a very high initial flash-over voltage.

Introduction.

The extent to which over-voltage surges may be present in transmission systems, and their responsibility for breakdowns, have long been subjects of discussion, with, however, few or no data based on definite measurement.

With some systems on which a great deal of trouble had been experienced it became necessary fully to investigate the possibility of surges under actual working conditions, to trace their source and to find a means of eliminating them.

Consideration of the apparatus available for the purpose led to the adoption of the klydonograph as being the most suitable apparatus for the continuous records required, and therefore the paper may appropriately start with a brief description of the instrument and its working principles.

The klydonograph is an instrument for continuously recording the voltage of a system, and it will record surges of very short duration and over a wide range of frequency. It has been used in America under practical conditions for some years now, and the authors think that a description of the apparatus and its operation, with the results obtained on various British systems and the conclusions to be drawn from them, would be of interest, especially in view of the modern extension of overhead-line systems.

The principle of the instrument as devised by J. F. Peters is based primarily on the phenomenon known as the Lichtenberg figure. Lichtenberg* showed that, under electric stress, particles of certain types of powder, and particularly sulphur, would arrange themselves in a definite manner in the electric field. Later, Brown† and Trouvelot‡ discovered that the emulsion of a photographic plate was affected by electric pressure much in the same way as the dust used by Lichtenberg. Since 1888 considerable work has been done by various investigators to determine the nature of the phenomenon, but up to the present it has not been satisfactorily shown whether the effect is the ordinary one of light on the plate—with the pressure that is used there is always a slight discharge which acts in the same way as ordinary exposure of the emulsion to light—or whether it is in the nature of a rearrangement of the particles of the emulsion, due to electric stress.

The main function of the work described in this paper has been to use the instrument to record surges and not to investigate its fundamental physical properties, but consideration and a certain amount of experiment have naturally been directed to this aspect, which is discussed later.

Peters§ applied the principle to produce a surge recorder, and a full description of his apparatus and its use is given in various papers. Briefly, the instrument consists of a photographic film passing from one spool over an insulated metal drum on to a take-up spool. At the point of its passage over the metal drum three electrodes rest on the film, the electrical pressure being applied between these electrodes (three for a 3-phase system) and the earthed metal drum. The voltage across the electrodes to obtain a record is of the order of 2 000 volts (R.M.S.), and for the purpose of using the instrument on high-voltage lines dividing condensers are used. These are described later in the paper.

Later came a paper by Lee and Foust‖ in which the phenomena of positive and negative surges and their effect on the size and type of figure obtained were shown, and a method whereby a double-connected instrument could be used was given. The circuits of the two instruments are shown in Figs. 1 and 2.

The Peters instrument was first used for the authors' investigations, but after some time it appeared that improvements could be effected both to overcome difficulties in operation and to facilitate desirable experimental work with the instrument. Therefore, in the later instruments used the design was radically changed. In place of the single wide film, ordinary cinema films of standard size were used—a cheaper and better arrangement—and the instrument was of the double-pole type. Fig. 3 shows the principle. The films are drawn by the sprocket wheels between the electrodes, so designed that they can be adjusted and interchanged, and are then taken through to the take-up spools. Moreover, the instrument is designed to permit of access to the films and electrodes and so that adjustments may be made without otherwise affecting the operation, and, most important, the exposed length can at any time be cut off and removed for developing.

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* See Bibliography, (1). † *Ibid.*, (3). ‡ *Ibid.* (2). § *Ibid.*, (7). ‖ *Ibid.*, (13).

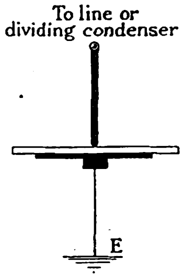

FIG. 1.—Direct-connected klydonograph.

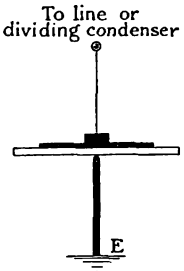

FIG. 2.—Opposite-connected klydonograph.

The type of figure obtained as a result of application of electrical pressure is becoming familiar from the American publications; and most interesting figures can be obtained with quite simple apparatus. An ordinary photographic plate in a lightproof box, placed with its glass side on a sheet of tinfoil and having a spherically ended electrode on its film side, can be made to produce remarkable figures.

CALIBRATION.

The factors which govern the size and type of figure obtained are peak voltage, polarity of the wave, and steepness of the wave-front.

In Fig. 11 (see Plate I) are shown typical examples of positive and negative figures obtained with steep-fronted waves, produced by the discharge of a condenser, and also some figures produced by alternating voltages of normal supply frequency. The negative figures obtained with the steep wave-front will be seen to be much smaller than the positive, and they are also less clearly defined. For this reason the double-electrode system has been adopted so that surges of negative polarity will be recorded on the reverse-connected electrodes as positive figures. Other observers hold that, in addition to altering the nature of the figure obtained (as shown in the illustration), the steeper wave-front gives a slightly larger figure.

For calibration purposes the authors used a 50-cycle sine wave.

It is usually stated that the klydonograph is entirely insensitive to voltages of less than about 2 500 (peak value), and in the American work the normal voltage applied to the instrument was of the order of 3 300 (peak). It was found, however, that quite definite figures were obtained at a lower voltage, although a marked increase in sensitivity occurs at approximately 2 500 volts (peak)* at normal temperature.

Working slightly below this steeper part of the curve an even more definite normal-voltage line is obtained, and it was considered important to make use of this critical point to record surges of moderate magnitude.

The difference between normal voltage and surge conditions is more clearly seen, and all this work has shown the importance of recording the oscillatory disturbances of comparatively small magnitude—small, that is, compared with a lightning stroke. A complete calibration curve is given in Fig. 4.

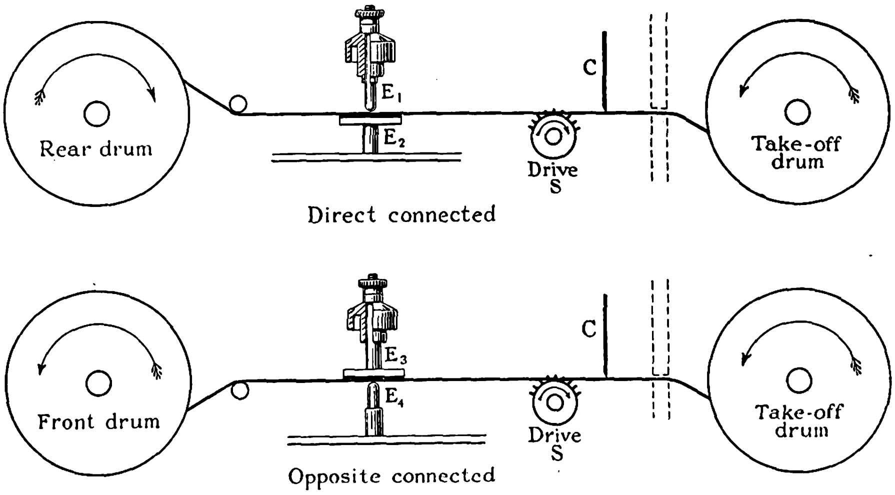

FIG. 3.

Care has to be exercised if consistent results are to be obtained, and it is important that a standardized developing process be adhered to. For their work the authors used Kodak special developer, the concentrated solution always being prepared exactly according to the instructions on the packet. This solution was diluted with tap water in the proportion of 3 parts of water to 1 of solution. The developer was maintained at 65° F. during use.

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* It will be noted that the voltages are all expressed as peak voltages since this is the value of importance in this type of work.

The film is wound from the detachable take-up box on to a glass drum capable of accommodating about 28 ft. of film. Beneath the stand on which the drum is mounted a dish of developer is placed so that the lower part of the drum rests in the developer (see Fig. 5). The drum is then slowly revolved in the solution for 5 minutes by the clock. The drum and stand are then transferred first to a dish of water where the film is rinsed, and then to the fixing bath.

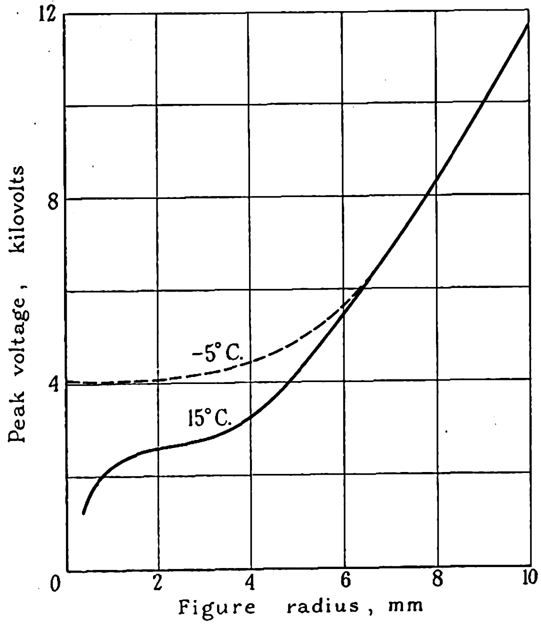

FIG. 4.—Klydonograph calibration.

SENSITIVITY OF TYPES OF FILMS.

In order to determine the most suitable type of film for klydonograph use a number of tests were made for sensitivity and general reliability of different types.

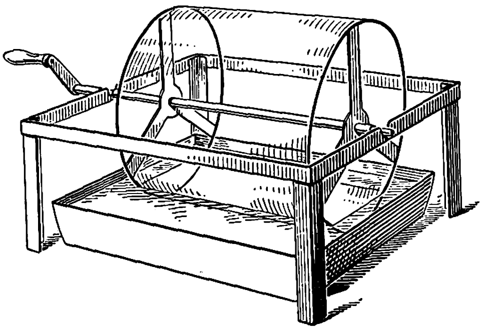

FIG. 5.—Film-developing drum.

In Fig. 6 are shown the approximate sensitivity curves of some of the types tested. It will be seen that the plates are the more sensitive.

The super-speed and par-speed cinematograph films were not very different. The latter seemed to give much more reliable results in the neighbourhood of the critical part of the calibration curve, and as these were more stable films generally they were adopted for use.

At best, however, the sensitivity of different batches of films varied somewhat, and on this account the limits of accuracy are probably not closer than plus or minus 10 per cent.

Effect of Temperature.—The upper portion of the calibration curve is practically unaffected by temperature variations, but it has been found that the lower part, in the neighbourhood of the critical point, is affected at low temperatures. Instead of the curve bending down again below the critical value it slopes straight away to zero, as indicated by the dotted line in Fig. 4. It is therefore necessary to maintain the instrument at a reasonable temperature, and in practice the temperature in the containing hut was so arranged that it did not fall much below 15° C.

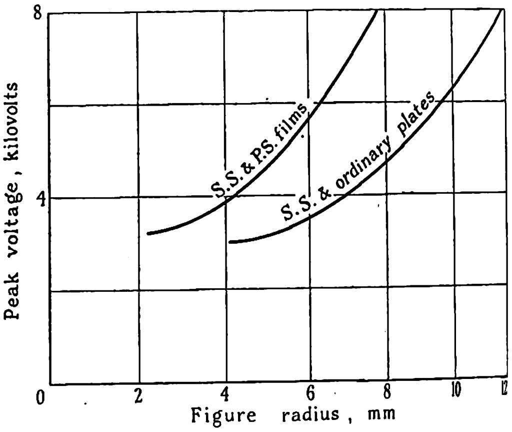

FIG. 6.—Relative sensitivities of plates and films.

Effect of Humidity.—The results obtained up to the present tend to show that the effect of atmospheric humidity is negligible, provided that moisture is not actually deposited on the film surface.

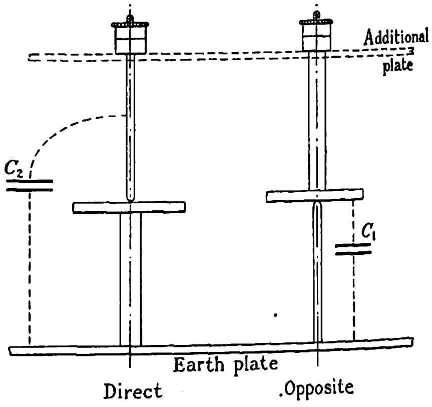

FIG. 7.

CAPACITIES OF ELECTRODE SYSTEMS.

The amount of energy involved in the operation of the klydonograph is minute, and for this reason the capacities of the 2-electrode systems must be exactly symmetrical if uniform results are to be obtained.

In Fig. 7 are shown the two pairs of electrodes and the capacities involved. It will be seen that the capacity C_1 of the live plate electrode to the earthed baseplate is much larger than that (C_2) of the earthed plate to the live point electrode. This has led, in some cases, to a smaller figure being obtained on the opposite electrode with an a.c. voltage applied through an electrostatic divider. This has been overcome, where necessary, by fitting the additional plate, shown in Fig. 7, above the live electrodes and connecting it to them, thus making the system symmetrical as regards capacity.

ELECTRODES.

A great deal of experimental work was done to determine the best shape for the end of the smaller electrode.

Hemispherical, pointed, and flat ends have been used by other investigators, but no reasons have been stated as to why any particular form was adopted.

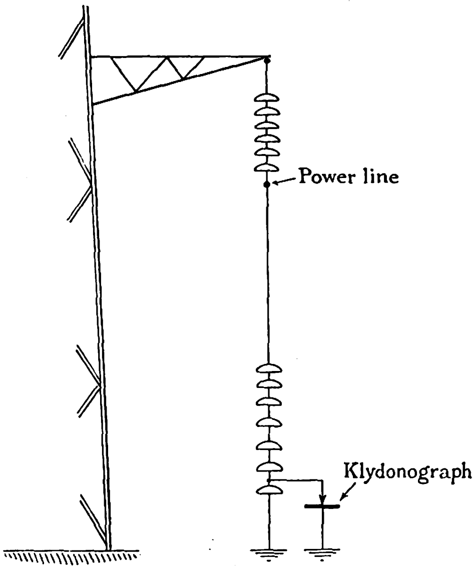

FIG. 8.

Sharp Points.—Although they gave good figures on stationary plates these points proved to be of no use when the film had to be drawn along under them, as they cut through the emulsion and gave very erratic results. In many cases the gelatine was actually torn.

Flat-Ended Electrodes.—These were found fairly satisfactory but gave such a wide normal-voltage line that small surges superimposed on it were easily overlooked. In addition, the flat electrode collects a certain amount of dust from the film surface. This dust becomes electrified and produces irregular fogging effects round the normal-voltage line, sufficient in many cases to mask the fine lines of some surge figures.

Spherically-Ended Electrodes.—These proved most satisfactory and were subsequently standardized. The line produced was of reasonable width, and it was found that by working with the normal voltage just below the critical point of the calibration curve the most sensitive arrangement could be obtained.

A firm normal-voltage line about 2 mm wide was obtained with this arrangement, and surges showed up well, above the critical part of the curve.

Diameter of Plate Electrode.—It has been found by experiment that, provided the plate electrode is slightly larger in diameter than the largest figure to be recorded, the instrument will function satisfactorily. In this case the plate is the full width of the cinematograph film.

Thickness of Ebonite under Film.—The ebonite cover to the plate electrode is not essential to the operation of the instrument; in fact better results may often be obtained by omitting it. It is necessary as a protection, however, when using inflammable films. Should the film run out, or run off its sprockets, a considerable amount of sparking will occur when the edge of the film reaches the electrode, and this sparking might ignite the celluloid of the film. The ebonite cap obviates this danger. A thickness of about 1 mm has been found ample from the safety point of view, and it makes very little difference to the size of figure obtained.

ELECTROSTATIC POTENTIAL-DIVIDERS.

Tapped Insulator String.—This is the simplest type of divider available, and one which has been much used in America. It consists of a string of suspension insulators suspended from the line with the lower end of the string connected to earth (see Fig. 8). The klydonograph is connected across one or more units at the lower end of the string. Such an arrangement works satisfactorily so long as the insulators composing the string are clean and dry. American experience has shown, however, that under wet conditions the division ratio is changed and the normal-voltage line may disappear completely in bad weather. At the same time it has been stated that the ratio remains unaltered so far as steep-fronted waves are concerned. In the present work, where disturbances of all sorts were being looked for, this type of divider was considered to be unsuitable.

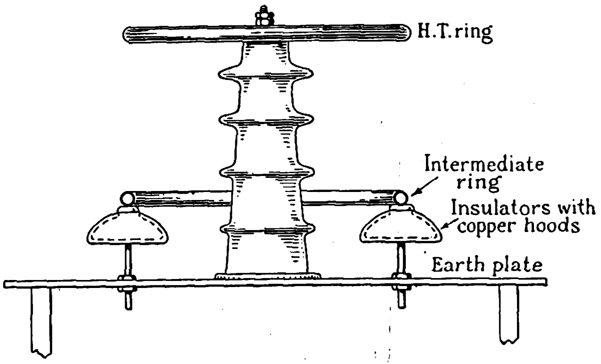

FIG. 9.

Antenna Type.—This type, which consists of an insulated aerial wire suspended beneath the overhead line, is only suitable for single-phase working, or in cases where it is not desired to trace the surges to any particular phase. It was, therefore, not considered for this work. In conjunction with capacity dividers, an antenna can be used to determine the direction of motion of a wave and its steepness, but its use in this connection is difficult owing to the direct electrostatic effects produced on the antenna from the overhead lines.

Ring Type.—This is another type used in America, and as it appeared suitable for use in this country a set of three was made up. It consists (see Fig. 9) of a large circular earth-plate about 5 ft. in diameter, in the centre of which is mounted a tall insulator supporting the high-potential electrode which is in the form of a tubular ring. A second ring, similar to the first, supported on three smaller insulators, is mounted between the h.t. electrode and the earth plate, at such a height as to give the required voltage for the instrument. This ring is adjustable for height over a limited range by means of the screw shanks of the insulator pins. The whole unit is placed on legs so as to bring the high-voltage portions out of reach of an operator working in the enclosure.

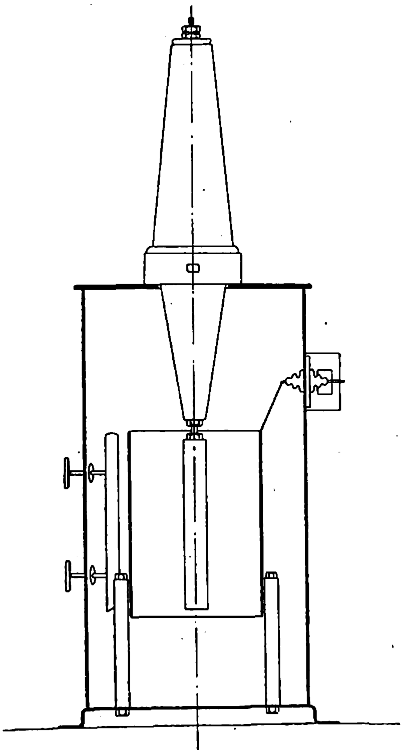

FIG. 10.

The divider in this form was used in America, but it was found necessary to make some modifications for use under English weather conditions. When the insulators supporting the intermediate ring became wetted their capacity to earth was increased to such an extent that the normal-voltage line disappeared. In order to obviate this these insulators were fitted with spun-copper hoods reaching below the bottom edge of the porcelain, and the ring itself was raised to compensate for the additional capacity inserted. With this arrangement the ring capacity was found to be sufficiently constant for reliable operation under wet conditions. Further trouble was experienced owing to the wetting of the centre insulator and to the proximity of other dividers and earthed metallic structures. This trouble was cured by blanking out the top ring so as to form a complete disc. Thus the centre insulator was protected to some extent at its upper end, and also the capacity of the whole system was considerably increased, thereby lessening the effect of stray capacities. With these modifications the dividers proved fairly satisfactory and were largely used in the earlier field work.

When, however, the effects of foul insulators became apparent, a new type was designed, since it was clear that the dividing insulator, although much longer than the line or other working insulators, was subject also to the same fouling from the atmosphere and consequently frequent cleaning was desirable.

Enclosed Cylindrical Type.—This was designed to satisfy the following requirements.

It should be:—

(1) A self-contained transportable unit.
(2) Entirely unaffected by weather conditions.
(3) Unaffected by neighbouring structures and the proximity of other dividers.
(4) Adjustable for secondary voltage over a limited range whilst under pressure.
(5) As small as possible consistent with safety of operation—bearing in mind that surges of four or five times normal voltage had to be allowed for.

The divider as finally made is shown in Fig. 10. It consists of two concentric cylinders forming the high-voltage and intermediate electrodes mounted in, and suitably insulated from, a cylindrical metal container which itself forms the earth electrode.

The electrodes and their insulators being thus enclosed are unaffected by weather and capacity effects due to neighbouring objects, and fouling of the external insulators does not affect the operation as they are outside the electrostatic field. It is of reasonable size and capable of being moved from place to place with moderate ease. Adjustment of instrument voltage to the extent of about 10 per cent is possible by means of the adjusting plate shown. This plate when pushed towards the intermediate cylinder increases the capacity of that cylinder to earth and thus alters the ratio of the divider. It was found necessary to ventilate and drain the containers so as to avoid condensation troubles.

A number of dividers of this type have been constructed and used with very good results.

RESULTS OBTAINED ON POWER SYSTEMS.

The first set of gear was erected in South Wales, to investigate the conditions on a most troublesome overhead line feeding a number of collieries and villages. The line pressure was 33 kV. The line was a composite one in so far as the terminal poles were in each case some distance from the substation, the current from the pole to the substation being carried by 3-core belted-type cable.

Inspection and consideration suggested that the most suitable place for the erection of the gear would be at

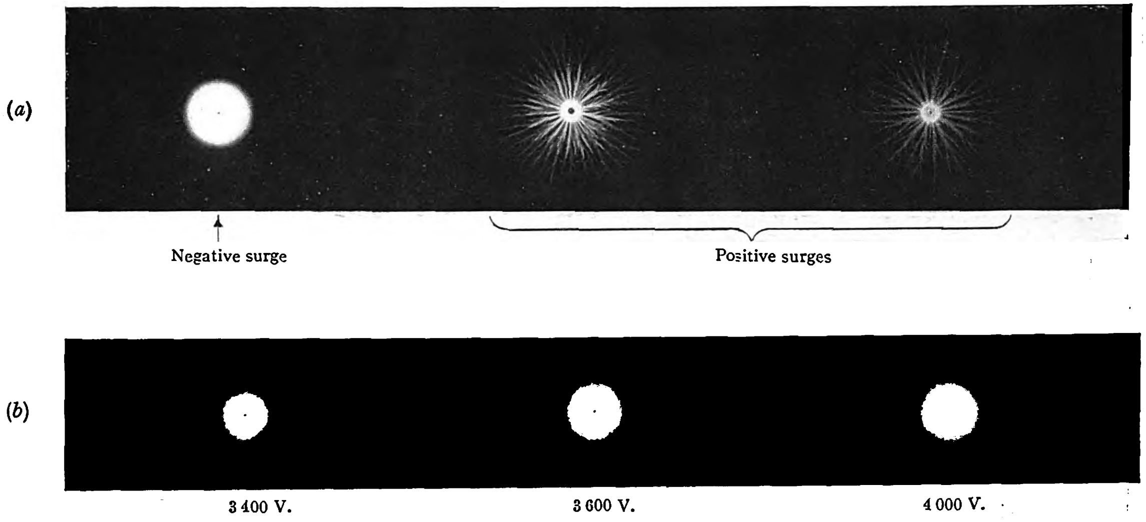
(a)
Negative surge
Positive surges
(b)
3 400 V.
3 600 V.
4 000 V.

FIG. 11.—Typical examples of (*a*) positive and negative figures obtained with steep-fronted waves, and (*b*) figures produced by alternating voltages of normal supply frequency.

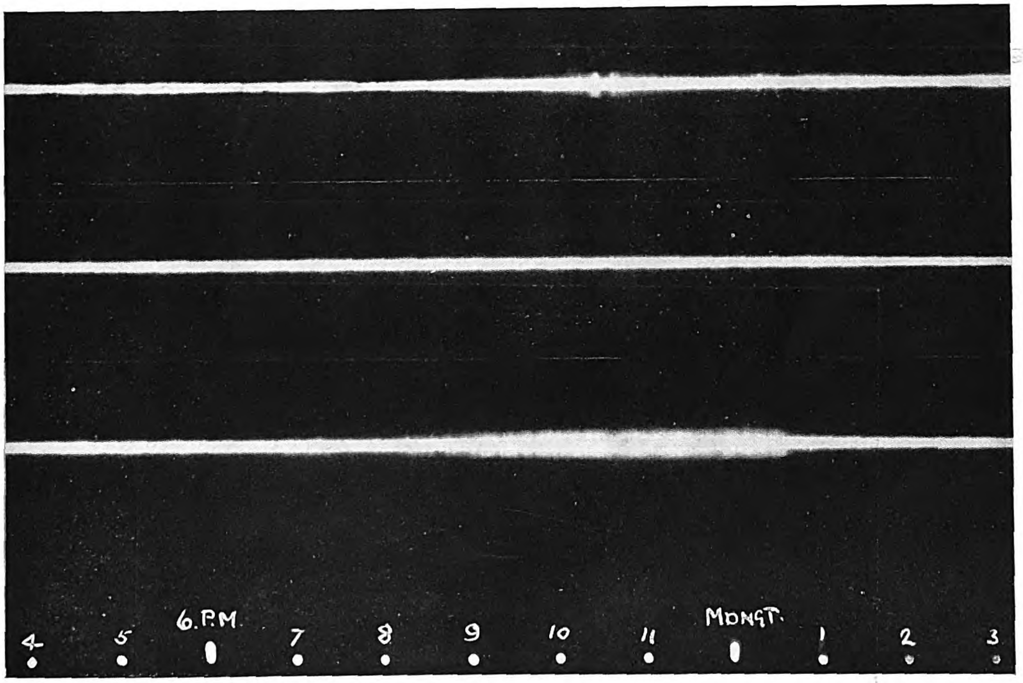

FIG. 12.

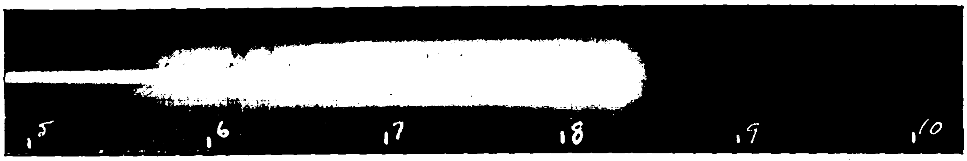

FIG. 13.

one of the terminal poles, where the abrupt change in line characteristics from the overhead line, of high inductance and low capacity, to the cable, of high capacity and low inductance, might be expected to be the point of maximum surge value, and the gear was accordingly erected on the hillside at this pole.

The results published in America, dealing more particularly with direct lightning strokes and large switching surges, led the authors to expect records of a similar spectacular nature, but the results obtained were of much milder type. The main fact that emerged was that during most nights there was a distinct thickening of the line, a sample of which is shown in Fig. 12 (see Plate I), where for a period of nearly 4 hours a series of almost continuous surges occurred. It will be seen that the effect was greatest on one phase, and that the phase recorded on the middle line of the record is practically immune. A great deal of work was done in investigating the line characteristics as affected by the running machinery at various points, and an oscillograph was installed to analyse more definitely the characteristics of the surges. These results proved that apart from switching surges of a momentary nature, with which the line was fully capable of dealing, there was no disturbance due to the machinery, and that the frequency of the surges was well above 3 000 cycles per sec.

It was not until the occurrence of a salt storm that the phenomenon was fully explained, and then it was in unmistakable fashion. By this time, owing partly to instrument trouble and partly to the desire to have an instrument that would give a more clearly defined line between normal and abnormal voltage, the improved instrument had been developed and was in service.

In November 1927, at a time when the klydonograph was in temporary use on another system, a series of shut-downs occurred during a heavy storm, or rather immediately after it. Investigation of the whole of the information available led to the conclusion that salt brought from the sea was the cause of the major part of the trouble.

Heavy brushing was noticed at the sealing ends, and it was not until the weather changed that the line would give continuous service. On being consulted, Dr. G. C. Simpson, F.R.S., who has been kind enough to give a great deal of assistance by way of explaining any possible atmospheric troubles, showed that the line trouble coincided with the somewhat rare occurrence of an abnormally dry south-westerly wind, and this led to the conclusion that a salt deposit was the trouble, not only on this but on many other lines throughout the country. This particular part of the line was 20 miles from the coast, and everything pointed to the conclusion that while with a normal moist south-west wind the salt taken from the sea would fall out quickly owing to its being wet, and therefore heavy, with the drier wind the salt spray taken up would immediately be dried by the air and be carried for a considerable distance as a fine, almost impalpable, powder. This salt impinges on the insulator in a high wind and, helped by the electric stress, adheres firmly to the insulator and does not wash off. While the dry wind continues the danger of complete flash-over is not great, but—and this is borne out by every case observed—flash-over occurs when the humidity of the air returns to a more normal value. The particles of salt then take up moisture from the air and the surface of the insulator is covered, or partially so, with a good conducting brine. If the insulator is not cleaned after the salt storm a part of the salt remains on the surface and is the cause of the surging shown in Fig. 12 (see Plate I) occurring during hours when dew falls.

Visual observation readily shows the nature of the effect on the surface of an insulator having salt deposit. During dew or a misty period large drops of water form on the surface, and as the mist disappears and the insulator dries in the sun the salt re-crystallizes and adheres so tightly that it has to be scraped rather than rubbed off.

An insulator was removed from the line some weeks after the heavy storm, during which interval it had been exposed to much heavy rain. Analysis of the surface deposit showed that there was a total amount of approximately 0·15 gramme of solid matter on the surface, consisting of chlorides, sulphates and carbonates of sodium, nickel, lead, tin and iron. Twenty-five per cent of the solids that were soluble in water were sodium chloride.

Records showing Effect of Salt Storm.—In Figs. 13, 14 and 15 (see Plates I and II) are shown some of the records obtained during and immediately after the storms in February, 1928, a period when there was much trouble with overhead lines all over the country. Fig. 13 (Plate I) shows first the comparatively clean normal-voltage line during the heavy dry wind. The point at which the line widens corresponds to that when the wind dropped somewhat and the atmosphere became cloudy. Then for some 2½ hours surging occurred, obviously due to brushing at the insulators, and at about 8.15 p.m. the breaker tripped. When attempts were made to re-set it it would not remain in and it could not be re-set until the following morning. When the switch finally held there was still considerable surging (see Fig. 14, Plate II), and at 1 p.m., when rain fell, the circuit breaker tripped out again. Then all the sealing-end insulators were scrubbed clean and the line was switched in again. Fig. 15 (Plate II) shows that the surging had practically disappeared.

It is noteworthy that the greater part of the surging occurred on one phase. That one was the nearest to the sea and the direction of the wind. Clearly the other two insulators were to a fair extent screened by the first and did not receive the same amount of salt deposit.

In November 1928 another salt storm occurred, and similar interesting records were obtained. These are too numerous for all to be published, but some of them are sufficiently different from those previously shown to be included. On one phase the oscillatory surging was practically continuous for several hours, and there were a number of oscillatory surges of comparatively short duration. Thus Fig. 19 (Plate III) shows these individual surges occurring on one phase during a period of 6 hours. Both directly and oppositely connected films gave practically the same figures, which showed that the surging was oscillatory (i.e. several cycles). The magnitude of these surges is approximately four times the line voltage, and it is somewhat remarkable that under these conditions the line was not tripped out. The same surges are shown on the other phases, accompanied by considerable brushing.

The experience during this latter storm was somewhat similar to the previous one, except that by this time the natural conservatism of the engineers in accepting the theory of salt had been somewhat overcome, with the result that now, when the line eventually came out, the insulators were promptly cleaned and the service was restored in a comparatively short time.

A large number of records on the system showed similar surging due to salt deposit, but those given above are sufficient to illustrate the nature of them.

Other Surges on this Line.—A number of other surges were recorded on the South Wales line. These were often of a minor nature, due to switching operations, but two of the more serious ones may be recorded here. Fig. 16 (Plate II) shows figures obtained on a surge due apparently to a cable failure 18 miles distant from the recorder, and Fig. 17 (Plate II) the surge produced when a phase wire fell and interrupted the current. Fig. 16 (Plate II) is of course ascribed to the cable fault, although it may be a matter of opinion as to whether the fault caused the surge or a surge brought about the fault.

Lightning.—Only one or two lightning surges were recorded, and these were due to storms some miles from the recording gear. One of these is shown in Fig. 18 (Plate II). It should, however, be noted that during the last two or three years there have been comparatively few lightning storms in this country. In fact, in South Wales the period covered by the observations was considered to be almost unique in its freedom from lightning trouble.

Midland Systems.—Similar investigations have been made on lines in the Midlands. The system in this case is a mixed one, consisting of a great deal of cable and several lengths of overhead line. In this case troubles with salt were not experienced, but some other interesting records were obtained. These results were not always fully explained, but in general the surging ceased when many line insulators had been replaced.

Curiously enough, the portion which consisted entirely of overhead line had, if anything, less surging than that which was partly overhead line and partly cable. One interesting and unexplained series of records, however, showed, during an otherwise quiet period, considerable oscillatory surges on several Sunday mornings at approximately the same time. These are shown in Fig. 20 (Plate III). The regularity of this occurrence was too marked to be accidental, and was probably due to some abnormal circuit conditions occurring at this period.

Perhaps the most outstanding record was where a cable fault occurred after a long period of surging, which latter was still evident after the fault had been repaired. Here it may be fair to say that the cable was probably injured and finally broke down as a result of many hours of oscillatory surging of comparatively small magnitude, i.e. about two or three times the normal line voltage. The day's record of one phase is given in Fig. 21 (Plate IV). The beginning of the record shows the heavy surging which had started some hours previously. This continued for about 12 hours and then ceased during the hours from noon until about 8 p.m., after which it restarted and the cable broke down. On the repair being effected the surging continued for a further 10 hours, fortunately without further breakdown.

Another case of a feeder breakdown occurring during periods of heavy surging is shown in Fig. 22 (Plate IV). Here again the breakdown and repair interrupted a long period of small oscillatory surging. Again, Fig. 23 (Plate IV) is a particularly clear example of the oscillatory surge line as compared with the normal-voltage line. The surging ceased as soon as the sun had dried the insulators. Shortly after this several insulators of the older type were changed and the cracked ones renewed. When this was completed the surging ceased.

Ice Deposits.—The atmospheric conditions known as a silver thaw, when a slight thaw with rain occurs during a frost, followed immediately by another frost, often results in the formation of ice on insulators. This is a source of occasional trouble, and, as shown in Fig. 24 (Plate IV), results in considerable surging. Somewhat similar results were found on the South Wales instruments during the same period.

Manchester.—A klydonograph set was installed at the outdoor substation at High Street, the system being entirely cable working at 33 kV. Records, continued for nearly a year, show that there is practically none of the oscillatory surging such as has been found where overhead lines form part of the system. A number of small surges were recorded and these always coincided with some switching operation. Otherwise, apart from a fault in a joint box on another system fed by Manchester, where the surge was recorded some 15 miles from the fault, the only surge of magnitude is that shown in Fig. 25 (Plate IV). This surge was clearly oscillatory and of nearly the same magnitude on both directly-connected and oppositely-connected films, and it is noteworthy that the cable system stood up to this surge of fully three times the normal line voltage.

General.—While the surges recorded have not been of the magnitude experienced by American observers, the records generally show that the klydonograph, if intelligently used, is a valuable and inexpensive piece of apparatus for recording most types of surges in overhead and/or cable systems. Possibly the results do not always lend themselves to the critical analysis and final interpretation as regards wave-shape and frequency that has been found possible by American observers, but, nevertheless, the instrument does definitely record an over-voltage due to any cause and of any frequency, and such records must lead to improvement in line operation. The records in South Wales alone resulted in an enormous saving in maintenance charges due to localization of the main cause of the trouble. In addition, the serious consequences and cost of interruption of supply for considerable periods were avoided. The authors would, however, emphasize the importance of the long series of oscillatory discharges detected by the more sensitive methods used; these are apparently of more serious import than short-time surges of greater magnitude.

With so many oscillatory surges superimposed it is hardly possible to analyse them as when a single surge of large magnitude is recorded, but for this purpose it is not necessary. From a purely technical point of view, however, it would be interesting to know more of the exact shape of the waves and of their frequency, and perhaps further experience will lead to enlightenment on these matters. Another noteworthy point is the distance which surges travel along a power line. Thus, on the overhead line in South Wales, lightning strokes were recorded some miles from the actual storm, and on the cable system in Manchester the surge set up by a fault was recorded some 15 miles away; even at that distance the value was approximately three times the line voltage.

PORCELAIN INSULATORS.

It is evident that the design of porcelain insulators for outdoor use requires a great deal of further consideration. For the pin- or suspension-type insulators the problem is fairly simple, but with sealing-ends the solution is really difficult.

The very severe conditions of fouling found in the case of the insulators mentioned have led to a thorough research into the performance of insulators both under dry and clean, and wet and foul, conditions. Whilst this work is still far from complete, a great deal has been done.

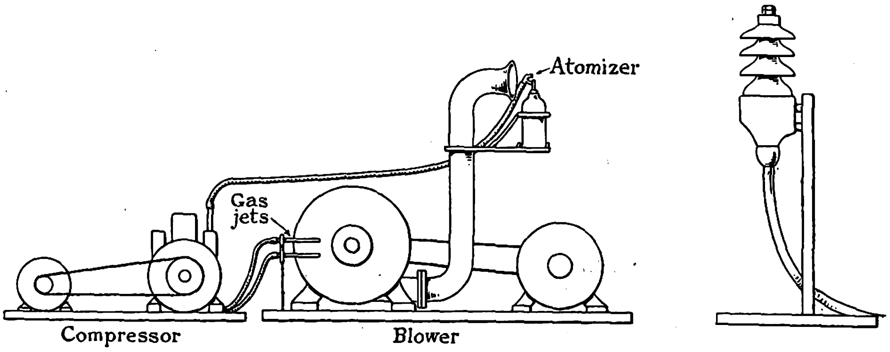

FIG. 26.

Apparatus was devised to imitate as nearly as possible the dry salt conditions previously referred to, and, after considerable experimenting, something very near to actual conditions was obtained. The apparatus used is shown in Fig. 26. A finely divided spray of salt solution is obtained from the atomizer operated from the small motor compressor to the left. The spray from this is projected into the current of air from the large rotary blower to the right, by means of which it is carried over on to the insulator under test. The drying action of the strong air-blast evaporates the water from the salt spray, leaving salt particles of minute dimensions which are deposited on the porcelain. In order to ensure the complete drying action it was found necessary, except in very dry weather, to warm the air intake to the large blower by means of the two gas burners shown.

Tests were also made under rain, fog, and salt fog, the last two states being obtained by two or more atomizers, according to the size of the insulator being tested.

It is usually found that, while pin insulators prove to be, on the whole, satisfactory in operation, the sealing-end insulators give trouble, quite severe brushing occurring at voltages less than the normal working voltage. The best design of insulator is that in which the surfaces subjected to the most fouling, i.e. the sheds in most shedded insulators, lie along equipotential lines in the electric field. With vertical sealing ends of the ordinary type this is not possible, as is indicated in Fig. 27.

Fig. 27 (*a*) shows roughly the electric field surrounding a live conductor emerging from an earthed metal cylinder (the " box " of a sealing end), the dotted lines representing the equipotentials. Fig. 27 (*b*) shows clearly how the sheds of a vertical type sealing-end must needs lie across these equipotentials. Tests involving the determination of the field diagram and surface-potential distribution of a large number of insulators of different types and sizes, and their performance under all atmospheric conditions, have shown that, although it is not possible to make any appreciable improvement to the final flash-over voltage of an insulator, the voltage at which brushing becomes serious can be materially raised. The flash-over voltage is invariably higher than the line voltage, and it is evident from the klydonograph records that the brushing is the vital factor and that improvement must be effected in this direction.

For the lower voltages the inverted type of sealing end shown in Fig. 27 (*c*) can be employed, the performance of a properly designed insulator of this type being quite good, even under severe conditions. Experiments with a vertical sealing-end have shown that it is possible to improve the brushing voltage by inserting metal sheds between the porcelain sheds in such a way that they distort the natural field and cause the porcelain sheds to lie nearly on equipotential lines. Fig. 27 (*d*) is an example of this type of treatment. Field-controlling sheds of this sort need, however, to be very carefully applied since, if improperly placed, they may bring about a large decrease in the flash-over voltage.

A great deal can be done by systematic cleaning where the line or a portion of it can be taken out of service for the purpose. The authors understand that, in those parts of America subject to alkali dust, a steam cleaning-plant is in continuous operation; as this would appear to be liable to set up small cracks in the insulators, cleaning at normal temperature would seem to be preferable. The authors have found that the vigorous use of a scrubbing brush and water is the most effective method of cleaning.

The optimistic school of thought is inclined to dismiss the subject by reference to over-insulating, but the authors are strongly of the opinion that something more than this is necessary. Even a larger insulator if left without cleaning will ultimately flash over, even if it does not shatter owing to the heat set up by the brushing, and, moreover, for a 132-kV line we are getting near to the limit of size at which single-piece sealing-end insulators can be made. It is true that very large insulators are now advertised, but they are expensive and unwieldy.

For very bad positions special arrangements might be made, and in this connection the experience in South Wales indicates a line that may be taken. The whole of the observations showed that roughly 80 per cent of the surging occurred on the line nearest to the direction of the dangerous wind, with the inference that the other two phases were to a great extent shielded by the first dividing box. Some intelligent shielding here might obviate a great deal of the trouble.

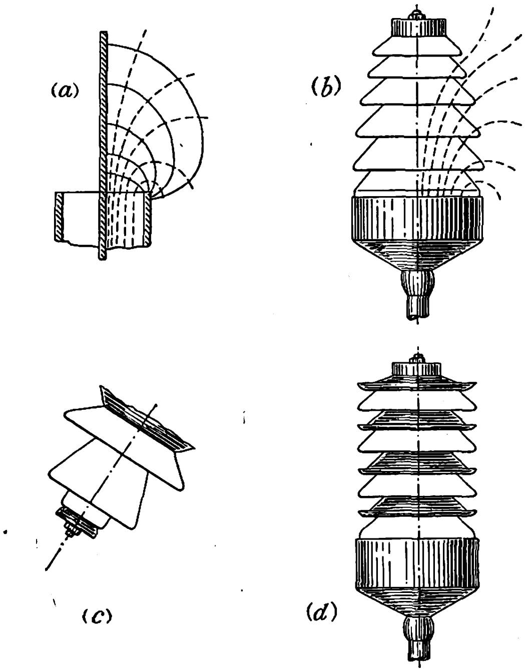

FIG. 27.

EFFECT OF SURGES ON CABLES CONNECTED TO AN OVERHEAD LINE.

While there is no definite experimental work showing that high-frequency voltage of the type recorded results in damage to the dielectric of a cable connected to the line, it must be assumed that the cable is submitted to an undue stress. Whatever the frequency of the over-voltage, it is superimposed on the normal line voltage, and in the cases shown the existence of this condition for many hours is subjecting the dielectric to a stress much larger than that for which it is designed. Although the capacity of the cable results in a considerable reduction in the amplitude of the wave, it cannot eliminate it unless the capacity is infinite, and the first part of the cable must stand up to the whole of the over-voltage.

A great deal of work has been done on this subject, but it is incomplete and is, in any case, too extensive to be included in the present paper, but probably if the length of cable is greater than one-quarter of the wave-length of the oscillatory voltage the latter may be reduced to as much as one-half of its initial value. A considerable length of cable is required, however, to effect even this reduction, and if cable is to be expected to take care of the surges a long length, very much over-insulated, must be used.

Some people hold the view that a cable having a high power factor, such as cambric cable, would deal with the surges by absorption through the wall of the dielectric, but consideration and experiment have shown definitely that this is not so. Whatever may be the merits of a cambric cable in other directions for use on terminal ends of high-voltage lines, there can be no effective reduction of surge voltage due to dielectric absorption unless a length of some miles of the cable is used. As pointed out above, however, the capacity of any cable will effect a reduction in the amplitude.

Lightning.—The question of the discharges likely to occur from atmospheric conditions has been largely discussed in American publications, in which various authors, and notably Peek,* have discussed atmospheric voltages, bound charges due to charged clouds, etc.

It is well known that a definite potential which may rise to as high a value as 1 000 volts per metre exists in the atmosphere, but the recent Kelvin Lecture by Dr. G. C. Simpson † showed that the greater part of atmospheric potential had little energy and that the only condition under which appreciable energy may be discharged is by a direct lightning stroke. This clears up the situation so far as the engineer is concerned and leaves him to solve the problem of how to deal with the lightning discharge. Fortunately, in this country we are not subject to the severe lightning storms experienced in many parts of the world, but interruptions due to lightning will and do occur. The authors do not wish to discuss protective devices, weak links, etc., but they would point out that the effects of lightning are not nearly so serious as the other difficulties enumerated above. A lightning stroke almost invariably causes the line to trip out; one or other of the insulators flashes over and a circuit breaker operates. Apart from the short interruption, however, the line is usually undamaged and can be put back into service almost immediately.

There is, however, one point to be made in connection with any system of spark gaps or weak-link insulators. For the protection of transformers and other apparatus it is essential that the protective device should operate at a definite voltage and be unaffected by weather conditions. This is hardly possible unless any gap on which operation depends is definitely under cover.

ACKNOWLEDGMENTS.

In the course of this work in several fields the authors have had to call on a number of people for help, and they gratefully acknowledge the keen interest taken and

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* See Bibliography, (19) and (23). † *Ibid.*, (17).

the great assistance given by everybody concerned. In particular, Mr. J. W. Burr, borough electrical engineer, Swansea, and his assistant, Mr. A. Jarratt, rendered invaluable help in the earliest and most difficult work carried out in South Wales. Dr. Simpson was consulted on possible weather disturbances and freely gave full advice and information on the atmospheric side of the subject, while Mr. J. C. Poole carried out most of the work of maintaining the stations and obtaining the records, his help being invaluable. Thanks are also due to Messrs. Callender's Cable and Construction Co. for permission to publish the results.

APPENDIX.

THEORY OF OPERATION OF KLYDONOGRAPH.

Although the klydonograph has now been put to a considerable amount of use, comparatively little work seems to have been done with a view to explaining the physical phenomena connected with its operation. An interesting series of experiments conducted by Magnusson * has led him to conclude that the image on the plate is actually due to light emitted from the discharge. In support of this theory he gave the following experimental results:—

(*a*) If the photographic plate be covered by an additional glass plate and the point electrode placed on this the figure produced is blurred. This fact, which has been confirmed in this investigation, was explained as being due to diffusion of the light by the intervening glass.

(*b*) With the same arrangement as above, and a sheet of black paper between the glass and the plate, no figure is produced. The authors' tests made to confirm this result led to the discovery that the screening effect only occurred when the paper was in good contact with the photographic plate. In places where it had been lifted, a portion of the figure was obtained. It was therefore thought possible that the effect might be due to the semi-conducting nature of the paper used (such papers being often of the carbon type). To test this the black paper was replaced by some red wax paper—definitely non-conducting—and similar results were obtained.

As a further test to ascertain whether light is the direct cause of the image, the authors took additional figures as follows:—

(1) With a plain glass plate between the photographic plate and the point electrode, as before.

(2) With a photographic "safe-light" glass instead of the clear glass. The "safe-light" gave complete screening.

A further useful experiment consisted in the application of steady d.c. potential to the klydonograph. This was done by means of a small high-voltage d.c. machine shunted by a condenser to smooth out any possible commutator ripple. Under these conditions no records at all were obtained.

From this it is clear that the actual electric stress is not the cause of the figure, and the screening experiments indicate that the image is due to a radiation capable of being absorbed by certain light screens. Whether this radiation actually falls within the visible range is most doubtful. McEachron * claims to have produced figures even when the voltage took 20 minutes to reach its maximum. He was, however, using much thicker plates and much higher voltages. The authors are of opinion that in his experiments some ripple of which he was unaware was present and caused the figure.

It would appear possible that the effect of applying a voltage wave to the instrument is to project electrons from the electrode over the surface of the plate. The acceleration of these electrons would depend on the peak-value and wave-shape, and a radiation corresponding to the acceleration would be set up. Such a movement of electrons might be considered to be somewhat similar to cathode rays, and a further experiment by Magnusson supports this theory. He showed that klydonograph figures taken under reduced air pressure were considerably larger than those at atmospheric pressure, and it is known that the range of a cathode ray becomes less the more gas is present in the tube.

It has been noticed in the American type of instrument, in which the film is drawn over a curved surface, that the figure produced is not circular but is of smaller radius in the direction of curvature. This again might be explained by the electrons being projected across the plate at the point of contact and flying off tangentially. If this is the case, it shows also that the range at which the radiation set up will affect the photographic film is very limited.

There appears to be evidence that a certain amount of light or ultra-violet radiation occurs during the formation of the figures. The effect is noticed only if moderately high instrument voltages are being employed. For instance, if an a.c. voltage is left on a stationary film for some time (half an hour or so) the dense black figure obtained is surrounded by a haze of fogging (similar to that associated with light leakages in a camera) extending for some inches.

The difference in the type of figure obtained with positive and negative surges has already been referred to and can probably be explained as follows. In the case of negative figures the electrons are projected outwards from the electrode in all directions, giving a uniform type of radial figure. The slight irregularities often observed are undoubtedly due to small projections, etc., on the electrode. With positive figures the electrons are drawn towards the electrode, the positive ions thus formed creating conducting channels through which the flow is continued in a manner similar to the formation of a lightning discharge, as described by Dr. G. C. Simpson † in the 20th Kelvin Lecture.

A further experiment which it is interesting to note in this connection is that made by G. L. Addenbrooke.‡ A point electrode was suspended about 1 in. above the surface of a shallow bath of oil, the bath having a metal rim. When the electrode was charged to a high potential, radial splashes were produced on the surface of the oil. The formation of these splashes for positive and negative electrification was almost identical with the corresponding klydonograph figures obtained, except, of course, that a much higher voltage was required for their formation.

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* See Bibliography, (16).

* See Bibliography, (11).

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‡ *Ibid.*, (12).

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Discussion before The Institution, 10th April, 1930.

Mr. E. B. Wedmore: The authors have dealt with disturbances on a particular system. From the point of view of the Institution they have introduced a much larger problem. Members are responsible for electric generating and distributing plant to the value of about 100 million pounds, the whole of which is subject to these disturbances. We are still largely ignorant of the nature and extent of these phenomena, mainly because appropriate methods of experimental investigation have been lacking in the past. We have fallen back upon elementary ideas of induction and capacity, and upon the appropriate formulæ for transients. Having predicted that certain actions would take place, we have been quite pleased when our predictions have been justified. But a formula will never give any information other than that which is put into it, and we have neglected the experimental work necessary to furnish the constants for the formulæ. The phenomenon described in the paper has in the past been more important, perhaps, in the United States than in Great Britain, on account of the very large overhead distribution systems in the former country. Hitherto we in this country have grumbled about phenomena which we did not understand, but we have not been driven to make such investigations as that described in the paper—a line of investigation which should, I think, be pursued. Electric waves are travelling day and night over this 100 million pounds' worth of plant and detecting all its weaknesses in a wholly destructive manner. We cannot gain too much information about the phenomenon, and we know far too little at the present time. British standard tests for the insulation of apparatus are based upon factors inadequately correlated with the conditions which the apparatus has to withstand. In dealing with the phenomena of circuit breaking we do not have to deal solely with the normal line voltage of the system. We may be circuit-breaking on systems which are at the same time continuously subjected to surges resulting from small amounts of energy. This energy may not be sufficient to show on the balance-sheet, but it represents high voltages which manifest themselves across the terminals of the circuit breaker and affect its performance. Surge phenomena are even more important in connection with insulation, as authorized undertakers incur expenditure amounting to about £500 000 per annum as the direct result of damage due to insulation failures. Such failures are, I think, largely connected with these over-voltages, which are constantly affecting the insulation in a destructive manner. If members of electricity committees could only see the electric waves travelling on their systems, they would realize the importance of the problem. The experimental method described in the paper is not in itself a new one, but certain of its details are novel. It enables us to make a fairly accurate estimate of the range of high voltage, and also to obtain a distinction as to whether we are dealing with an impulse or with an oscillatory discharge. It lacks in precision, however, when measuring the frequency of the disturbance. Oscillograph films run at high speed have to be used instead, and the cost of the equipment is very greatly increased. We should consider whether it would not be practicable, by some not-too-expensive addition to the apparatus described, to record the frequency of, at any rate, those phenomena that are constantly repeating themselves. It might be possible to use a group of such devices each tuned to respond to a wide band of frequencies and together covering the whole range of frequencies in question, and to observe at which of them discharges are obtained under any particular condition. A calibration curve for the apparatus itself has been shown and two curves taken at two different temperatures have been obtained. The one for the higher than atmospheric temperature was straight over a much larger range than the one for the lower. I should like to know whether the authors have worked at higher temperatures still, which, while perhaps not convenient for their work, might be suitable for laboratory work. For so far as the indications go, the straight part of the curve might be extended if the temperature were raised, and the utility of the apparatus would thus be increased. With regard to the calibration of the apparatus, the authors give a figure of 10 per cent for the probable error: this, if obtainable, is a very good value for work of this kind. I should like to have more information about the calibration of the instrument itself, and also of the potential divider used in connection with it. I am uncertain whether, when the instrument itself is discharging, the energy taken by it disturbs the distribution of the potential across the condenser arrangement, or whether such action is negligible within the 10 per cent error range. Has any estimate of the amount of this energy been made, and does such energy affect the initial calibration of the device proper? The subject of the authors' paper is overdue for consideration in this country. The Electrical Research Association now has funds which it could allocate next year to work of this kind. Apart from the surge problem, the wide question of testing insulators subject to the weather conditions referred to is already being considered, and I hope we shall soon make progress in the solution of that problem also. We should welcome any communications from members interested in the investigation of surge phenomena.

Prof. E. W. Marchant: The results obtained by Magnusson with reduced air pressures were, I think, taken over a limited range, and I should be glad if the authors could give some actual values for the increase in size of the klydonograph figure which is obtained when the air pressure is lowered. With regard to the temperature effect, is this mainly due to alteration in the sensitivity of the film at the lower temperatures, or to an alteration in the discharge? In connection with the surges observed, was an earth wire fitted to all the lines on which very high pressures were obtained? The ordinary method of protecting against lightning is to have an overhead earthed wire connecting the poles, and I presume that this arrangement was adopted on these lines, and that it was in use when the test was made. The surge pressures that have been observed are alarming from the point of view of operating engineers, as they are very much higher than those which would be anticipated. I think that the chief operating difficulty to be dealt with is that of finding a method for preventing these surges from causing damage in the stations. Mr. Paton, of the North Wales Power Co., recently told me of his experience with regard to surges on their system. The normal method of protecting the transformers is by means of thickened insulation at the point where they are connected to the overhead line. This tends to prevent the surge from coming back into the transformer and damaging or breaking down the insulation. A very large number of the faults that have occurred on the North Wales Power Co.'s system, however, have been found at the earth end of the transformer, i.e. at the other end of the winding. A surge presumably travels along the line, from the point where the arc or flash-over occurs, but it travels along the overhead line and also through the earth. Because of this latter action, the apparently anomalous result of a very high pressure on the first few turns at the earth end of the transformer is obtained. From the point of view of protection, therefore, it is as important to thicken the insulation of the turns of the transformer at the earth end, as it is on the high-pressure side of the system. For a number of months we have been making investigations on the strength of insulating materials when subjected to high-frequency discharges. Very little information seems to be available regarding the electric strength of insulating cables at anything above quite low frequencies. About three years ago Goebeler showed that the electric strength of fibrous insulating materials at frequencies of the order of 100 000 or 200 000 cycles per second was negligible compared with that at 50 cycles. It is fairly well known that at 100 000 cycles the electric strength of a material like glass is about 0·3 of the corresponding value at 50 cycles. Ebonite shows similar characteristics, but for fibrous materials the ratio is much smaller, i.e. the electric strength at 50 cycles is much greater than it is at the higher frequencies. Any information which the authors are able to give on this subject will be of value. It is clear that, if adequate protection is to be provided against the dangers that may arise from the presence of high-frequency surges, insulating material of far greater thickness than would otherwise be necessary must be provided at points where such surges are likely to attack the distribution system.

Mr. N. Herwald: That climatic conditions have a great deal to do with the efficient maintenance of a transmission line is, I think, well known, but I do not know whether specific reasons exist to explain the occurrence of surges in particular localities, such as those which occurred on the South Wales line and are described in the paper. I am interested in the question of surges in composite conductors, and as this is an important factor in connection with over-potential in lines it seems probable that voltages in the overhead section will cause surging to take place. The surge would travel along the line until a cable was met with, and the comparatively high inductance of the cable section with respect to the overhead section would tend to make the potential build up at the junction point. I think that the question of wave-shape analysis is only one of time, now that a start has been made in the use of the klydonograph in this country.

Mr. B. L. Goodlet : The main thesis of the paper is that the discharges which occur on dirty insulators, apart from damaging the insulators themselves, react on the transmission system, producing therein voltage surges of dangerous magnitude. I do not think that this suggestion has been put forward before, and if it is correct it will produce some very radical changes in our ideas on the subject. I will accordingly discuss briefly (1) the origin and peculiarities of the insulator discharges, and (2) the nature of the disturbances so set up. Troubles due to fouling of insulators are encountered in many parts of the world. The mechanism in every case is the accumulation of a surface deposit on the insulator which when dry has little effect but when damp causes surface discharges and a large reduction in the spark-over voltage. The power dissipated in these discharges is often quite considerable, and, as the resultant heating is very localized, cracking of insulators often occurs. In the cases investigated by the authors the troubles seem to have been due mainly to salt. The insulation of coastal lines is, of course, a traditionally difficult matter, but I am of the opinion that the atmospheric conditions encountered in some of our industrial districts will probably be equally difficult to deal with. The authors find that salt is not carried far inland except by a dry wind, that the deposit is localized towards the windward side, and that the use of insulators with deep vertical sheds, such as the inverted sealing-ends mentioned, minimizes the trouble, as the salt accumulates mainly on the exposed vertical surfaces and not to any great extent inside the insulator. In a smoky, industrial atmosphere, however, the suspended particles are very small and light and, owing to their tar content, they are also very sticky. The slightest air eddy carries them right up inside the insulator, where they stick even to the under surfaces of the sheds. On surfaces exposed to rain the non-adhesive and soluble components of the deposit are soon washed away, so that the film on these surfaces grows only very slowly. On the protected surfaces where this washing does not occur the deposit accumulates very rapidly. In one particular case investigated by us the monthly increment on the shielded surfaces was found to be about 0·5 milligram per cm^2— a figure which is nearly 60 per cent of the mean monthly precipitation of total solids for the locality as measured by the standard pollution gauge, which retains everything falling into it. A few months after this particular line was put into service the insulator discharges were sometimes so severe that policemen on night duty rang up to say that some of the towers were on fire. It is quite obvious that operation under such conditions soon becomes almost impossible. I am inclined to think that this trouble of atmospheric pollution is going to be our national trouble, just as lightning is in the United States and earthquakes in Japan. At present, however, no solution of the problem seems to be available, apart from the washing of the insulators at frequent intervals. I agree entirely with the authors' remarks about the futility of over-insulation; really serious trouble will not be cured in that way. There are about a dozen different insulators designed for use in foul localities. Most of these depend for their efficacy upon the shielding action of deep petticoats, and where the impurity is heavy and carried by a side wind this may be fairly effective. I do not know of any insulator the interior of which will keep clean in a really smoky atmosphere. The damaging effects of discharges on the line insulators are, of course, well known. The authors' contribution to the subject is the discovery that these discharges produce, in the system, surges of sufficient magnitude to endanger connected apparatus. The fact that these discharges do produce oscillations is, of course, well known, and the problem of radio interference from transmission lines has been studied quite extensively. I am, however, a little surprised to learn that the magnitude of these oscillations is as great as the authors state, and I cannot help wondering whether a slight error has not crept into their measurements. If I understand the matter correctly, the authors calibrated their klydonograph by measuring the size of the figures produced by various 50-cycle voltages, and obtained in this manner the curve shown in Fig. 4. They then assumed that this relation remained the same whatever the frequency of the voltage applied, so that the voltage of the high-frequency disturbances observed could be deduced from the measured dimensions of the figure and the 50-cycle calibration curve. Actually, however, the figure produced by a high-frequency voltage may be considerably larger than that produced by a 50-cycle voltage of equal magnitude, and, if this frequency effect is neglected, voltages of high frequency would appear to be of much greater magnitude than they are in reality. For this reason I am inclined to doubt the figure of 3 times working voltage given in the paper for the amplitude of surges produced, unless the authors have checked this value by an independent method. I should be surprised to learn that any voltage in excess of twice normal was, in fact, present. In this connection it is a pity that the authors can give us no idea of the frequency of the disturbances set up. Although the tuning bands would probably be quite wide I think that wavemeter measurements would probably give the required information, and this would at once settle the question of the frequency error I have mentioned. If the frequency of the oscillations proves to be only a few thousand cycles this error will probably be quite small. The final point I should like to make is the importance which the authors' investigations impart to apparatus testing with damped oscillations. In surge testing at the present time the fashion is set strongly towards the use of impulsive voltages. The authors show that damped oscillations of appreciable magnitude may be maintained in a system for long periods of time; the behaviour of apparatus when subjected to this type of disturbance is therefore a matter of considerable interest.

Mr. N. E. P. Harris : If the statements made in the early parts of the paper were accepted at their face value, it would be hard to believe that any transmission line, either in an industrial or in any other area where salt is prevalent, could go on working at all. We have to remember that transmission lines in some of the most difficult parts of the British Isles have been giving satisfactory service for the past 20 years, at any rate. In this connection I was interested to note the definite statement made by the authors that voltages of the order of 4 times the normal working voltage have been observed not only for short periods but even for 8, 10 and 12 hours. Judging by the information given in the paper, it is remarkable that frequent spark-over did not occur under these conditions. I have based the following calculation upon a typical example and have used the authors' figure of 4 times the working voltage. I think that the voltage which I have selected is the same as that in South Wales on the transmission line under discussion. Transmission-line engineers in this country often use an insulator larger than the British standard design for any particular voltage rating. Let us assume that a normal 50-kV insulator has been used on a 30-kV line, which gives a maximum value of $(30/\sqrt{3}) \times 1\cdot 4 = 24\cdot 5$ kV to earth. As is pointed out in the paper, it is always the maximum value which is recorded. The spark-over under rain of a British Standard 50-kV insulator is 125 kV (maximum value 177 kV), and 4 times the maximum value of the line voltage to earth is 98 kV. From experiments in the laboratory with artificial salt deposits obtained in a way very similar to that employed by the authors, the reduction in the wet value is of the order of 30 to 50 per cent. Assuming as an illustration the intermediate value of 40 per cent, I should expect the 177 kV on the British Standard 50-kV insulator to be reduced to about 50–60 per cent of its normal value. This indicates that the figure at which I should expect spark-over to occur under the given conditions would be of the order of 105 kV. A comparison of this with the value of 98 kV, which I assume is about the voltage obtained, leads me to think that not only the sealing-end insulators but also the pin insulators (assuming that pin insulators were used) were actually *on* the point of sparking-over. I was interested in the authors' remarks on the subject of insulator design; I regard the statement that "the best design of insulator is that in which the surfaces subjected to the most fouling, i.e. the sheds in most shedded insulators, lie along equipotential lines in the electric field," as pointing in the same direction as Mr. Goodlet's statement made at the Institution rather more than a year ago. This was to the effect that the minimum of disturbance of the electrostatic field will occur when an insulator is so shaped that deposits form on those surfaces which are equipotential surfaces. I conclude that the authors really had in mind the question of the disturbance of the original field. While agreeing with the principle, I still hold the view that the ability of an insulator to give good service under difficult conditions depends upon the length and efficiency of the paths which separate the equipotential surfaces. I am not in agreement with the statement that "although it is not possible to make any appreciable improvement to the final flash-over voltage of an insulator, the voltage at which brushing becomes serious can be materially raised.' 'If the voltage at which brushing starts were increased, I should be surprised if the voltage at which ultimate spark-over takes place were not increased also. I refer here not to the spark-over of a new, clean insulator, but to the spark-over of an insulator which has been the subject of deposits. In connection with the statement that the best performance is obtained when the surfaces of the sheds follow the equipotential surfaces, I re-read a paper * presented by C. L. Fortescue and S. W. Farnsworth in 1913. The authors had no idea of the troubles which were to come through the fouling of insulators. They put the same idea forward, however, in rather a different way. The body part of their insulator was shaped like an inverted pineapple, so that it followed the flux lines of the electrostatic field, whilst the sheds were at right angles to them and approximately along the equipotential surfaces. The so-called "Faradoid" insulator was developed upon the recommendations of this paper, but it has not been a conspicuous success under conditions of polluted atmosphere. It may be that the fact that it has sometimes failed has nothing whatever to do with the correctness or otherwise of the design. The ideal shape from electrical considerations may have been advanced without regard to the necessity of providing an insulator which will give good service under ordinary conditions of atmospheric pollution. Even when severe and frequent salt storms are experienced, as described in this paper, the insulators should possess that margin of security which will enable the necessary periodic cleaning to be carried out at convenient times separated by reasonable intervals.

Mr. T. N. Riley: The authors have demonstrated clearly that discharges over insulator surfaces are responsible for the surging effects on overhead lines. They have also recorded a number of surges on lines in cable systems without suggesting any definite cause in those cases where there has been *no* fault. It struck me that discharges in the interior of a cable, such as may occur on high-voltage cables without equipotential sheath, might be responsible for similar surges on cable systems. If so, such surges would occur during periods of light load when voids are most likely to be formed. Some of the diagrams given in the paper seem to support this view. Fig. 20 shows that on three Sunday mornings—periods at which a feeder cable is probably running at its coldest—the surges arise, disappearing again later in the week. It is hardly likely, I think, that exactly similar atmospheric conditions would occur on three successive Sundays. Again, Fig. 21 shows that there is heavy surging from 12 midnight. This begins to die off soon after 9 a.m., has practically disappeared by noon, and does not recur until the evening. I believe the authors suggested that the gap in the curve indicates a fault at about 8 p.m., but the repair of this fault does not appear to have affected the surge. The cable having cooled down, the surge again commences. Fig. 22 also exhibits similar characteristics. It is possible that a breakdown and repair at one point of the cable might still leave distributed voids along its length, and that these might still initiate surges. Such surges would not necessarily be very great except where overhead-line sections existed, when their inductance, together with the cable capacity, might give rise to resonance effects. It would be of interest if the authors could add to these diagrams some statement of the period of the year to which they refer, and of the current loading of the cables during the periods recorded. On page 1485 it is stated that no records were obtained by the application of steady d.c. potential to the klydonograph. I cannot quite harmonize this statement with the explanation of the action given—that of an electron discharge, which should occur equally well under d.c. potentials. I have therefore made some tests with a view to obtaining a check as to whether such action did, in fact, occur. The apparatus was very simple, merely consisting of a pin put through the top of an ordinary negative box so that it touched the film of a plate resting with the glass side on a sheet of tinfoil. Voltage was applied between pin and tinfoil from an accumulator battery giving up to 8 640 volts. With the needle positive the figures were similar to those of the authors' Fig. 11. With the needle negative the discharges were of the same type as those described by the authors, with the exception that the higher voltages produced a few streamers round the central nucleus. [Mr. Riley here exhibited two slides showing the results which he had obtained at various voltages.] It has been stated that the diagram obtained varies according to the steepness of the wave-front. McEachron's tests show relatively weak evidence for variation of the radius with steepness of wave-front. The small increase in size with increased steepness of wave-front could quite well be due to partial reflection at what amounts to the open end of a circuit causing an effective rise of potential. Such a reflection effect might be expected to be a maximum when the rate of rise of voltage is greatest; this may be a phenomenon similar to the one obtained by Mr. Goodlet at high frequency, because under such conditions the rate of voltage-rise would be more rapid than at low frequencies. It would be of interest if the authors would give the results of any investigations which they may have made on this point, with a view to explaining the mechanism of the action.

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* "Air as an Insulator when in the Presence of Insulating Bodies of Higher Specific Inductive Capacity," *Transactions of the American I.E.E.*, 1913, vol. 32, p. 893.

Mr. A. G. Collis: The paper appears to be confined to a description of the klydonograph and the effects of brush discharges over insulators. Whilst I have no experience of the method adopted, I am doubtful at the moment of its mathematical accuracy in the determination of design. Is it not true that its adjustment ratio, being variable by the situation of the cylinders, is affected by capacity to earth? I should prefer the oscillograph, which would enable the physical relations of the circuit to be determined. An analytical assumption from such tests as those described is limited, owing to the absence of details of the transmission system under review. Was the system earthed or insulated? The effect of a brush discharge or a surge attending a fault on an earthed system is of greater dimensions than that produced on an insulated system. If the insulated transmission is large, so that the electrostatic capacity between conductors and ground is high, a proportional charging current will flow into the fault. Again, the potential between the other two conductors will be 1·73 times its normal value, with a corresponding increase in charging current. Although the question of the relative merits of earthed and insulated systems is not discussed, it has a bearing on the tests described and the subject of the paper. The absence of oscillograph records makes diagnosis difficult, as a fault to earth, according to its resistance, naturally distorts and affects the power factor of the system. Technical particulars such as the impedance and reactance of the equipment would also be of some assistance. With regard to the condition for resonance, is it possible for the self-induction and capacity to be so proportioned that the current flowing when the capacity is short-circuited equals that flowing when the self-induction is short-circuited? The construction of any transformers or synchronous condensers which may be connected to the line affects the situation. The former may be of the star-star type for the sake of economy, or they may be provided with a tertiary winding to avoid trouble due to the third harmonic. I hope that the authors will include in their reply some information regarding these points. The application of reactors also affects the voltage surge on the line. Under normal conditions there is no voltage-drop across the reactor, but abnormal conditions give rise to a tendency for such a voltage-drop to be built up, and the energy from this is dissipated in the resistance of the reactor circuit. If an oscillograph record had been included in the paper it would have been possible to determine whether or not the wave-form was symmetrical with twice or three times its peak value, and whether in consequence the electromechanical stresses of the latter were directly proportional to the square of the current and inversely as the distance between transmission phases. I have conducted a large number of tests on surges, chiefly on those introduced by the rate of change of electrical phenomena, and in the early days I used a spark-gap to earth. It was then supposed that the operation of closing the circuit of a long underground transmission line produced high electrical pressures which broke down the end-turns of stator coils. These were reinforced by insulation, and at that time surge resistances were employed to limit the pressure when switching in, but such precautions were not entirely justified. In regard to the design of transformers, the end windings are at present reinforced in order to preserve a high factor of safety, and for this reason we must first consider the effect of an alternating pressure upon a conductor with inductance and capacity in parallel. If the applied pressure is constant, the current taken by the capacity is directly proportional to the frequency, while the current taken by the inductance is inversely proportional to the frequency; the particular frequency at which these two currents are equal is termed the resonant frequency of the combination. At frequencies below that of resonance the current taken by the inductance is in excess of that taken by the capacity, while at frequencies greater than that of resonance the reverse condition holds good. If the alternating pressure is connected to the inductance and capacity in series, the same current flows through each but the pressures across them are in opposition. The current is initially limited by the inductance and eventually by the capacity, so that the e.m.f. oscillates from a maximum across the inductance to a value 100 per cent in excess of the applied pressure across the capacity, and so on. My experience is that a large number of breakdowns result from defective switchgear, the chattering or unequal alignment of the contacts of which produces high-frequency waves which impinge upon the transformer. The general practice is to close the primary circuit first, and this to a certain extent eliminates distortion of the windings due to heavy current-rushes. When opening the primary, however, excessive potentials are imposed upon the circuit, particularly if the flux intensity drops with a rapidity greater than the normal cycle rate. Instability of the arcs formed on breaking circuits is productive of high-frequency pressure oscillations, and it is for this reason that oil circuit-breakers are preferable to air-break switches. These points are mentioned in order to show that the brush discharge is a comparatively small matter connected with the other transients on the circuit. It is comparatively easy to design an insulator of such a potential gradient removed from earth potential as will eliminate brush discharges or ionization, but it is not easy to meet the conditions of transients inseparably bound up with the phenomena attending transmission. If we could eliminate the power-factor effects of the loads connected to the system, we should be able to reduce the consequences of over-voltages resulting from changes in the circuit conditions.

Mr. F. E. J. Ockenden: The design of the condenser used by the authors as a voltage divider is of interest since it is not easy to design a condenser of this type which will maintain its accuracy under varying conditions of temperature and atmospheric humidity. The form of insulator used for the low-tension end of the condenser as shown in Fig. 10 is, in my opinion, unsuitable for the purpose. The capacity current available at the low-tension terminal is only of the order of a few microamperes, and a very minute leakage through the insulator may represent a large proportion of the total current, and therefore a large error in the voltage ratio. In practice this leakage may take two forms. The first and less serious is that resulting from direct leakage over the surface of the insulator. If, however, the surface is long and is kept reasonably clean the leakage is small, and is in any case in quadrature with the capacity component, so that its effect should be extremely small. The second form of leakage is the result of a conducting film forming on the surface of the insulator and linking up with the earthed case to which the insulator is attached. This film acts as an electrode surrounding the leading-out terminal, and capacity currents induced in it flow directly to earth through the metal case, thus causing a leakage current to flow which is both of considerable magnitude and in phase with the main capacity current. In Fig. A the capacity leakage film is shown by the dotted line. It will be noticed that it is not affected by the length of the insulator, and is but little affected by the "amplitude" of the corrugations if these are shallow, as shown in the sketch. The resistance of this film is of course considerable; thus it is only effective for a small distance along the insulator, but this distance is very variable, depending on the humidity of the surrounding atmosphere. The film is, moreover, very tenacious and it is my experience that no ordinary dry cloth, even when warmed, will completely remove it. An effective solution to this problem may be obtained by constructing the insulator with corrugations the sides of which are vertical, the first of them being mounted very close to the metal case. Fig. B shows the general arrangement of such an insulator. The position of the conducting leakage film is shown by the dotted line. It will be noticed that variations in the length of this film tend to occur only up and down the sides of the radial fin, and consequently these variations will have little or no effect on its capacity to the leading-out conductor. Condensers used as potential dividers for operating electrostatic voltmeters have shown a consistency of nearer than ½ per cent even under the most adverse conditions when fitted with this type of insulator on the low-tension end. The authors' remarks on the origin of the difference between the records obtained from positive and from negative surges remind me that some while ago I was investigating the difference between the positive and negative electrodes of an ordinary d.c. spark-gap of the order of about 1 mm in length, such as the gap in a magneto-operated sparking plug. As will be seen from Figs. C and D (see Plate IV, facing page 1481), the difference between the two electrodes is very marked. Fig. C shows the positive electrode. The discharge is in intimate contact with the end of the electrode. Fig. D shows the negative electrode. Although the discharge is taking place in air at normal pressure the dark space intervening between the discharge and the negative glow is plainly visible, and close examination will reveal a second dark space, exceedingly narrow, surrounding the end of the electrode. In view of the fact that the operation of the klydonograph must consist of a minute discharge to the film in air, the difference between the figures obtained for positive and negative surges may perhaps be the consequence of differences in the nature of the discharges similar to those shown in the photographic reproductions.

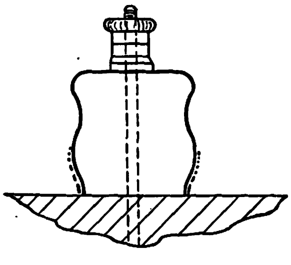

FIG. A.

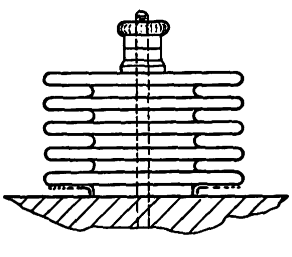

FIG. B.

Mr. G. L. Addenbrooke: My work on this subject, which has been referred to by the authors, is contained in a paper [*] published in 1927. When Lord Armstrong published his fine volume [†] on the subject not much was known beyond the original Lichtenberg figures. He made photographic reproductions of such figures in an improved form and published illustrations of them on a large scale. The work was continued under his auspices by Prof. Stroud and gorgeous effects were produced, but they were practically inexplicable at the time. Sir J. W. Swan published a paper [‡] in 1898 in which, in my opinion, the whole question of these figures was first put on a proper basis. His experiments were carried out with a frictional machine and with points or spheres placed over various compounds of resin and oil. Not only did the resin when charged show figures such as those which have been described, but the surface became indented. Swan was able to keep such charges on a plate of resin for two or three months. I myself have kept a charge for over a month; on heating such charged plates a set of depressions is produced which show as an image of the original charge. My own paper, mentioned above, describes in detail what occurs and shows that the whole effect is due to ionization. If the distance between the electrodes is increased a beautiful effect, which was shown at the Physical Society's Exhibition two years ago, is produced. A large number of impacts take place, as of particles of dust thrown down on the dielectric surface. These particles indent the film and usually have two or three little points running out of them. If a sufficiently viscous dielectric is used it is possible actually to see these charges spreading out towards the circumference of the vessel, and at the same time indenting themselves further in. This seems to me to be the most complete visible demonstration of the action of ions in air that has hitherto been discovered. Effects of this kind are very useful in showing surges on lines, and such surges doubtless occur electrically to a large extent. The difference between the positive and negative discharges has been referred to. Since 1927 I have been trying to measure the currents which pass through insulators owing to these electrical discharges. I find that, for the same voltage and distance between the electrode and the plate under the dielectric, great differences exist between the magnitudes of the currents which pass through as their signs are changed. The current is always much larger when the point in air is positive. With the point actually entering the dielectric, I find again that there is a similar difference in the magnitudes of the respective currents, although the ratio may not be quite so large as when the discharge is partly through air. The experiments seem to show that if any point or sharp edge carrying a higher alternating potential than its surroundings is within a dielectric, say a liquid, there will be a tendency to discharge from this and the discharge with an ordinary alternating current will be greater in the positive phase than in the negative phase. The discharge of negative ions is not sufficient to neutralize the discharge of positive ions, so that there exists in the dielectric a small permanent positive ionization which is certain to give rise to chemical action. This, I think, is the cause of sludging in oils, and actions which occur in cables.

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[*] "Dielectric Attraction in Electric Fields," *Philosophical Magazine*, 1927, vol. 3, p. 1166.

[†] "Electric Movement in Air and Water."

[‡] "Stress and Other Effects Produced in Resin and in a Viscid Compound of Resin and Oil by Electrification," *Proceedings of the Royal Society*, 1898, vol. 62, p. 38.

Mr. J. J. C. Berkeley (*communicated*): During the early part of January, 1930, strong gales swept over Holland and north-western Germany, and frequent failures of supply occurred. The whole of the Lower Rhine district is supplied with current at 220 kV and 100 kV by the Rheinisch Westfälisches Elektricitätswerk (the R.W.E.). In the daily Press the cause of the failures was attributed to flash-overs due to deposits of salt on the insulators. Rhenish Westphalia is about 180 miles away from the sea coast, and the strings of insulators, of the cap-and-pin type, are from about 4½ ft. to 6 ft. in length for the high voltages employed. In my opinion the deposit was due to the strong winds having carried moist air, saturated with salt, so far inland; on the moisture evaporating, a crust of salt was left on the insulators. This opinion was shared by the R.W.E.

Mr. J. H. C. Brooking (*communicated*): The paper refers to a number of shut-downs, due to salt being deposited on the insulators during storms from the sea, and to the difficulty in recommencing the supply, due to the salt adhering firmly. No cure is given for this trouble, except systematic cleaning of the insulators with scrubbing brushes and water; and the opinion is offered that "something more than over-insulation is necessary." It may, therefore, be useful to mention the experience of the Lothians Power Co., who have found that where their lines, situated right on the sea coast, were fitted with Pernax patent bird guards there was no trouble during the worst salt storm experienced (November, 1927); but that lines fitted with similar insulators, without bird guards, 10 miles from the coast, flashed over several times during that storm. The Lothians Power Co. consider that these guards were entirely responsible for this difference in results, thus serving the double purpose of preventing birds and conductive deposits from damaging the lines and plant.

Dr. J. L. Miller (*communicated*): The klydonograph has been too long neglected in this country, owing, I suppose, to the comparative rarity of severe thunderstorms and, until recent years, the small number of high-voltage overhead lines in operation. In the United States, however, it has been a very valuable instrument in the solution of many of their lightning problems. In the Ferranti Laboratories we have been using several klydonographs for some time, and the experience we have gained may prove of interest. The first thing which impressed me was the small size of the figures, but I presumed this was necessitated by the limiting width of the film. If I am correct in this assumption, I feel that it might have been desirable to use a wider film and work higher up on the calibration curves by altering the potentiometer ratios, as I am of the opinion that the larger figures are always more reliable. At the same time, it must be remembered that the records obtained by the authors show a series of small surges rather than a few high-voltage lightning transients, and, as they point out, a critical analysis, which is often attempted in the latter case, was both impossible and unnecessary. I was glad to see some information regarding the shape of the electrodes, as this appears to have been neglected in the papers previously published. As we usually employ the instrument on artificial surge work, the time element does not enter into the matter, and so we are able to use plates and needle-point electrodes. I note that the authors calibrated their records on a 50-cycle wave, at the same time mentioning that some observers had noted a larger figure with steeper wave-fronts. I should therefore be glad to know whether they have observed any difference between the 50-cycle calibration and, say, a calibration with the wave having a front of 5 micro-seconds. Compared with the former, the latter is a relatively steep wave. Actually, we have found that the 50-cycle calibration is generally slightly smaller than the impulse figure, and that the difference between waves of different wave-front steepness, if it exists at all, is so slight as to be masked by the other inaccuracies of the instrument. It has been suggested that surface leakage across the plate would account for this variation in size with the slower waves. Obviously, with steep-fronted waves which rise to their maximum value in a micro-second or so, surface leakage will be of no importance, whereas with 50-cycle waves it might have some important bearing on the results. Referring to Fig. 6, where the relationship between the radius of the figure and the impressed voltages is given, I find that there is a difference between the authors' calibration and our own. A few typical records obtained in our own laboratory have been collected in Table A, the figures given therein being obtained with the usual simple series impulse circuit with the klydonograph connected across the resistance.

Assuming that the calibration law is a linear one after the critical point is passed, and making the further assumption that both the authors' figures and our own are averages of a large number of experiments, the table gives $E = 5 \cdot 65r$ (approx.), where E is the stress (kilovolts) and r is the radius (cm) of the positive figure. In Fig. 6, at 8 kV the radius of the figure is about 11·8 mm, giving $E = 6 \cdot 78r$, indicating a smaller figure than our own at the same voltage. I feel that this difference is due to calibrating with 50-cycle sine waves, because tests 5 and 6, which were obtained under these conditions, give $E = 6 \cdot 34r$, which is nearer the authors' figure. It might also be stated that the discrepancy is due to a different speed of plate, but test 4 indicates that this is not the solution. It might be added that Magnusson in his paper suggests $E = 5 \cdot 9r$, which is very near our own constant, and a similar agreement is obtained with the records of McEachron and Cox and Legg. With an ordinary Kodak film, figures similar to those obtained with plates were found. It can be seen that agreement between the results is very good, but more erratic figures are to be expected with the lower voltages, and for this reason we prefer to use the larger ones. However, with the latter, records appear to go wrong now and then, and I feel that the authors' figure of ± 10 per cent as the possible error is about right for our own experiments if extreme records are eliminated. Some of the American papers, however, give about 25 per cent as the possible error. In connection with the theory of operation of the klydonograph, I am of the same opinion as the authors when they surmise that the figures are caused by light emitted from the discharge, and we have performed many experiments which tend to confirm their conclusions. For instance, Magnusson obtained a blurred figure by placing an additional glass plate on his photographic plate, and we did the same thing by reversing the photographic plate and placing the electrode on the glass side. We have also attempted to take records under oil, but we failed to obtain a result. Thin films of oil on the plate gave a lighter and more hazy figure, indicating that the discharge took place on the top surface of the oil. We also took records using a colour plate of the type where the screen is combined with the emulsion. With the electrode on the emulsion side, a clear white figure of standard size was obtained. With the electrode on the glass side (so that the light would have to pass through the filter before reaching the emulsion), a blurred light-blue figure was obtained. The plates used, however, from my experience with ordinary colour photography, are liable to take on a blue tinge, and perhaps the blue figure was due to some inherent quality in the plate, but I give the idea for what it is worth. In this connection I should like to know what type of "safe light" was used in the authors' experiments. We have obtained records when the potential has been increased very slowly, and they were much smaller than the average figures. In appearance they were similar to McEachron's, and, as he describes them in his own words, they "consisted of fine straight lines emanating from the centre and perhaps extending only partially round the entire electrode. The appearance is much like that of fine hair being blown out by some force at the centre." Turning to the other aspect of the paper, I feel that the importance of a trip-out due to a lightning stroke hitting a line is rather underrated. The voluminous literature in American journals and the amount of money expended on investigational work rather tend to disprove this.

TABLE A.

Test	Plate speed	Capacity of condenser	Voltage across resistance	Diameter of figure	Type of figure
		μF	kV	cm	
1	H & D 400	0·01	12·2	4·28	Positive
2	H & D 400	0·05	12·2	4·5	Positive
3	H & D 400	0·05	13	4·9	Positive
4	H & D 90	0·05	12·2	4·2	Positive
5	H & D 400	—	13 (50-cycle wave)	4·1	Positive connection
6	H & D 400	—	13 (50-cycle wave)	4·1	Negative connection

Mr. J. E. Taylor (*communicated*): The effect on which the klydonograph relies for the measurement of instantaneous voltages is one to which I have, in the past, given some little attention in connection with apparatus for wireless transmission. The best clue to the causes contributing to the electric brush effects concerned, both on the line insulators and on the photographic film in the instrument, is perhaps afforded rather by a close examination of the Lodge experiment on overflow of Leyden jars than by a consideration of the Lichtenberg figures. In this well-known experiment a highly charged Leyden jar is discharged through a suitable circuit so that a strong brush discharge is set up from the edges of the tinfoil coatings along the surface of the glass. If the insulating surface on the jar is not sufficiently extensive a direct flash-over discharge round its edge will occur each time the ordinary spark-gap discharge takes place. The brushing may also be accentuated and the flash-over precipitated by a slight deposit of moisture on the glass surface. In the past this effect has been attributed to surges in the main discharge circuit producing accumulations of voltage at the coatings of the jar. A little consideration, however, shows that this explanation is hardly tenable. Increased voltage at the coatings must mean either an addition to the energy of the system, since the jar must then be more highly charged than at the start of discharge, or a considerable decrease in the specific inductive capacity of the glass. In any case, surges are ruled out by the first consideration. The second is also ruled out for several reasons, the chief being, perhaps, that the effect is independent of the material of which the dielectric is formed, though some materials may offer better surface conditions for its development than others. The conclusion is that there is no rise of voltage that matters at the coatings. An explanation which I gave some years ago * is that there is a progressive surface ionization resulting from an initial creeping away of the charges along the glass surface when the jar is charged. This is permitted by the normal surface conductivity. The circuit becomes oscillatory on discharge and at the first reversal of charges on the coatings the surface-charges then facilitate the production of a high potential gradient over any intervening surface, and, since this gradient rises above that whch can be sustained by the air, a brush discharge ensues whereby an ionized path over the glass is formed. This not only discharges the glass surface but conveys a full reversed charge. At this stage the brush is of a comparatively minor character. The reversal of the surface charge being now affected and having the same sign as the coating from which it was charged, the brush ceases and the ionization fades out before the next reversal occurs. A similar process is again gone through at each reversal of the main oscillation, but the charge on the glass surface creeps a little more, to a degree depending on its duration, each time it is formed and thus continues to extend further away over the glass surface, the brush following suit. The distance to which the brush will extend will be a function of the surface conductivity so long as that conductivity is not too large to keep the potential gradient below the critical limit of air breakdown. The oscillations over the insulators on a high-tension power line are doubtless initiated by the discharge between the creeping charges on the insulators and the power line. The high-frequency effects thus set up appear to be conveyed to the klydonograph. It is within my experience that wireless receivers in the vicinity are strongly affected when the discharges occur, even without actual " flash-over."

Mr. E. Wilkinson (*communicated*): In connection with the effect of d.c. voltages upon the film in a klydonograph some interesting experiments have been carried out in the University of Liverpool. The authors claim that no figure is obtained by the application of d.c. stresses, but such figures have been recorded and they cannot be explained by the existence of ripple in the output voltage. The result of the experiments supports this opinion, and, moreover, it illustrates how the figures observed by McEachron are formed. A supply of direct current at 10 000 volts was available from a full-wave kenotron rectifier set, the circuit diagram of which is shown in Fig. E. The stress was applied directly to the klydonograph in series with a protective resistance. In the first of two tests a current of 200 mA was passed through the resistance R, the variation in voltage under these conditions being about 0·5 per cent (calculated and measured). A specially constructed klydonograph was used, through which the film could be wound by hand. The voltage was first switched on and the film was moved a few inches while the voltage was maintained. It was then left in this position for 10 minutes, the purpose of this procedure being, of course, to separate the initial surge figure from any figure due to the direct current. A figure was produced under these conditions (see Fig. F on Plate IV, facing page 1481). The radius of the figure is smaller than that of a figure obtained by a surge at the same voltage (the circle in Fig. F shows the size of a positive surge of 9 600 volts). It seemed possible that the figure was caused by the ripple, even though the maximum deviation was only about 50 volts. Another test was performed, therefore, with the valves on open circuit ($R =$ infinity, in Fig. E). The output voltage under these conditions is theoretically perfectly smooth, but a figure of similar shape and magnitude was again obtained. As a final and conclusive test the condenser of the smoothing circuit was charged and the power supply disconnected. The condenser alone was used as the source of stress. In this case also the figures were formed. It seems, therefore, that the effect is due to the total stress and not to the ripple. That the authors did not observe such figures may be due to one of two causes. The voltage employed by them may have been insufficiently high. Secondly, the voltage may not have been applied for a sufficient length of time. The figures definitely take time to form, the actual formation of the d.c. figure being shown in Fig. H (see Plate IV, facing page 1481). In this test a d.c. stress was maintained while the film was moved through the klydonograph [from (*d*) to (*e*), Fig. H]. Streamers will be noticed leaving the zero line. When the film is stationary for a period of time the lines build up into a full figure (at the rate of about 40 lines per sec., in one test). Another interesting result was

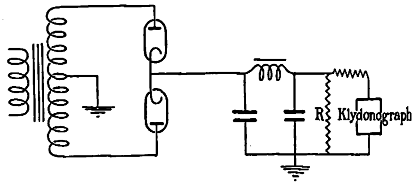

FIG. E.

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* *Journal I.E.E.*, 1922, vol. 60, p. 853.

noticed. If a steady potential was applied to the klydonograph and this was suddenly raised to a higher value, the size of the figure produced seemed to depend upon the final voltage reached and not upon the rise in voltage. Figs. G and H (see Plate IV) are the results of two experiments which demonstrate this. The klydonograph was connected across a portion of a potentiometer resistance the other portion of which was paralleled by a short-circuiting switch. The film was first calibrated by applying a surge corresponding to the voltages across the klydonograph when the switch was in the open and closed positions respectively. With the switch open, the lower voltage was switched on. The film was moved a short distance and the short-circuiting switch closed, thus increasing the voltage suddenly to the higher value. In the experiment of Fig. G the power was then switched off, while in Fig. H the film was turned through before switching off. The results show fairly definitely that the value of the surge does not control the size of the resultant figure. The size is determined by the final voltage reached.

Messrs. S. W. Melsom, A. N. Arman and **W. Bibby** (*in reply*): We have to thank Mr. Wedmore for his helpful and instructive contribution to the discussion, and especially for suggesting that the Electrical Research Association might proceed to investigate fully the whole question of surge phenomena. In view of electricity supply developments, the large units involved and the extension of overhead-line systems, such an investigation is imperative unless the electricity supply authorities —and subsequently, of course, the consumers—are going to bear the very heavy cost of a large number of breakdowns such as have occurred quite recently on power supply systems where high pressures have been used without adequate knowledge either of manufacture or of operation. It is safe to say that the cost of such a complete investigation would be not more than one-tenth of the cost of making good the breakdowns resulting from the lack of knowledge. From this point of view, it is disappointing that those more particularly interested in transmission-line design, manufacture and operation, have not taken part in the discussion of the paper, but one may hope that they will co-operate when the Research Association formulates its proposals for the research.

Dealing with the questions of detail put by Mr. Wedmore, we did not attempt to work with a higher temperature, but we agree that there are possibilities in this direction. Actually, more recent work carried out on the effect of temperature gave conflicting—or, at least, irregular—results, and a good deal of further work on those lines is probably required. The amount of energy taken by the klydonograph is minute, and, while definite measurements were not made, there seems to be little doubt that any energy loss here does not affect the calibration beyond the limits of error stated.

We are glad to learn from the remarks of Prof. Marchant and others that further investigations are being made into the physical properties of the instrument. Such complete work is needed, but it was hardly possible for us to undertake it all, in view of the importance of obtaining roughly quantitative results so as to clear up difficulties on certain lines. In reply to Prof. Marchant's specific question, we have not done any work with reduced air pressures. The effect of temperature is dealt with in reply to Mr. Wedmore; work on this subject is proceeding and it seems possible that some factor other than film sensitivity is having an effect. The usual type of earth wire suspended from pole to pole and beneath the line conductors was used. The point mentioned about the thickened insulators at both ends of the transformer is interesting corroboration of the view which we have put forward, and Prof. Marchant is to be congratulated on his investigation on the strength of insulating materials under high-frequency discharge. Practically no modern information is available on this subject and Prof. Marchant's results when available should be of the greatest value.

In reply to Mr. Herwald, South Wales has been stressed in the paper, but solely because of a combination of circumstances which led to a great deal of trouble on one particular line. Climatic conditions were undoubtedly responsible for a great deal of the trouble, but such conditions and surges occur on other lines, especially composite ones. Possibly there is a clerical error in Mr. Herwald's results which show the high inductance of the cable section as compared with the overhead line. Actually, the cable has a much lower inductance and much greater capacity than the overhead line; consequently, the tendency will be for the cable to reduce the voltage component of a wave. As mentioned in the paper, however, the cable must be of fair length to effect any appreciable reduction.

We agree with the greater part of Mr. Goodlet's remarks and we have to thank him for the interesting additional information which he adduces. The improved performance claimed for the inverted type of sealing end, however, is mainly due to the fact that with this design the sheds can be correctly arranged in the electric field. We are of opinion that the deep sheds are beneficial in most cases, but we agree with Mr. Goodlet that in some situations they would not greatly improve matters. Regarding the size of the figure with high-frequency oscillations, we did not make definite measurements but relied on the American investigations. It is interesting to note that Dr. Miller states in this discussion that the high-frequency figures are slightly larger than with the usual frequencies of power supply.

Mr. Harris is no doubt correct when he says that most of the insulators on the line were near the flash-over point. This is evident from the amount of discharge on the line. But the fact that flash-over and more intense discharge occurred always on the sealing-end insulators bears out our theory that with the sheds correctly disposed there is less discharge and the insulator does not so readily flash over. In fact, on this particular line, there was not a single instance of flash-over on a sound pin insulator. We are confident as to the accuracy of our statements regarding the increase of the voltage at which discharge commences without a corresponding change in the flash-over voltage. A number of tests on various insulators—some specially made—proved this, and one case may be mentioned of an insulator where the field was altered by the interposition of metal sheds and where the voltage at which discharge commenced under wet and dirty conditions was doubled, while the flash-over voltage was actually reduced by about 20 per cent. As mentioned in the reply to Mr. Goodlet, the success of the inverted type of sealing end was due to the arrangement of the sheds with regard to the field rather than to the depth of the sheds, although it was felt that the latter was an advantage.

In reply to Mr. Riley, it is quite possible that discharge occurring in the interior of a cable may have produced the oscillations shown. In fact, examination of one set of films led us to expect that a breakdown would occur, and this duly took place, but it would be necessary to consider many other features of the circuit before we could say definitely that this was the cause of all the surging. Mr. Riley's results with direct current are interesting—we had not facilities for such high voltages—and it seems probable that with such voltages definite figures can be obtained with direct current.

Mr. Collis raises a number of points, possibly from a rather different angle. First, the oscillograph available did not respond to the very high frequencies; it seems doubtful whether an instrument which does not show the surges actually present—admirable as are its characteristics in other directions—can be considered to have a higher mathematical accuracy than one which does record them, but to a comparatively low order of accuracy. The system was, of course, earthed, as are practically all 33-kV transmission systems. The complete system was so intricate that it was difficult to arrive at even a rough approximation of the impedance and resistance, but we were satisfied by a long series of experiments that there was no question of resonance on the system and especially no possibility of resonance due to the transformers or synchronous motors. Mr. Collis is probably thinking of indoor insulators when he says "it is comparatively easy to design an insulator . . . that will eliminate brush discharge or ionization." It is certainly not an easy problem in the case of outdoor and dirty conditions.

We agree with Mr. Ockenden that leakage along the insulator shown would have a serious effect. The first insulators used were of porcelain and had the shape illustrated, but owing to trouble with leakage they were replaced by ebonite insulators having a special petticoat with a very long leakage path, the two main surfaces being protected by the petticoat. These insulators were completely satisfactory.

We have to thank Mr. Addenbrooke for the further description of his work which bears on this subject.

Mr. Berkeley appears to have had similar experience abroad, and it is of great interest to note that in his case salt was air-borne for a distance of 180 miles.

Mr. Brooking's communication draws attention to the efficacy of shielding and, in this respect, bears out the statements in the paper.

Dr. Miller has given a great deal of additional information which it is not possible to deal with except by way of thanks. On the question of the accuracy obtainable with the wider initial line, we agree that where the highest possible accuracy is required, that is to say in the actual measurement of the voltage, the wider initial line is to be preferred. Where, however, as in our case, the existence of surges under normal line operation, and, in particular, their incidence, are of primary importance it seemed better to use the instrument as a surge detector with the times of occurrence most clearly marked, even although this involved the sacrifice of some accuracy in the determination of the actual voltage. The decision to make use of the critical part of the curve in this way was taken deliberately and we still consider that for that particular type of service it is the better method. The difference found by Dr. Miller in the size of the figure due to wave-front is about what we should have expected after a study of the work done on this subject in America. We were unable to make definite calibration with waves of varying steepness, owing to lack of a cathode-ray oscillograph. Calculation is hardly sufficient for such a purpose. The "safe light" used was a "Wratten."

The points raised by Mr. Wilkinson have been partly dealt with in our reply to the other speakers. The interesting results with direct current confirm those referred to by Mr. Riley. Mr. Wilkinson's contribution draws attention to the large amount of work that is required before the physical properties of this very interesting instrument are properly understood.

THE METERING ARRANGEMENTS FOR THE "GRID" TRANSMISSION SYSTEM IN GREAT BRITAIN.

By C. W. MARSHALL, B.Sc., Member.

(*Lecture delivered before the* METER AND INSTRUMENT SECTION, *2nd May,* 1930.)

SUMMARY.

The lecture reviews briefly the provisions of the 1926 Electricity Act which relate to metering. It describes the system of measurement which has been adopted for the main classes of electricity stations connected to the " grid " system, and mentions the constructional features of the instruments used in the Central Scotland and South-East England electricity schemes which differ from recognized meter engineering practice.

The novel features of the general scheme are the use of summator meters, long-scale maximum-demand indicators, special devices for recording maximum power demands, and reactive-component meters.

Actual instruments were used for demonstration, and slides of typical installations were shown at the lecture.

GENERAL METERING REQUIREMENTS.

The provisions of the Electricity (Supply) Act, 1926, which specifically relate to the subject of metering are summarized here, as they form the basis of the measuring arrangements which have been adopted by the Central Electricity Board for the " grid " system.

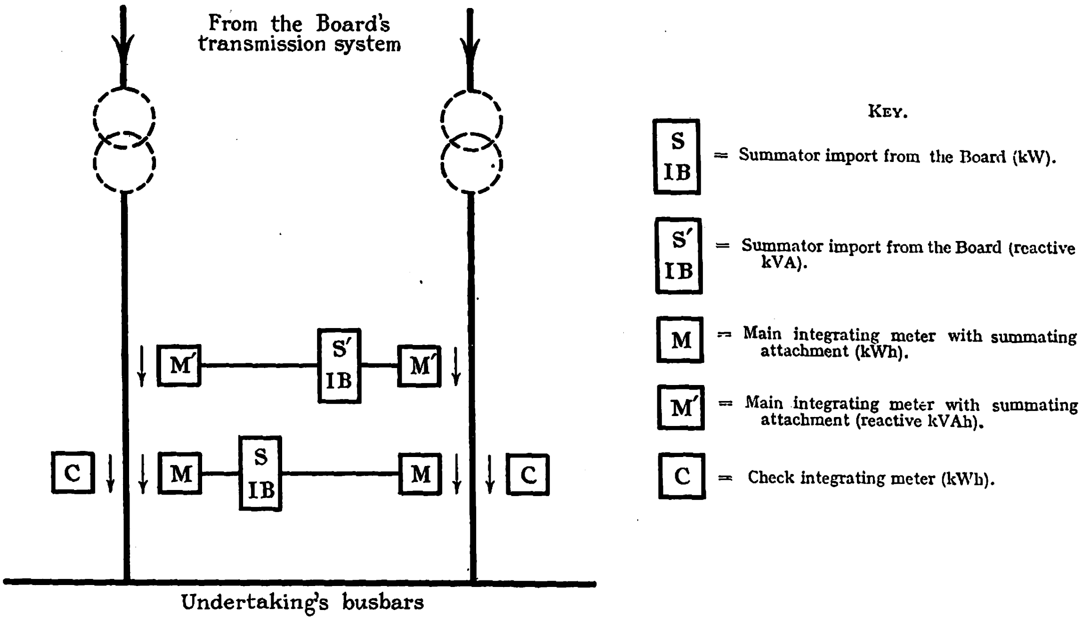
From the Board's transmission system
M'
S' IB
M
S IB
C
Undertaking's busbars
KEY.
S IB = Summator import from the Board (kW).
S' IB = Summator import from the Board (reactive kVA).
M = Main integrating meter with summating attachment (kWh).
M' = Main integrating meter with summating attachment (reactive kVAh).
C = Check integrating meter (kWh).

FIG. 1.—Metering scheme for stations without generating plant.

Under the Act, the price at which the Central Electricity Board can supply the owners of a selected station will, unless otherwise agreed, be

(*a*) The cost of production, ascertained in the manner prescribed in Sub-section (3) of Section (7) of the Act, adjusted according to the load factor and power factor of the supply given to the owners of the selected station; together with a proper proportion of the Board's expenses, other than those incurred by the Board in the purchase or generation of electricity; or

(*b*) According to the Board's tariff.

Kilowatt-hours, kilowatts of maximum demand, and power factor are elements which enter into the determination of cost of supply in both cases. The same units of measurement will enter into the Board's tariffs in most cases of supplies to non-selected stations.

Measurement of kilowatt-hours, kilowatts of maximum demand, and power factor of individual circuits had previously been developed to a high standard of accuracy and reliability. The problems introduced by the Act therefore related principally to extension of existing methods to multiple circuits, together with obtaining accuracy of measurement commensurate with the importance of the supplies, as far as is commercially practicable.

The general methods of measurement which have been adopted will first be described, and then particular examples of typical equipments will be illustrated and demonstrated.

Stations to be connected to the grid system may be divided into two main types:—

(i) Those in which there will be no generating plant in operation.

(ii) Those in which there will be generating plant in operation.

The equipments provided in the two cases are illustrated diagrammatically in Figs. 1 and 2 respectively.

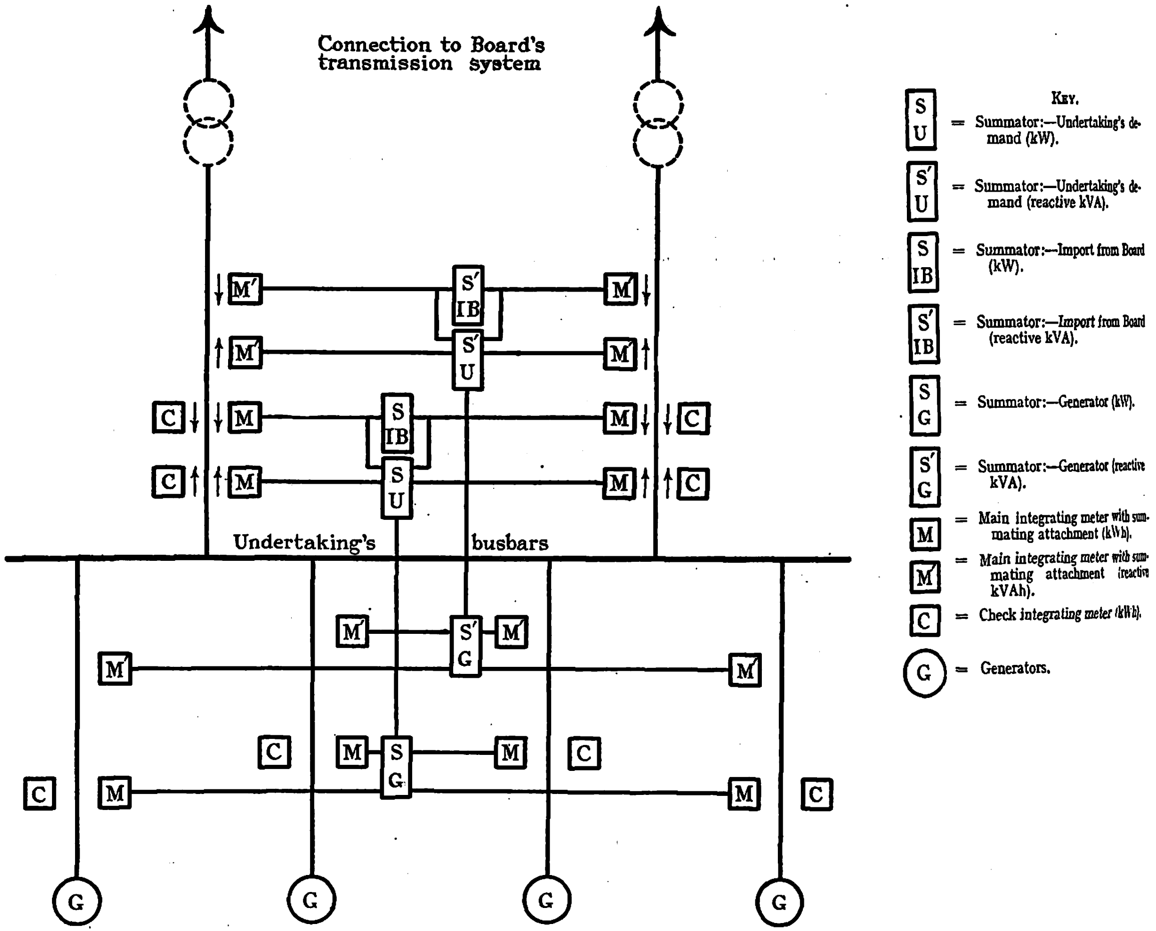
Connection to Board's transmission system
M′
S′
IB
S′
U
M
C
S
IB
S
U
Undertaking's busbars
S′
G
S
G
G
Key.
S U = Summator:—Undertaking's demand (kW).
S′ U = Summator:—Undertaking's demand (reactive kVA).
S IB = Summator:—Import from Board (kW).
S′ IB = Summator:—Import from Board (reactive kVA).
S G = Summator:—Generator (kW).
S′ G = Summator:—Generator (reactive kVA).
M = Main integrating meter with summating attachment (kWh).
M′ = Main integrating meter with summating attachment (reactive kVAh).
C = Check integrating meter (kWh).
G = Generators.

Fig. 2.—Metering scheme for stations with generating plant.

Fig. 1 shows that each incoming circuit from the grid system is equipped with a kWh meter and a reactive kVAh meter, the purpose of the latter types being to determine, in conjunction with the energy meters, the power factor. There are, in addition, summator meters for determining the total energy input and the maximum power demand, and the corresponding reactive quantities.

The equipment for a station in which generating plant will be in operation is shown in Fig. 2, and is as follows. There are input and output kWh meters and reactive kVAh meters in each connection between the grid and the undertaking, and an output kWh meter and reactive kVAh meter in each generator circuit. Summator meters are provided to give the total energy and maximum power demand and the corresponding reactive quantities of (*a*) the import from the Board, (*b*) the output from the generators, and (*c*) the supplies to the undertaking for its own requirements. The energy supplies to the station auxiliaries are also measured, but the reactive quantities and maximum demands relating to the auxiliary supplies are, in general, estimated. The supply to the undertaking for its own purposes is the sum of the corresponding imported and generated quantities, minus the sum of the quantities exported and used for auxiliary purposes. Check equipments are provided on main circuits for energy measurements. There are no check reactive-component meters. The summators are verified by comparison between their registrations and those of the component meters (termed summating meters).

These are very briefly the general provisions which are made for measurement. The classes of instruments used are, kWh meters, reactive kVAh meters, summator meters and maximum-demand indicators and recorders. The term "recorder" is used in its most general sense and includes printometers and graphic meters.

The instruments which are being used on the Central

Scotland and South-East England Schemes will now be described, the schemes being considered in chronological order.

The kWh meters used in the Central Scotland scheme are of the Metropolitan-Vickers N.A. type. The new or unusual constructional features of this instrument are as follows. The voltage and current magnetic circuits of the electromagnets form an almost entirely closed circuit, so that flux leakage is negligible. There are four permanent brake-magnets, thus ensuring that the probability of large changes of accuracy due to change in braking flux is reduced relatively to that of most commercial models of energy meter. There is partial correction for changes in accuracy due to temperature-changes. A device used for transmitting impulses to summators is fitted to all main-circuit meters and takes the form of a 3-segment commutator mounted on an auxiliary spindle driven from the main spindle of the meter. The reactive-component meter is identical in general construction with the energy meter. The windings of the potential coils are different, however, a series non-inductive resistance being used in conjunction with each element. The object of this is to cause the potential flux to lag 60° behind the applied voltage, instead of 90°, as in the case of the normal energy meter.

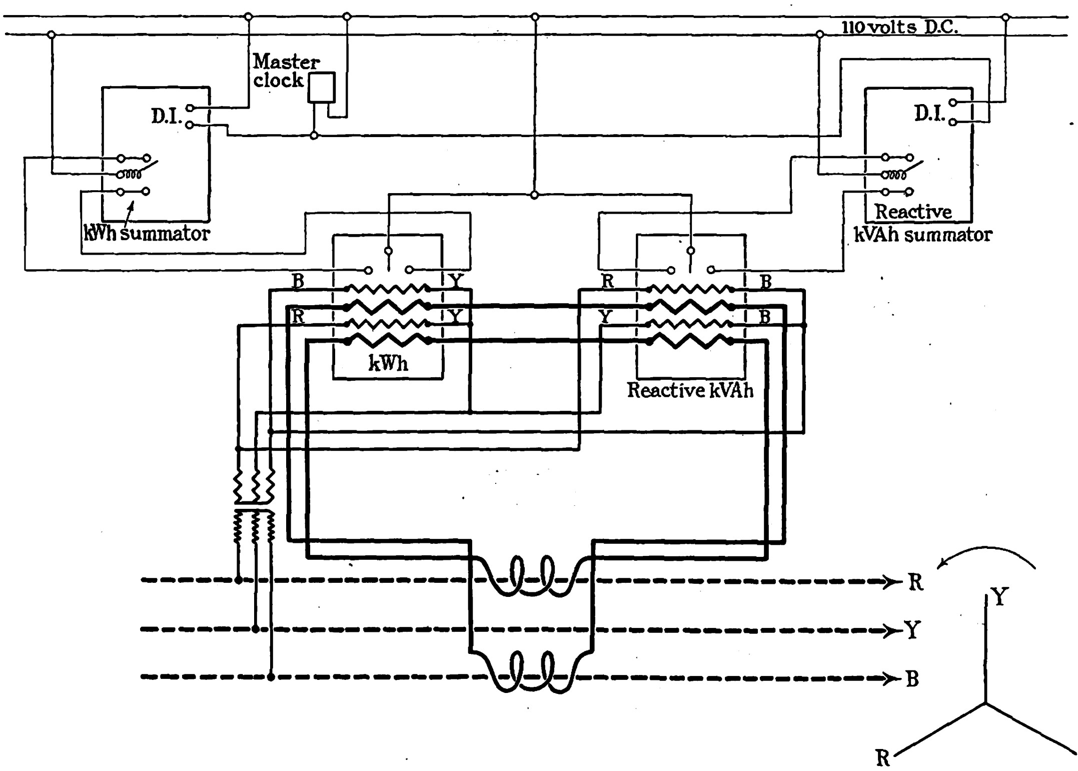

FIG. 3.—Diagram of connections of kWh and reactive kVAh meters on the Central Scotland Electricity Scheme.

Fig. 3 shows the general diagram of connections of the energy and reactive-component meters used in Central Scotland. It also shows diagrammatically the connections between these meters and their associated summators.

Vector diagrams showing the phase relationships between voltage, current, and flux for each element of an energy meter and of a reactive-component meter are shown in Fig. 4, together with the contributions of the separate elements to the total torque. The net result is that the total torque in the energy meter is proportional to cos ϕ, while in the reactive-component meter it is proportional to sin ϕ.

SUMMATORS.

Impulse summators are used in all cases in the Central Scotland scheme. The general principle on which these instruments operate is as follows. Each summating meter in a group of which the resultant is required is provided with a contact-making device, by means of which the circuit between a source of energy and a receiving circuit in the summator is closed. By this means current impulses are transmitted from the summating meter to the summator at definite energy intervals, as registered by the summating meter. The source of energy for supplying the impulses is a storage battery, and the contact-making device is the commutator previously mentioned in the description of the summating meters. The receiving element in the summator meter is a solenoid electromagnet, which actuates a ratchet and pawl for registering the number of impulses passing through the solenoid circuit. Each summator receiving element has a standard meter dial attached to it, but this is for convenience in checking the components and is not an essential feature from a theoretical standpoint.

Fig. 5 shows diagrammatically how the registrations of two elements of a summator are combined to give their resultant. The scheme employed is to couple the driving shafts of the two elements through a differential gear. This principle can be extended to any desired extent, but in practice it is found to become somewhat cumbersome if the number of elements exceeds 12. The chief objective aimed at in the summator meter is the maximum demand. This is obtained by fitting maximum indicators of the Merz type on the " resultant " section of the instrument. In view of the extreme importance of the maximum-demand measurements, accurate and definite readings are essential. Permanent records of the readings are likewise wanted for operating as well as for accountancy purposes.

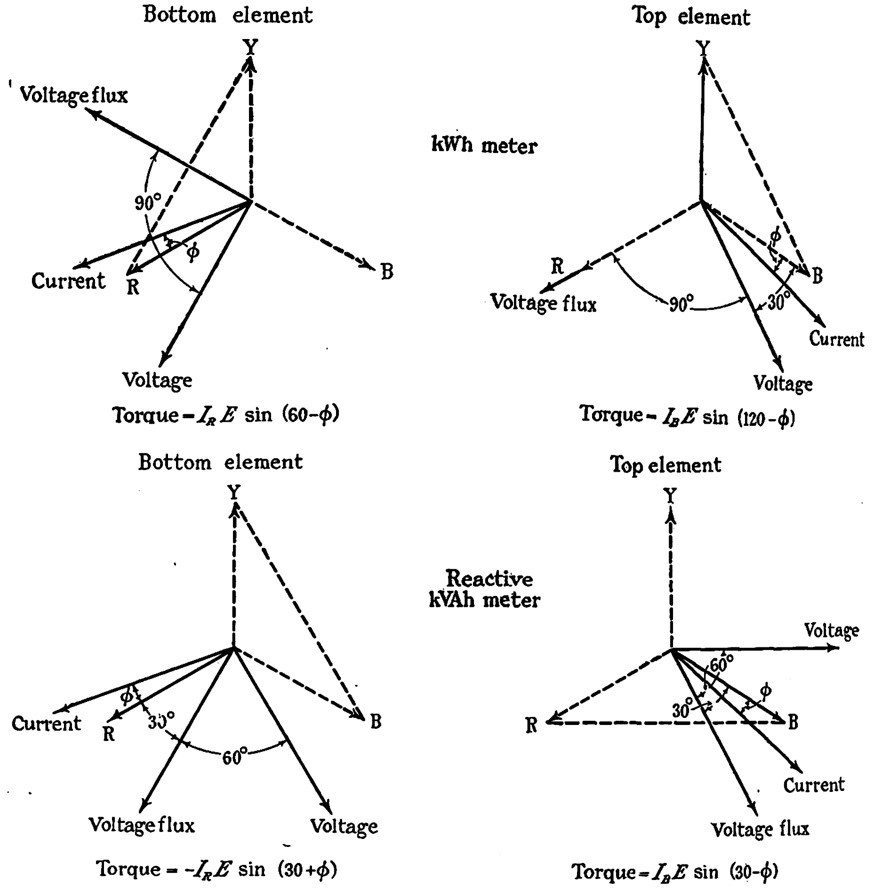
Bottom element
Y
Voltage flux
90°
ϕ
Current
R
B
Voltage
Torque = $I_R E \sin(60-\phi)$
kWh meter
Top element
Y
R
Voltage flux
90°
30°
ϕ
B
Current
Voltage
Torque = $I_B E \sin(120-\phi)$
Bottom element
Y
ϕ
Current
R
30°
60°
B
Voltage flux
Voltage
Torque = $-I_R E \sin(30+\phi)$
Reactive kVAh meter
Top element
Y
Voltage
60°
ϕ
30°
R
B
Current
Voltage flux
Torque = $I_B E \sin(30-\phi)$

FIG. 4.—Vector diagrams of energy and reactive-component meters on the Central Scotland Electricity Scheme.
Resistance is inserted in series with each voltage coil to allow the voltage flux to lag behind the current by only 60°.

The indicator part gives an exceptionally long scale, due to the use of the device shown in Fig. 6. This was invented by Mr. O. Howarth, of the Lancashire Electric Power Co., and was developed by the Metropolitan-Vickers Electrical Co. Gravity resetting is used to overcome the difficulties encountered when spiral springs are employed through very large angles. A record of each maximum demand is printed every half-hour. The printometer attachment prints four significant figures definitely and a fifth figure can be read accurately from a side scale.

SOUTH-EAST ENGLAND SCHEME.

The energy meters for the South-East England electricity scheme are of the Ferranti F.G.L. type and have also many interesting and novel features. There are two driving elements per disc and these are so placed that side-thrust on the bearings is eliminated, with the result that the spindle has no tendency to move from the centre of the jewel. About 80 per cent of the weight of the rotor is borne by permanent-magnet suspension, so as to relieve the bottom jewel of excessive mechanical stress. Eight permanent magnets are provided for each meter. The object of these features of design is to ensure that the life of the meter will be long even in comparison with that of normal induction kWh meters, which are already very satisfactory in this respect. The reactive-component meters for this scheme are identical with the energy meters. In this case the potential to the reactive-component meter is supplied through a quadrature transformer.

The general diagram of connections of the energy and reactive-component meters for one circuit is shown in Fig. 7, and a vector diagram illustrating the principle of the quadrature transformer is shown in Fig. 8.

It will be recognized that this scheme for measuring the reactive component, although involving the use of

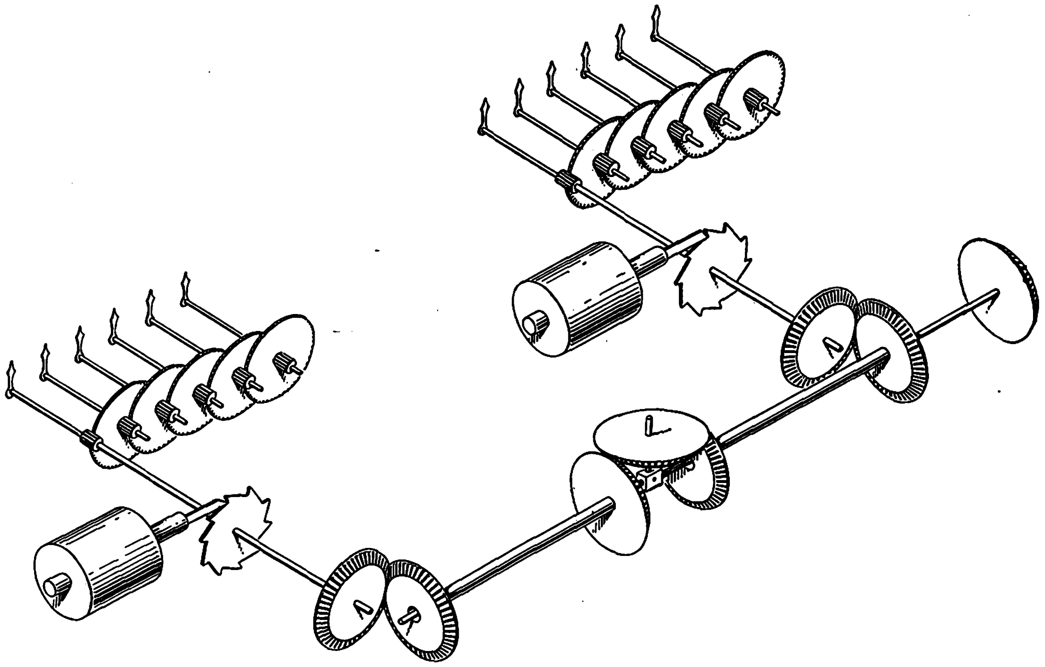

FIG. 5.—Mechanical addition of registrations (diagrammatic).

an additional piece of apparatus and increased volt-ampere consumption, has advantages in regard to standardization of material and calibration methods. The contactor attachment, which is used for summating purposes, is a cam-operated 2-way switch.

In the summators, mechanical addition by means of differential-gear couplings is used, and the scheme does not differ materially from that previously described. There are, however, numerous interesting differences of detail in connection with the types of impulsing electromagnet, and the arrangement and type of differential, for example.

The long scale of the maximum-demand indicator has been obtained by direct gearing-up, but the disadvantages of high driving torque and excessive backlash usually associated with this arrangement have been eliminated by fitting spiral-spring control to both gear elements. The energy required for driving the higher gear is then derived from resetting, which is done by hand.

The maximum-demand printer is a separate element. A motor-driven chart is used, and carbon type printing, similar to that employed in typewriters, has been adopted in preference to ink printing. General information regarding the performance of meters and current transformers is given in an Appendix.

APPENDIX.

GUARANTEED PERFORMANCES OF METERING EQUIPMENTS.

The guaranteed accuracies of the energy and reactive kVAh meters are indicated in Table 1, which shows the maximum errors under different loading conditions.

The conditions are made somewhat less difficult for meters on generator circuits, so as to allow lower-grade—and consequently cheaper—current transformers to be used. This is justifiable because of the fact that the generator circuits work on much higher average loads than the other circuits. The actual accuracy obtainable on the generator meters will therefore be at least as high as on the others. The current-transformer accuracies

TABLE 1.

Conditions of test		Limits of error, per cent (±)			
Range of load, per cent	Power factor	Board's circuits		Generator circuits	
		Energy meters	Reactive kVAh meters	Energy meters	Reactive kVAh meters
125 to 10	1·0	0·5	2·5	1·0	2·5
	0·5	1·0	2·5	2·0	2·5
10 to 5	1·0	2·0	2·5	2·0	3·0
	0·5	2·5	2·5	—	—

TABLE 2.

Load range, per cent	Ratio		Phase angle	
	Variation, per cent	Absolute error, per cent	Variation	Absolute error
125 to 10	± 0·3	± 1	min. 12·5	min. —
125 to 5	± 0·75	—	20	30

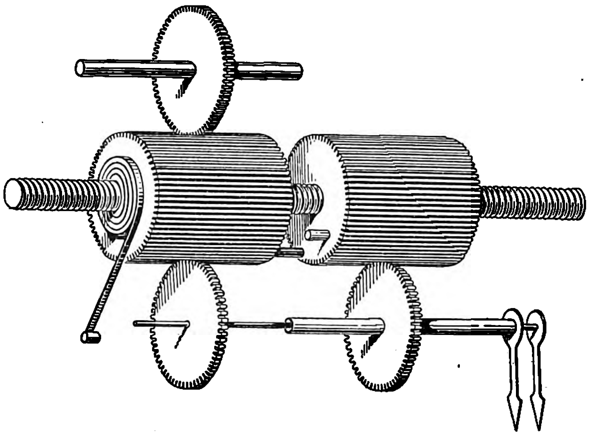

FIG. 6.—Method of obtaining long-scale indicator.

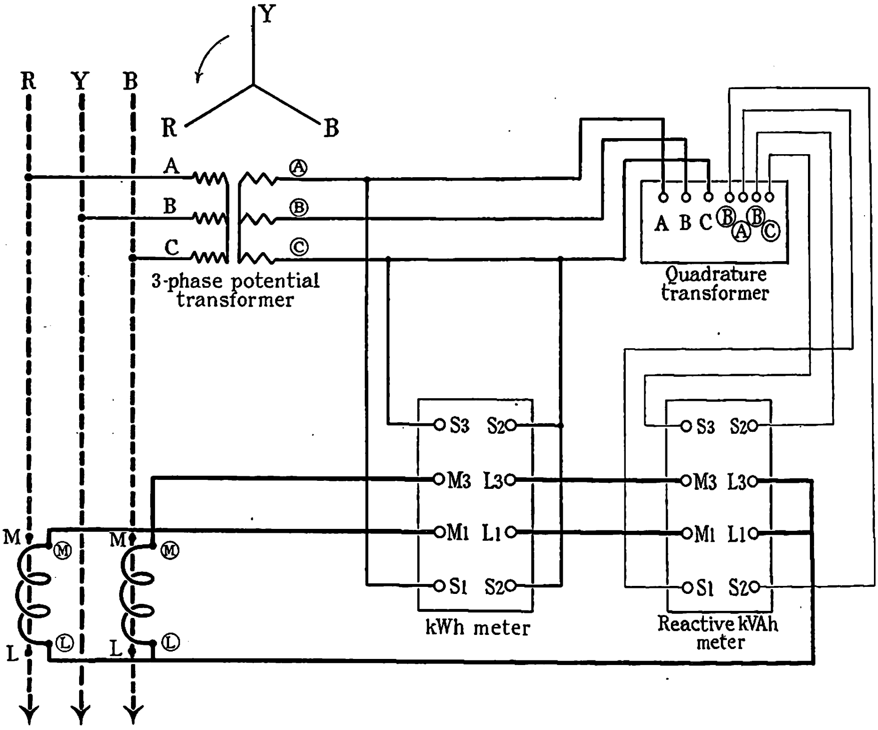
Y
R
B
R
Y
B
A
B
C
Ⓐ
Ⓑ
Ⓒ
3-phase potential transformer
A B C Ⓑ Ⓐ Ⓑ Ⓒ
Quadrature transformer
S3 S2
M3 L3
M1 L1
S1 S2
kWh meter
S3 S2
M3 L3
M1 L1
S1 S2
Reactive kVAh meter
M Ⓜ
L Ⓛ
M Ⓜ
L Ⓛ

FIG. 7.—Diagram of connections of kWh and reactive kVAh meters on the South-East England Electricity Scheme.

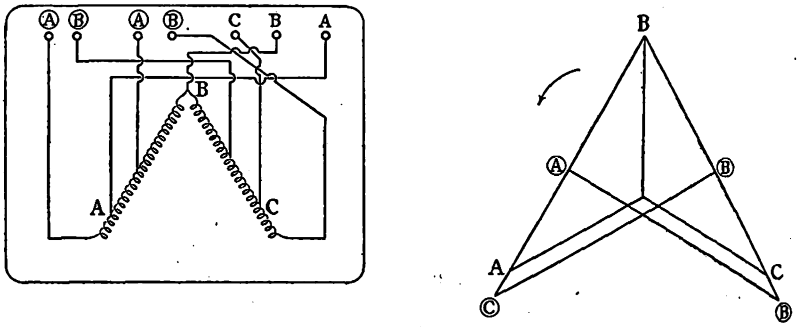

FIG. 8.—Diagram of connections of quadrature transformer.

also vary with the loading conditions of the circuits on which the transformers are used. Those in generator circuits are British Standard class A, while those in auxiliary circuits are class B, both classes being those given in B.S.S. No. 81 for instrument transformers.

The Board's circuits carry loads which vary between wide limits and which may have low power factors. For this reason it was imperative to give the meter manufacturers every assistance by providing highly accurate current transformers. The accuracies which transformer manufacturers have been able to guarantee are shown in Table 2.

The potential transformers are of grade B, to B.S.S. No. 81. The guaranteed maximum temperature-coefficient of the meters, both for kWh and reactive-kVAh measurements, is 0·1 per cent per degree C. The guaranteed maximum error in transmission between summating and summator meters is 0·1 per cent.

Discussion before the Meter and Instrument Section, 2nd May, 1930.

Mr. T. G. N. Haldane: I think that in many respects the equipment which has been adopted by the Central Electricity Board is likely to be a standard for the whole country in the future. The author's task has been a difficult one, because it is inevitable that the Board's metering equipment should be essentially complex. I should like to deal with a few points in connection with it for the sake of those who are not, perhaps, very familiar with the provisions of the 1926 Act and the reasons why the somewhat elaborate equipment is necessary. As the author has explained, the three essential quantities to be metered are, first, the total units and the maximum demand from the generators; secondly, the total units and the maximum demand imported from the "grid" through the Board's transformers; and thirdly, it is necessary for the purpose of the Act to arrive at the total units and the maximum demand supplied to the undertaker for his own purposes from the station. It is this third quantity which has led, I think, to the more serious complications in the metering equipment. When the matter was first being considered two methods were available for dealing with this point. First it was possible to put integrating meters on each feeder going out from the station and to sum these and thus obtain the total demand. The other method, and that which has actually been adopted after careful consideration, is to add together the readings of the generator summator and the "grid" import summator and to subtract from the sum the amount exported to the "grid" system, the total necessarily giving the balance which goes to the undertaker for his own purposes. This method was adopted because the first alternative would have involved a larger number of integrating meters and, furthermore, every time any feeder was altered in the station an alteration in the Board's equipment might have been required. Of the various new features in the equipment, I think that the use of impulse summation is possibly the most striking and in some ways the most novel. When the problem was first considered meetings were held with all the meter manufacturers. The various methods of summation were all considered very carefully, and the conclusion arrived at was that the impulse method was the only practical way of dealing with the rather complicated problem of the selected station, i.e. the station where there is generating plant. The impulse summation method was therefore adopted and developed; the panels and summators exhibited by the author are the result. Whereas this method of impulse summation is adopted in the complicated case of the selected station with generating plant, at non-selected stations where there is no generating plant other methods have been adopted. In certain cases current transformers in parallel or multi-element meters are used. Although these methods are simpler they cannot be applied to the complex case of the selected station. I should like to mention that the use of demand recording equipment was not, strictly speaking, essential for the Board's purposes, as by means of Merz type maximum-demand indicators it would have been possible to measure all the quantities necessary for accountancy purposes and required by the 1926 Act. It was felt, however, that the Board's metering equipment had more than one purpose to serve. Primarily it has to measure the quantities required for accountancy purposes, but it will doubtless supply also much information which will be of great value from the point of view of operation. The charts for recording the maximum demand in every half-hour of the day will provide information never before available about the whole supply to the country. For instance, they will allow the diversity of load between different areas in the country to be fairly easily determined with reasonable accuracy. After the points that I have mentioned, and various others, had been settled, a whole host of details remained to be dealt with. Some of these were concerned with the technical construction of the meters—these naturally interested in particular the meter manufacturers—whilst others dealt with the question of whether the proposed equipment would really give the quantities that were required. I think that all these problems have now been solved, and although they were of a very intricate character the outcome has been the production of a fine type of metering equipment. The manufacturers are, I think, to be congratulated on the results.

Mr. O. Howarth: A consideration of the "grid" metering from the supply undertaking's point of view leads one to realize the great importance of accuracy in the measurement of the quantities required. I am glad to see that temperature compensation has been provided, as in this way a little extra accuracy has been gained. The importance of accuracy in the demand-indicator measurement can best be realized, perhaps, by taking an actual case which may occur in the future. I have in mind a station where the generating plant may be dealing with a load of about 62 000 kW and the local load may be of the same order—66 000 kW for instance; thus 4 000 kW will be imported from the "grid." This amount will presumably be measured on the import meter shown in the diagram of metering equipment for selected station with local load, but the maximum import load for which this will have to be arranged is of the order of 60 000 kW, so that the 4 000 kW will be measured by an instrument reading up to 15 times the actual load which it is then measuring. Thus the kW purchased at "grid" price will be purchased at one-fifteenth of the full-scale reading. As the demand on the "grid" at the time when the undertaking's maximum demand occurs may not be the actual maximum demand imported, this reading may have to be taken (for charging purposes) from the chart. Assuming a price of £3 per kW, 4 000 kW represents £12 000 per annum and an error of 1 per cent in this represents £120 per annum, so that it is obviously quite worth while to spend a little extra money on metering in order to cut down this possible 1 per cent. Further, the reading for several months may depend on that of one particular month. The measurement of the reactive kVA is also connected with this question. Where the generating station is supplying a load almost, but not quite, equal to the undertaking's load, the balance of load may be imported from the "grid" or exported to the "grid" at a leading power factor without disturbance of the usual operating conditions on the system. A possible case is that in which this small extra load is being imported from the "grid" at a low leading power factor. Assuming that non-reverse stops are put on the reactive meters, the import summators will register this load as having unity power factor, whilst the undertaking's load and the station load will be measured at their correct power factors. Will the undertaker pay for the imported load at the "grid" rate, unity power factor? Considering the case where the generating station is producing rather more current than is required locally, the time of maximum load is the critical period and at maximum load a little may be exported at a leading power factor. The local and station loads will again be correctly registered, but the import reactive summator will also register. Will this registration be ignored in the charge? It seems to me that rather a large sum of money is being spent in order to measure the power factor, because I feel that operating conditions are such that the power factor at times of maximum load is apt to be an arbitrary quantity. In the case of selected stations, where conditions of loading are fairly steady, the variation from one month to another of conditions just at the time of maximum load will perhaps be so great that the Board and the undertaking may come to terms as to what is the power factor at the selected station and of the undertaking's load. We can hardly expect the Board to get these rather complex metering arrangements into satisfactory operation without encountering difficulties. I think that the British manufacturers who have gone out of their way to develop this metering equipment are to be congratulated; it would have been a great pity if, having established our grid, we had had to go abroad to buy suitable metering equipment. British meter manufacturers have not only developed the step-by-step summation gear, but in addition they have increased the accuracy of their ordinary designs of meters, which were already very accurate.

Lieut.-Col. K. Edgcumbe: I should like to hear rather more about the current transformers used with the Board's testing equipment. In general, I hardly think that engineers, when specifying current transformers, pay sufficient attention to the value of the secondary burden. In many cases a burden as high as 40 VA is called for, whereas the demand made by the integrating meters and their connecting leads would not, I imagine, exceed 10 or 15 VA. With "wound" current transformers this question is of minor importance, since such transformers can be designed for 1 000 or 1 500 ampere-turns, but with bar-type current transformers (which are now so popular for e.h.t. circuits) the ampere-turns are definitely limited to the full-load current of the line. This may amount to 200 amperes or even less, and to give reasonable accuracy at a burden of 40 VA with only 200 ampere-turns is quite impossible. For this reason, every item of the burden should be carefully scrutinized and the total, including that of the connecting leads, reduced to an absolute minimum. In some cases, in addition to the integrating meters, it may be desired to operate indicating meters, or even protective relays, from the same current transformers. In that event it will prove far more economical and satisfactory to employ two, or even three, separate cores, mounted upon a single bushing, each core being designed for the particular burden and degree of accuracy demanded by the gear which it is to operate. The cost of an e.h.t. current transformer depends so largely upon that of the insulator that the provision of two or more cores adds but little to the cost. Another matter which I should like to emphasize is the importance of reducing the external diameter of the bushing to the lowest possible figure, consistent of course with adequate electrical properties. The accuracy of a current transformer is very adversely affected by any increase in the length of the magnetic path. The author mentioned the necessity for a clock to operate the maximum-demand indicators of the meters. Although he did not describe it, I believe that he uses an impulse master clock. Has it occurred to him to use this same master clock for controlling the frequency? There is no doubt, I think, that in a short time every power station will have to use a standard clock for frequency control. It is now becoming impossible to leave frequency to look after itself; it has to be kept accurately constant, more especially when stations are interconnected. If a master clock is already available for the maximum-demand indicators, it can either be used to drive the frequency-controlling meter, as is now being done by the London Power Co., or, if once the frequency has been controlled, that frequency can be used for driving synchronous motors in each of the maximum-demand indicators, thus ensuring that they are all in step and all accurate as to timing. This is already being done in several stations.

Mr. G. A. Cheetham: In order to appreciate the problems of inertia, mass, etc., with which we have been dealing, it must be realized that each of the impulse elements probably makes about 2½ million impulses per year. As a previous speaker has said, the results prove that if problems are given to British engineers they can satisfactorily solve them without going abroad.

Mr. Wilfred Holmes: Regarding the current transformers which are being used for the grid, I should like to say that I am quite satisfied that their capacity and accuracy have been thoroughly investigated. The meter engineers were asked to get a certain accuracy and in order to obtain it they had to demand a certain accuracy in the current transformers. Thus the precision transformer as required for the grid was produced. I should like to know the author's opinion regarding the testing of meters operated from transformers. I find that first to test the transformers, then the meter, and finally to combine the two curves is a method which gives the best results. There is great difficulty in obtaining a large-current standard wattmeter reasonably accurate and robust enough for commercial use, while a 5-ampere standard wattmeter is very satisfactory. There are now many methods of measuring accurately the ratio and phase-angle error of the current transformers, and accurate methods of testing such transformers have been described in the *Journal.*

Mr. C. G. Mayo: I agree with Colonel Edgcumbe that with bar-primary current transformers for small primary currents it is extremely important to keep the burden to a minimum; in fact, below certain values of primary current the costs and dimensions become quite excessive if the burden is of the order of 40 VA, and I think that, generally speaking, this magnitude of burden is not realized. Another point raised by Colonel Edgcumbe is that all the burden does not require the same accuracy, and a very great economy could be obtained, as he suggests, by splitting up the burden and supplying it from two separate cores. With regard to the quadrature transformer on the South-Eastern metering, it is not clear whether this is what is usually called a quadrature transformer, i.e. a reactance with two windings, or a transformer supplied from different phases in such a way that the phase displacement required is obtained between the phases without shunt impedance. If the quadrature transformer takes the form of a reactance with two windings it will be slightly more complicated, but will not differ materially from the other arrangement. If the quadrature transformer obtains its phase displacement without the use of shunt reactance, will it in all cases give precisely correct results, i.e. will the voltage obtained depend only on the voltage upon which it *should* depend?

Mr. S. B. Jackson: Colonel Edgcumbe has raised an important point regarding the frequency control of the system, and I think that everyone recognizes the absolute necessity for controlling frequency within such limits as he suggests, by means of the Warren type of apparatus. It is well known that the obligations which the Act imposes are such that it is impossible to escape from considerations of frequency, but I should like to ask the author what would be the effect of different frequency upon a current transformer and its meter indications. What percentage error would exist at 49 and 51 cycles respectively? Closely associated with this is Colonel Edgcumbe's suggestion that the drive of these instruments should be controlled by synchronous motors. I recognize the great accuracy of the Warren type of control, but it nevertheless has an error due to system frequency variation, and in view of the use of the synchronous clock in driving these instruments and the fact that such equipment permits of a much finer reading than the Warren type of apparatus I suggest that we should not complicate matters any further by introducing frequency drive through a motor from the main system. I should like to refer next to the position of the manufacturer. The case with which the manufacturers were presented had for long been felt to be desirable in the industry, and I am sure that the Act was regarded as a welcome opportunity for the industry generally, because up to the present time there has been no proper method of controlling the meter readings. The necessity for accurate meter readings or for accuracy in general was, I think, admirably expressed when Kelvin remarked "If you want to know anything you must know how to measure." Information of great value, such as system diversity, is obtainable by the use of such instruments. If the electrical industry wants to know anything at all, it must not rely upon the inaccuracies of the human element but it must seriously apply itself to the problems presented to it. It is surprising that the manufacturers waited for the Act before taking advantage of the opportunity which presented itself.

Mr. C. W. Marshall (*in reply*): The discussion has revealed the points of view of practically all classes of engineers who are interested in the operation of the 1926 Electricity Act, these classes being consultants, electricity supply authorities, manufacturers of instrument transformers and meters, and operating engineers.

Mr. Haldane outlines the reasons for adopting the general metering system which is being used. His contribution is complete and calls for little comment. It is authoritative, as he has been in touch with both manufacturers and users of meters since the commencement of the "grid" system. It should be noted, however, that there are additional objections to feeder metering besides those mentioned by him. The loads on feeders are extremely variable and it is difficult to measure them accurately during the light-load periods. Interconnectors introduce further difficulties due to varying power factor, and, finally, extensions to systems are more difficult to take into account than with the arrangement adopted. He has perhaps overstressed the novelty of impulse summation. Twenty years ago, at least, the oscillating meter of the A.E.G. included some of the most important elements of the summation system and was a beautifully developed instrument.. With regard to the use of parallel current transformers and multi-element meters for simple cases of summation metering, these systems will be used when applicable and advisable, and it should be noted that the possibility of simple mechanical summation is not excluded.

Mr. Howarth illustrates the extreme importance of obtaining high accuracy because of the large amounts of money directly involved. It was precisely this circumstance which led to the exacting meter specifications which have been used. The reactive kVA metering equipment in selected stations has been installed primarily to obtain the power factors of the undertaking's loads and of the load on the associated generating stations. I agree that when these loads are approximately equal, accurate metering becomes very difficult. In practice it is impossible to obtain high accuracy at much below 10 per cent of full load, even with energy meters. With reactive-component measurements the difficulties are accentuated. No better method of making the necessary measurements than has been adopted was known to the Board's engineers or their consultants, nor has any better method been suggested in the various conferences which have taken place with engineers of authorized undertakings or meter manufacturers. I also contend that the equipment cannot be simplified if the requirements of the 1926 Act are to be fulfilled. There are, however, circumstances in which it is advisable to come to special agreements on power-factor charges, and a number of such agreements have already been made.

Col. Edgcumbe considers the subject of current-transformer loading in great detail. He can be assured that care has been taken to ensure that the specified loadings for the current transformers required by the Board are not arbitrarily fixed. The actual loadings in a particular case examined to test this point were:—

3 Integrating meters	9 VA
2 Indicating meters	3 VA
1 Telemetering equipment and connecting leads	7·8 VA
Total	19·8 VA

The transformers specified are the nearest British Standard to those required by the loading conditions. The suggestion that multi-core current transformers should be used is a good one, but it introduces the disadvantage of additional pilot-cable cores. System-frequency control clocks appear likely to come into general use and it would be readily possible to adapt them so as to work maximum-demand indicator resetting devices and printometers or recorders. It was considered, however, that the metering equipment was of sufficient importance to justify the use of separate clocks.

Mr. Cheetham draws attention to the mechanical problems involved in the production of the summation equipments. I recognize the fact that this lecture by no means does justice to the detailed design of the instruments involved, and hope that one or more of the designers responsible for these will devote a paper to the subject.

Mr. Holmes introduces the very controversial subject of calibration methods. I, personally, favour his own method whereby meters and current transformers are calibrated separately. The last occasion on which this subject was exhaustively reviewed before the Institution was in 1911, when Messrs. Ratcliff and Moore read their paper * on " Electricity Meters, with Notes on Meter Testing." At that time they showed conclusively that collective calibration of meters and their associated transformers was advisable. The situation has in the interim materially altered. Current transformers have become instruments of extreme precision and their characteristics can be measured accurately and conveniently. The performance of energy meters has also been improved. The convenience of low-current standard wattmeters and of modern current-transformer testing instruments, in conjunction with the above-mentioned improvements in meters and transformers, seems to me to provide sufficient justification for giving separate calibration a definite legal status. Further, the impracticability of testing the complete equipment of meter, current and potential transformers is in itself a justification at least for re-examining the situation.

Mr. Mayo endorses Col. Edgcumbe's opinion regarding the importance of loading in deciding the dimensions and cost of bar-primary current transformers. He also asks for information regarding the construction of the quadrature transformer employed in conjunction with energy meters used for reactive-component measurements. This device is illustrated in Fig. 8.

The information for which Mr. Jackson asks, regarding the effect of frequency variations on meter performance, is dealt with in the Appendix. He is not quite fair to the manufacturers of meters when he expresses surprise that they waited for the 1926 Act before applying themselves to the problems of large-power metering. The Fawssett precision energy meter has long been recognized as an instrument of extreme accuracy and constancy of calibration, and the long-scale maximum-demand indicator had been at least partially developed by the Metropolitan-Vickers Co. before the 1926 Act came into being. Summation equipments have been made by several manufacturers, notably the Aron Co. and Messrs. Landis and Gyr, for many years.

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* *Journal I.E.E.*, 1911, vol. 47, p. 3.

A FEW NOTES ON THE DESIGN, CONSTRUCTION AND MAINTENANCE OF RAILWAY ELECTRICAL SIGNALLING APPARATUS.*

By H. C. TOWERS, Associate Member.

(*Paper received* 17*th October*, 1929.)

SUMMARY.

Although several books and many papers have been written on the subject of railway electrical signalling, it is thought that the following notes may be of interest, as they are intended to bring up points not usually mentioned.

With regard to the remarks on track circuits, the author has recently heard of a new type of impedance bond track circuit employing condensers at each end of the track. It would be interesting to obtain a description and criticism of this type of track circuit.

It is not intended in this paper to deal at all fully with any one of the three branches mentioned in its title, since to do so would necessitate something of the nature of a complete treatise. The object is to deal critically with the main features of each branch and to compare one method with another.

It is assumed that those who will peruse this paper are well versed in the science of railway signal engineering, and are familiar with the usual methods of employing electrical power to further its application. This being understood it will be known that the railway signal engineer has to deal with both the mechanical and electrical side and with other subjects as well. As it is intended to deal with the electrical side only, the main examples chosen will be applicable to main-line suburban systems, rapid-transit lines and the electrical interlocking of large and important yards.

During the last few years traffic on our suburban systems, both at home and abroad, has grown to an enormous extent, and with it has come the necessity for the signalling department to assist in coping with the problems that have arisen. Mechanical installations are perfectly sound and efficient where traffic is light, but where it is heavy it is necessary to employ electricity to assist the signal engineer in his problems. The method of employment will vary with the conditions and will be discussed later.

In all railway signalling departments the one ideal to aim for is standardization of equipment. From a broad point of view equipment may be taken as representing not only individual parts of apparatus, but the principles of the administration as a whole.

In the author's opinion the signalling drawing office should be in the charge of a man who has had practical and theoretical experience in railway signal engineering and who can appreciate the difficulties of the work on the track whilst he is deciding problems in the drawing office. If he has had this practical experience he will aim at standardization of parts and their improvement so that the efficiency of the system as a whole will improve. The designs should be carefully thought out, not only with regard to their efficiency electrically or mechanically but also taking into consideration their accessibility from a practical point of view and the ease with which they may be installed.

It is of great assistance if all such parts, when designed and manufactured, are stamped with a type number or with their respective drawing number. It is then possible to refer to them with precision either in correspondence or when ordering materials.

Another product of the signal engineer's drawing office is the wiring diagram. A wiring diagram for any phase of railway signalling is totally different from the usual type of diagram which is used for general purposes. It therefore deserves special consideration. The designer of circuits for an installation should not only know the general principles of interlocking and that a return is necessary for a feed, but he should be fully alive to the fact that his diagram will be the guide for the signal wireman or installer and that usually this man will, if possible, put his wires where the diagram tells him to. The draughtsman should realize the limitations of one relay or terminal, as far as the accommodation of wires is concerned, and also that only a certain number of wires will go through one hole. If it so happens that the diagram is impossible to follow practically the wiring outside will be altered to suit the conditions and the diagram will no longer be a true record. This is the worst possible thing that can happen, since in complicated electrical interlockings it is absolutely necessary to follow the wiring diagram. If a lineman is out on a signal failure and he finds that his diagram shows three wires on a terminal whereas there are actually only two, he is apt to become confused, particularly if that section is strange to him. During this time trains are being delayed. It is therefore absolutely essential that the wiring on the apparatus should agree with that shown on the diagram.

This points to the fact that the signal draughtsman should be a man with considerable experience in electrical and mechanical railway signalling and with a technical education.

Signal engineers should give their staff the opportunity of being trained in every branch of the work, and it is a great advantage if a signal school is formed. Lectures followed by practical demonstrations will further the usefulness of the artisan staff, and will also enable the administration to learn the progress of apprentices. From the results of a term's work and examination it will be possible to select candidates for vacancies in the department as they occur.

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* Thesis accepted in lieu of the Graduateship Examination.

Railway signal engineers adopt various methods of making their wiring diagrams for railways, and although in the main their principles agree they are often different in details. A general discussion might enable a decision to be reached as to the best type of diagram to employ.

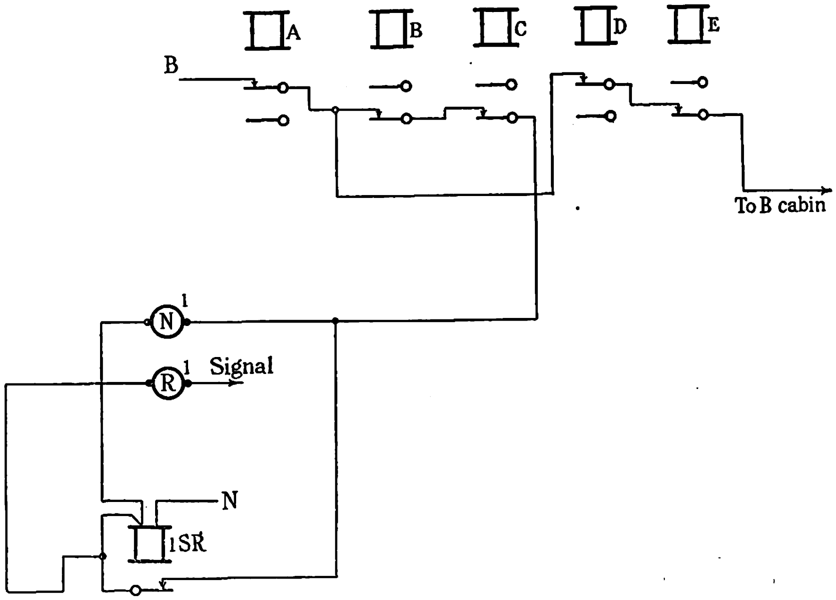


FIG. 1.

Fig. 1 shows a type of diagram which is now obsolete on many railways. The author believes, however, that there are still many that continue to use it. It is only a portion of a complete wiring diagram for track circuit interlocking, set out for discussion. It will be observed that the several branch circuits are shown tapped off other wires in the centre. It can only be assumed in this case that somewhere between two points a wire is joined on, soldered and probably taped. This is, of course, ridiculous. The linesman into whose hands this type of diagram falls has to go first to one end of the line and then to the other to find out which terminal holds the wire belonging to the branch circuit. This type of diagram may save the draughtsman drawing a few additional lines, but it certainly will not enable the original circuit to be traced. A branch circuit should be shown tapped from its correct place. This method, which in the author's opinion is the only one permissible, is shown in Fig. 2.

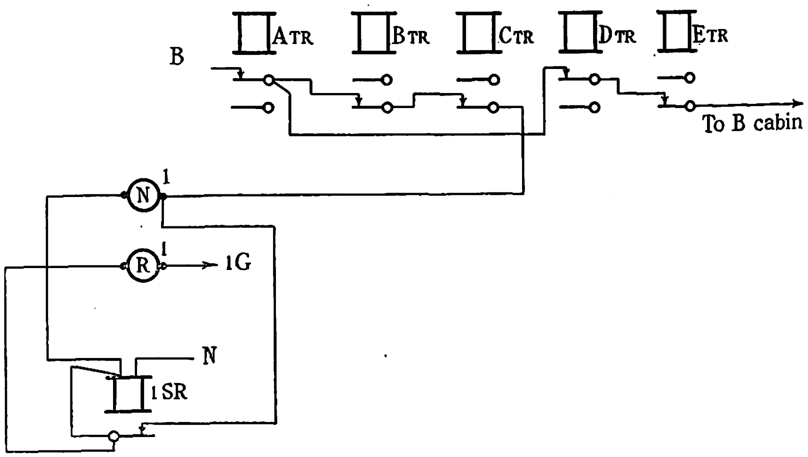


FIG. 2.

In connection with wiring diagrams it is necessary to mention the use of symbols. Symbols are used by power railway signal engineers to label the wires, relays, fuses, etc., on their diagrams. They standardize at once the general terms used and obviate the necessity of lengthy explanation. On most railways to-day which employ power signalling, symbols are used which originate from a signalling association. It is not intended in this paper to discuss their merits. It is only intended to point out that symbols of any form are an advantage and are extremely useful for reference. A standard system is certainly a step in the right direction, since it ensures that any man going from one line to another, as is frequently the case, will not be confused. When one considers that in a large power installation there are perhaps 500 fuses in the basement of the signal cabin, it must be obvious that some system of labelling is necessary. The available space is usually small and will not permit of lengthy explanation, which in some circuits would be necessary were it not for the symbols which are engraved on a suitable label and fixed beneath the fuse base or terminal. To those who may not be familiar with this method the Table on this page will show what is actually meant by a symbol. In addition to the numerical or alphabetical symbols graphical symbols should also be employed so that on wiring diagrams a particular kind of relay, lock or other apparatus may be readily recognized. Many types of relays and locks are used on an electrical interlocking and it is necessary to differentiate between them. In the earlier days it used to be the practice to draw contacts on wiring diagrams, with the object of representing the purpose of such contacts. It is still necessary to do so to-day, but owing to the many varied positions in which one unit may open one circuit and close another such a system would be very difficult to follow and would also be extremely

TABLE.

Letter symbols for wiring diagrams, fuses, relays, etc.

FIRST LETTER.		SECOND LETTER.	
A.		A.	Armature of relay
B.		B.	Back of bottom contact
C.	Control	C.	Point valve
D.	Distant	D.	Distant
F.		F.	Front or top contact
G.	Signal	G.	Signal-operating mechanism
H.	Home	H.	Home
J.		J.	Ground lock
K.	Indicating (visually)	K.	Indicator (visual)
L.	Locking	L.	Lock preventing initial movement of lever from normal or reverse
M.		M.	Lock preventing final or indicating movement of lever
N.	Normal	N.	
P.	Repeating	P.	Repeater
Q.		Q.	Local coil (2-element vane relay)
R.	Reverse-red	R.	Relay
S.		S.	Stick relay
T.	Track circuit	T.	
U.	Route indicator		
V.	Train stop	V.	Train stop
W.	Switch	W.	Switch-operating mechanism
X.	Bell	X.	Bell
Y.	Slotting	Y.	Slot
Z.	Treadle	Z.	Treadle
BX.	; AC. "positive energy"		Used for differentiating polarity of circuits
NX.	; AC. "negative energy"		
Shown (N.)			
B.	Battery feed		
N.	Battery return		

EXAMPLES.

9 G.	9 Signal	9 NW.	Normal control of No. 9 points
4 HR.	4 Home signal relay	9 RW.	Reverse control of No. 9 points
10 V.	10 Train stop	10 T.	10 Track circuit
(N) 10V.	Return of 10 train stop	10 TR.	Track relay

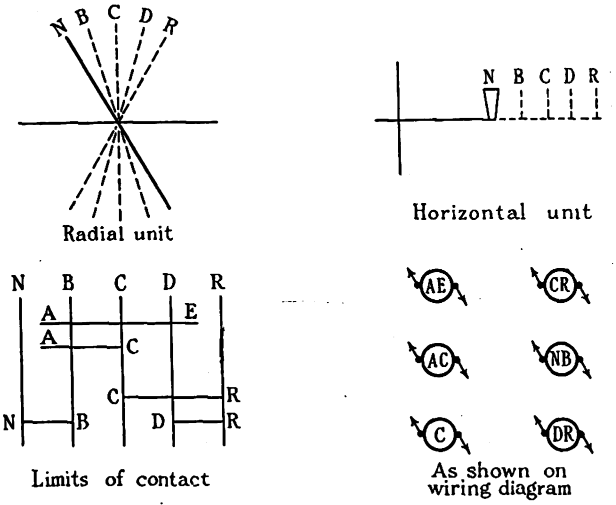


FIG. 3.—Some types of lever contacts and methods of showing them on wiring diagrams.

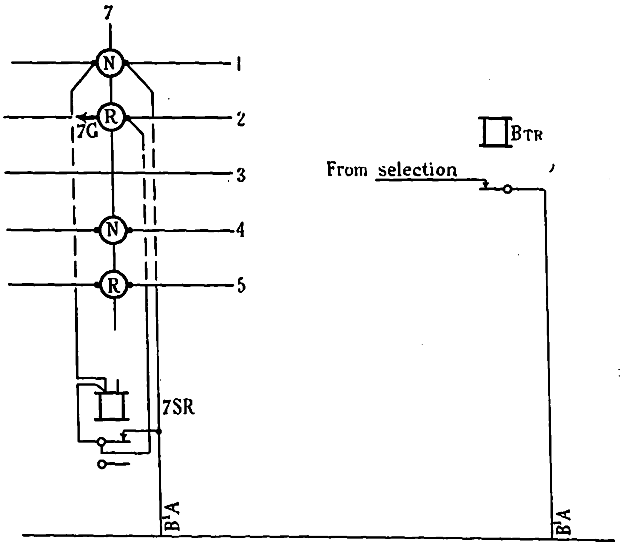


FIG. 4.

complicated. Fig. 3 shows what the author considers to be the best system to employ, and was arrived at by an association of railway signal engineers. The sphere of operation of a lever unit, whether it is a power frame, mechanical frame, or any other lever frame, is indicated by two vertical lines marked N and R, meaning the normal and reverse positions of that unit. Terminations of intermediate positions, that is where contacts are broken, are shown by intermediate positions B, C and D. C is obviously the central position of the unit. This applies to levers that operate radially or horizontally. The first half of this diagram explains where the various contacts make and break, and the second portion indicates how they are shown on wiring diagrams. An example of how and why these various contact positions are necessary may assist the reader to recognize the utility of this method of showing them. The normal and reverse contacts are necessary for point controls, tor selective purposes and for signal levers, the normal to pick up the stick relay and the reverse to close the signal control circuit. The C position may indicate a long contact made in the central position of lever operation to energize a special lock. The AB position would be used for signal indication circuits to close the lock circuit while the lever is being replaced to normal, and to break it when the lever is in the normal position and the lock no longer required.

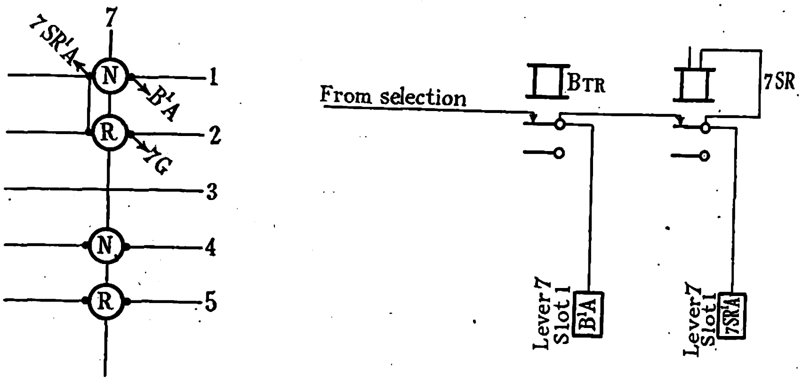


FIG. 5

Returning to the question of wiring diagrams and to the method that may be employed in drawing a wiring diagram for power frame interlocking, the various methods of doing this may now be discussed. Fig. 4 shows one method. In this case the contacts on the power-frame levers are drawn out in plan as they would be seen in the actual frame, the levers being drawn vertically and the rows of contacts horizontally. The track and line relays are drawn on the right of the diagram, and the main run of wires between power frame and relay cabinet is shown by one line. All wires from the relay contacts are drawn down to this run, and wires going up into the frame are shown going to the contacts in the same way. The terminal connected to the pivoted side of the relay contact is termed the armature and is known as A, while the terminal connected to the fixed contact side is known as the point and is termed P. Such connections are therefore known by the letter of the relay, the contact number, and whether the connection is an armature or point one. For instance, the end of the wire coming from contact B'A is lettered in this manner and a similar line similarly lettered, will be found going up into the power frame. This is the continuation of that wire going to the power-frame contact. A reference to Fig. 4 may make this clear.

This system is quite satisfactory for a small power frame containing some 30 to 50 levers, but even then it becomes very complicated with present-day methods employing check locking, track locking, route locking and proving. The diagram becomes a mass of lines and is difficult to follow quickly.

Fig. 5 shows another method of making the same kind of diagram and is used on at least one railway. In this case the lines are not fully drawn. A flag is drawn on the relay contacts bearing the number of the lever and the number of the slot in the frame where the contact may be found. It is then only necessary to follow the vertical line down that lever until the slot number mentioned is found. The arrow heads on the contact are similarly labelled and the whole circuit may be followed quickly. In this manner a geographical wiring diagram of a much larger frame may be drawn and is, in the author's opinion, a great improvement on the method shown in Fig. 4.

Although a geographical wiring diagram of a power installation is of great advantage from the point of view of locating an individual contact on a lever, it is also necessary to be able to trace through a complete signal selection with much more rapidity. This means that it is also necessary to have a circuit diagram; this will take the form of that shown in Fig. 6. In this case relay and frame contacts are numbered in order that they may be located, but at the same time the whole of the controls of an individual signal may be followed quickly. In America this type of diagram has been superseded by what is known as the written circuit. This is shown in Fig. 7. In this case all the contacts are drawn in one line, the difference between point and armature of a relay being indicated by a tiny arrow head or a small circle. The main advantage of this type of diagram is that it can be drawn quickly. In addition, a man who is used to power signalling work will have no difficulty in following it. A man who has had no previous experience, however, will probably find that the method shown in Fig. 6 is easier to understand.

One of the biggest problems which a railway signal engineer encounters is that of signalling an entirely new yard or railway. The location of signals themselves is not difficult, as it merely depends on known principles and traffic conditions that will have to be dealt with. These conditions may be such that he will be compelled to consider power working of some description, and in this case it may be difficult to determine exactly what system to adopt. Some points may already be determined for him. If electric traction is going to be employed it will be necessary to discover whether an insulated or an earth return is to be used. These considerations, together with the fact that signalling apparatus to-day is generally manufactured in types for which there is most demand, will lead him to some definite decision.

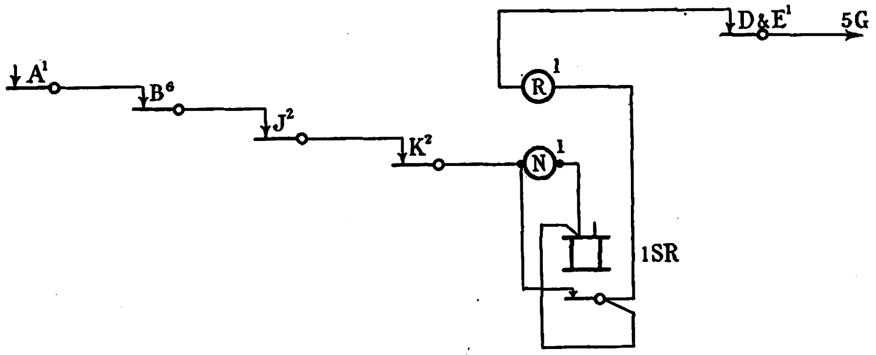


Fig. 6.

The best type of track circuit to employ will obviously depend entirely on the prevailing conditions. For track-circuiting a large lay-out where only steam traffic is in operation the ordinary battery track circuit is undoubtedly the best, since it is simple to operate and cheap to install. If d.c. traction with an insulated return is in use d.c. single-rail track circuits may be employed, providing the relays are of a polarized type. This is necessary, since faults are apt to develop on trains, and currents flowing back to the substation will traverse the track relay track coils in order to find a parallel circuit. Two relays must be used to each track, one at each end, so that, according to the direction of the earth current, one relay will be energized in the up position and the other in the down position. Large return currents, however, are apt to burn out the relays.

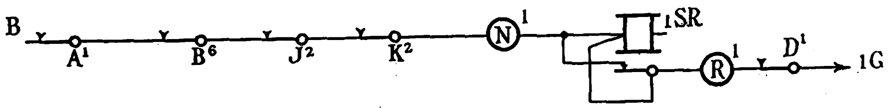


Fig. 7.

In this case it would be better to consider the single-rail a.c. track circuit. The tracks are "opposed" in this case so that in the event of the block joint insulation breaking down (for mechanical reasons) the adjoining track relay will be energized with reversed polarity. Two-element vane relays or galvanometer track relays may be employed. This type of track circuit is quite efficient and is to be recommended in the case of an electrified system with an insulated return. In some cases, however, failures will occur owing to train faults, the return leakage current sometimes saturating the iron core of the track-feed transformer.

Where an earth return is in use for traction purposes, impedance-bond track circuits are the only kind that may be adopted. They are not so efficient as the single-rail a.c. track circuit but their efficiency can be improved by adopting a resonated bond or a condenser feed.

The track circuit problem having been decided, the question of signal and point operation must be dealt with. In the author's opinion the best signal to adopt for outdoor purposes is the daylight colour-light signal. It is more efficient than the semaphore for sighting purposes where backgrounds are unsatisfactory. It also has no moving parts to get out of order. It is necessary in this case to use alternating current throughout, since the particular design of lamp used in this signal calls for low voltage and as this will be required at every signal location it is obvious that a transformer is the only solution. Two or three small transformers are placed in each signal, according to whether it is of the 2-position or 3-position type. If daylight signals are used all signals may be operated by alternating current from local track-feed transformers. The line relays, however, may be operated from batteries housed in or near the signal cabin. Point mechanisms of the battery machine type may also be employed and operated from the same source.

There is something to be said in favour of operating point machines by battery power. The battery may be kept floating and in the event of the power supply failing its capacity will keep the installation running, at least for several hours. During a total breakdown the chief cause of trouble in a busy yard is the operation of points. If all points and signals fail owing to a breakdown of supply these points have to be operated by winding a crank provided with the machine. If the signal line relays are operated by battery power they will be useless, since the signal lights themselves will be extinguished.

It would, however, still necessitate the attendance of the signal lineman in the signal cabin to release the electrical locks on the point levers.

The author is of the opinion that, under normal conditions, the ideal system for a yard is colour-light signals controlled by a.c. line relays and battery machine point operation.

In the case of an extension of a railway where the new terminal point may be some miles from the last sub-station, the question of battery machines may be looked at in a different light. If no direct current is available for charging purposes it will be necessary to run a d.c. main, and as this will be required at intermediate points for various roadside interlockings the capital cost may be appreciable. It may be argued that d.c. traction current will be available for traction purposes. The voltage will, however, have to be reduced, and this calls for motor-convertors or charging sets and therefore further expenditure. It may be necessary in this case to adopt a point machine with an a.c. motor working with a point controller at the site, since otherwise the power-frame contacts would have to break an appreciable current. Even if this is done there will be an appreciable drop on the main while the point is being operated, and this will have to be considered carefully beforehand. In this case the signal engineer, once he has decided to adopt electric power for his apparatus, should not hesitate to utilize all the known methods of counteracting loss. The voltage-drop on the main may be counteracted at chosen points by the use of condensers so that a leading current is taken to oppose the wattless component. It is also possible, where direct current is required for station lighting, to superimpose this on the a.c. main, employing chokes at distribution points. This system is adopted on one railway.

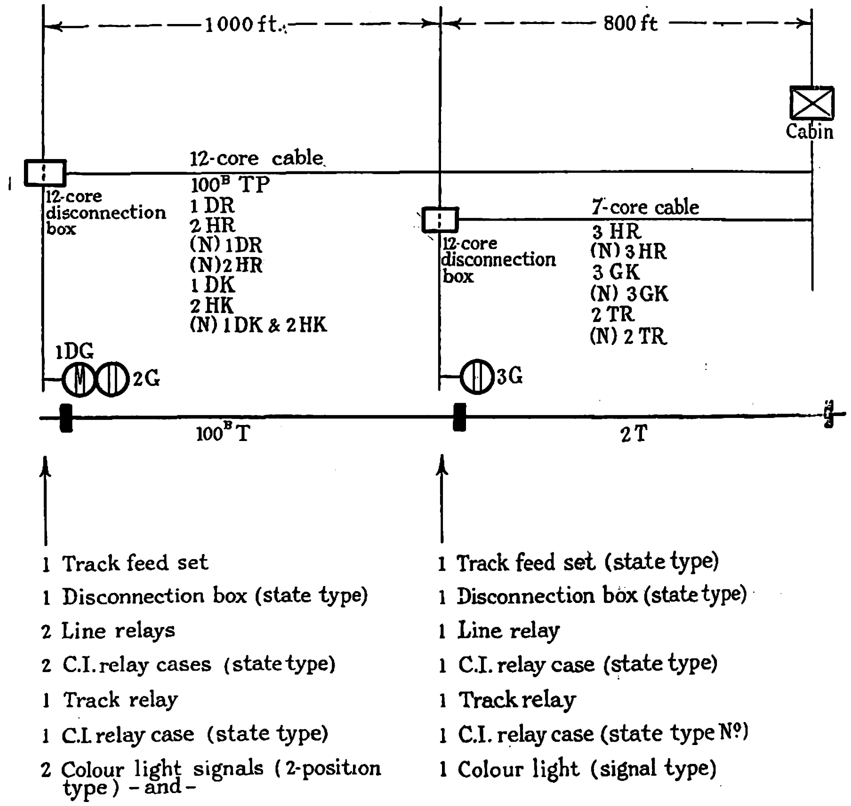

1000 ft.
800 ft
Cabin
12-core cable
12-core disconnection box
100^B TP
1 DR
2 HR
(N) 1 DR
(N) 2 HR
1 DK
2 HK
(N) 1 DK & 2 HK
12-core disconnection box
7-core cable
3 HR
(N) 3 HR
3 GK
(N) 3GK
2 TR
(N) 2 TR
1DG
2G
3G
100^B T
2 T
1 Track feed set
1 Disconnection box (state type)
2 Line relays
2 C.I. relay cases (state type)
1 Track relay
1 C.I. relay case (state type)
2 Colour light signals (2-position type) - and -
1 Track feed set (state type)
1 Disconnection box (state type)
1 Line relay
1 C.I. relay case (state type)
1 Track relay
1 C.I. relay case (state type No.)
1 Colour light (signal type)

Fig. 8.

The type of system having been chosen, it will now be necessary for the man in charge of the drawing office to order his materials. One large factor in the choice of material is cable. There are three main types that may be employed. The first is armoured cable, buried in the ground, or supported above ground, the second lead-covered cable run in brackets on posts, and the third a pole line of either insulated or uninsulated wire. Dealing with the third first, this may be quite suitable for battery circuits where there are few lines, but for complicated interlockings it is out of the question.

The choice is thus narrowed down to lead-covered or armoured cable. The author considers that a lead-covered cable run neatly in specially designed brackets on posts or along walls is the ideal type to employ on a railway where there are no trespassers. Where there are many trespassers, as on some railways abroad, it is better to use an armoured cable and bury it in the ground, or support it in such a position as to be out of harm's way.

The method of running lead-covered cable is fairly straightforward. The ends of the cable are run direct into the holes in the various apparatus cases. In the case of armoured cables, many circuits in bulk will be carried by certain cables, specially near the signal cabin, and in order to tap the various circuits a disconnection box must be used. This should be designed to suit the various sizes of cables employed, and a double row of links or terminals should be placed inside and labelled accordingly, the location circuits being tapped out in the middle.

A cable chart is a necessity and should be employed by all railways on which there is power construction work. This will not only assist the indoor assistant to estimate his requirements, but will tell the outdoor assistant exactly what cables he has to run and what they are for. The apparatus to be placed at each location should also be indicated on the chart. This type of chart is shown in Figs. 8 and 9.

Great consideration should be paid to the signal cabin, since it houses all the controls of the outside apparatus. The upper portion will only house the upper portion of the power frame and the illuminated track diagram. Other requirements for the upper portion are equally applicable to a mechanical cabin and will therefore not be dealt with here. A word or two with regard to the illuminated diagram may, however, be of advantage.

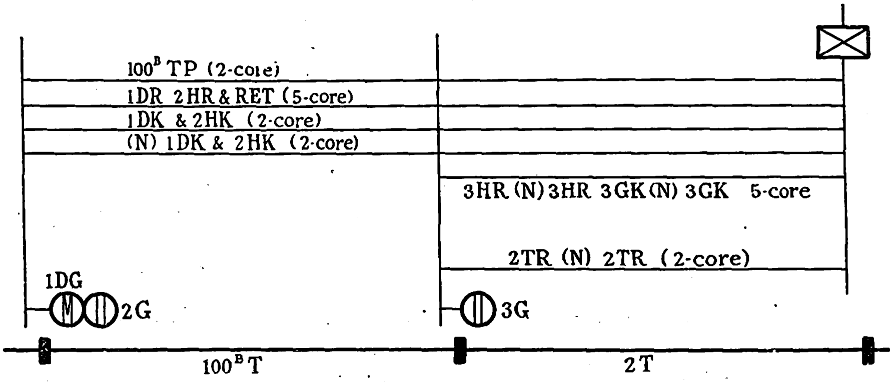


Fig. 9.

For a large and complicated diagram, strip lighting is the ideal method. To reduce the number of lamps, on some diagrams, spots or oval slots, placed in the middle of the diagram, are provided, the rest of the track circuit being painted on the diagram. This is satisfactory for a small diagram. For a large diagram strip lighting is, however, better from a signalman's point of view since it provides him with a more accurate idea of the conditions existing outside the cabin. The glass may be protected against the extra heat radiated by the additional lamps by thin copper gauze placed under it, but this will only be necessary where a very large variation of temperature is found.

The track circuit indication itself is usually the natural colour of the lamps, which will vary from nearly white down to a light yellow, according to the voltage at that particular place and the efficiency of the lamps. Sometimes the voltage is low, with the result that the diagram tracks do not show up so brightly as usual. It has been thought that strip lighting puts an undue strain on the signalman's eyesight, as he is continually looking at the plan of the yard represented by brightly coloured lines. In order to minimize this effect some railways place a piece of coloured gelatine between the plain and frosted glass so that the tracks are shown up in colour when they are clear. This is certainly a good scheme and in the author's opinion green is the best colour to adopt, firstly because it is fairly restful to the eyes, and secondly because it is the colour chosen to represent a clear road.

With regard to visual signal indications, some railways place these in the illuminated diagram or in special cases on the instrument shelf. In the case of a power frame it is far better to place the visual indication at the top of the lever plate bearing the title of the lever, and this is now usually done.

The wires from the basement or relay room to the power frame may be run up through a hole in the cabin floor straight into the frame. With a large frame, however, of over 100 levers, with perhaps 10 to 20 contacts on each lever, the problem of accessibility arises and it is not easy to reach the contact terminals, which are vertically beneath the contacts, from the side panels of the frame when it is open. If possible it is better to place the frame over an aperture made in the floor and looking directly down into the relay room. The wires can then be directly run up into this place, and a suitable platform can be fixed underneath with a ladder from the floor of the relay room so that men may stand in comfort under the frame and reach the contact terminals.

Opinions differ widely as to the best method of accommodating relays. Some railways place them in glass-fronted wooden cabinets, others in steel cabinets. Inter-relay wires are laced up as they go from terminal to terminal, but those going from one shelf to another are usually run in closed trunking.

The author thinks that the best method is to place the relays on an open rack and in such a position that one may walk all round it if space permits. The wires should be run along the edge of each shelf on specially designed hooks made of wood. Inter-relay wires should be run in the same way and drop from the edge of the shelf to the relay below. Wires going from shelf to shelf should be run up the edge of the end posts, neatly laced up together and held in position by hooks. If relays are placed on an open rack and can be seen from both sides there is certain to be more light available for their examination and they can easily be kept clean. The racks may be made either of metal or wood or a combination of both. Metal uprights and cross members may be used with wooden shelves.

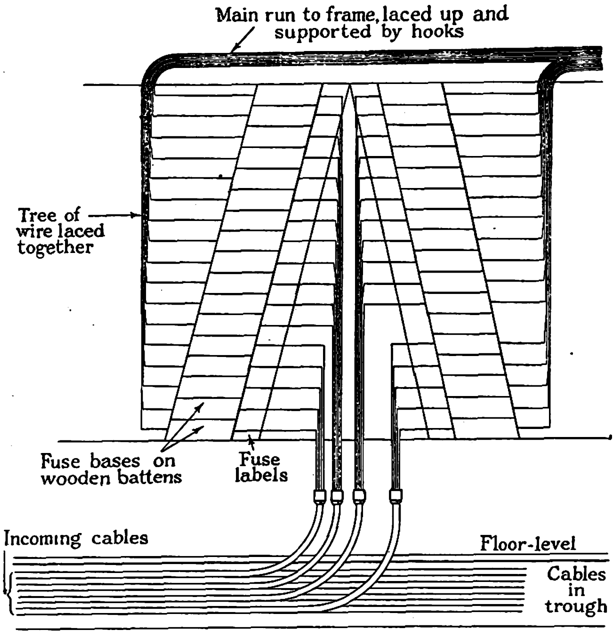

Main run to frame, laced up and supported by hooks
Tree of wire laced together
Fuse bases on wooden battens
Fuse labels
Incoming cables
Floor-level
Cables in trough

Fig. 10.

One popular method of accommodating fuses was to place them at the bottom of the relay cabinet, screwed on to a board with the wire pushed through a hole just large enough for one wire. Only the end of a wire going to a fuse base could be seen, the rest of the run being covered and out of sight.

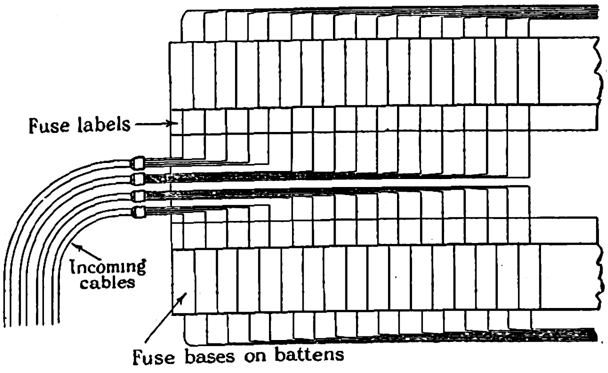

Fuse labels
Incoming cables
Fuse bases on battens

Fig. 11.

As long as wires are covered or run in trunking they will always be the rendezvous of mice, rats and other pests, which destroy the insulation material. The author has often found the wires, in such cases, badly mutilated and the run full of dirt carried in by these animals.

Figs. 10 and 11 show two methods of fixing fuse-bases so that the wires can be run very neatly and on the open system. Both lend themselves to a very neat method of running in the cables. These may be brought up through the floor or through the end wall of the cabin and may be supported on cable brackets a foot or so above the floor or run in an open trough made in the basement floor. The ends of the cable, or at least the lead covering or armouring, may be cut away at the point where the cable runs up to the fuses, and the various cores run neatly upwards in a vertical direction.

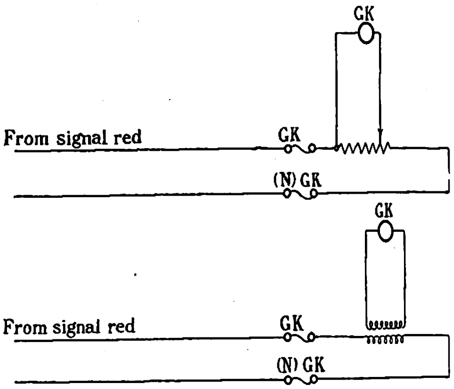

GK
From signal red
GK
(N) GK
GK
From signal red
GK
(N) GK

Fig. 12.

Where the cabin floor is left open beneath the power frame and a platform is provided, a very neat arrangement is to build the relay rack to form three sides of a square around the floor aperture, the platform being fixed to the relay rack.

With regard to signal indication circuits, no circuit is really efficient unless it really detects whether the signal light is in or out. With daylight or lantern signals a circuit should be employed in which the return of all indicators is run back to the cabin and through the primary of a special indication transformer. The visual indicator over the power-frame lever plate is connected across the secondary so that if the signal light burns out the visual light in the cabin will also be extinguished.

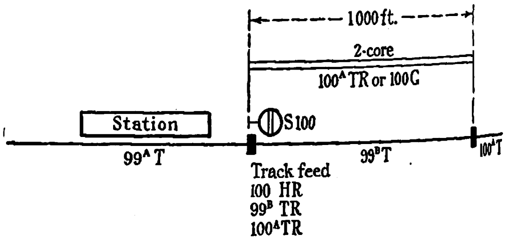
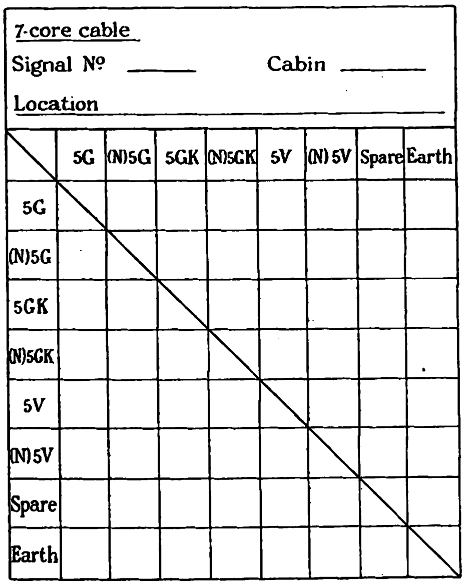

1000 ft.
2-core
100^A TR or 100C
Station
S100
99^A T
99^B T
100^A T
Track feed
100 HR
99^B TR
100^A TR

Fig. 13.

With d.c. working the indication circuit may be identical, a resistance being employed instead of a transformer and the visual indicator being lighted by the voltage-drop across the resistance. This is shown in Fig. 12.

Point indication circuits should operate point indication relays in the cabin. If this is not done the indication locks on the point lever will be energized directly from the point detection cables and it will be necessary to take the signal selections reading over the points over contacts on the point lever and also through detection boxes on the ground before reaching the signal control relay. If a relay is used the locks are operated through a local circuit in the cabin. The signal selections may also be wired in the cabin so that the signal control cable leaving the cabin goes direct to the relay. From the point of view of testing this is a great advantage since all the apparatus will be centralized, and it is much better from an electrical point of view.

In automatic signal territory, where overlap track circuits are in use, the question arises as to whether the track circuit ahead controlling the signal should have its relay situated there or at the signal. A reference to Fig. 13 will make this clear. This shows an automatic starting signal at a station. $\mathrm{T}99^{\mathrm{B}}$ is the overlap on S100, the startor, and the track controlling the signal is $\mathrm{T}100^{\mathrm{A}}$ and the overlap on the next signal, with which we are not concerned in this instance. The relay for $\mathrm{T}99^{\mathrm{B}}$ will be at the signal, whilst the relay for $\mathrm{T}100^{\mathrm{A}}$ will be 1 000 ft. ahead. If it is retained there the signal control for S100 will have to be run up to this relay and back again, necessitating a 2-core cable. If track relay 100^{A} is placed along with track relay 99^{B} at the signal a 2-core cable for the track relay leads will still be necessary. The question of the resistance of the track relay leads will of course have to be considered, but if a track circuit employing a 2-element vane relay is used there will be no difficulty in this. This method may also be adopted on other types of track circuits with shorter overlaps. The advantage of placing track relay 100^{A} at the signal is again to provide centralization of apparatus and convenience of testing. On a tunnel section this may be more readily appreciated.



7-core cable
Signal No ______ Cabin ______
Location

	5G	(N)5G	5GK	(N)5GK	5V	(N) 5V	Spare	Earth
5G								
(N)5G								
5GK								
(N)5GK								
5V								
(N)5V								
Spare								
Earth								

FIG. 14.

After a power interlocking or a power signalling system has been commenced it is important to arrange for some definite scheme of maintenance. All cables should be tested for insulation resistance at least once in two years and a chart should be drawn up so that each cable is tested periodically. As signal circuits are more or less standard on one railway, it will be convenient to draw up a cable testing-sheet somewhat on the lines shown in Fig. 14. From this it will be seen that if either side of the diagonal line is used each cable will be tested to earth and between cores without repetition.

A chart of apparatus-changing should also be drawn up so that any one piece of apparatus has only a definite spell of duty before it is removed for examination and overhaul.

With regard to signal failures, these are an evil which no railway can avoid, however efficient its system may be. As signal failures are likely to occur owing to causes over which the department has no control it is better to adopt some system of analysis so that at the end of a given period the signal engineer may be able to differentiate between his failures and see how many can be directly charged to him on the grounds of bad maintenance, defective design, etc. It is extremely useful if a proper analysis sheet be drawn up, dividing the signalling system into its individual component parts, and then subdivide these. The particular piece of apparatus that causes the most failures can then readily be identified and investigated with a view to making it more efficient.

Nowadays electric power can be obtained all over the country from outside sources and the signal engineer should not hesitate to take advantage of this fact. In addition it must be remembered that, as far as signalling is concerned, all traffic movements are generally thought out and assisted by the signalling department. The traffic department should be encouraged to bring its problems to the signal engineer and if he takes full advantage of all the resources available there will not be many problems which he will not be able to solve for them.

On one railway of which the author has knowledge the signal engineer is responsible not only for the signalling but also the current-rail connections, telephones, lighting and other auxiliary apparatus. It is not suggested that any particular railway might benefit by such an organization, but where it does exist there is no doubt that good results accrue. It must of course depend on the type of railway, for the signal engineer of an electrified railway or of a railway where there is an extensive electrified area must be an electrical engineer as well as a signal engineer.

THE LOADING OF TRANSFORMERS ON A THERMAL BASIS, WITH SPECIAL REFERENCE TO TEMPERATURE INDICATORS.*

By T. A. LONG, Student.

[ABSTRACT *of paper read before the* NORTH-WESTERN STUDENTS' SECTION *26th February, and before the* MERSEY AND NORTH WALES (LIVERPOOL) STUDENTS' SECTION *26th March,* 1929.]

The fundamental limit to the load a transformer will safely carry is the maximum temperature which its constituent material will stand without deterioration.

Excessive temperature of material if maintained for a fair length of time will cause deterioration of the insulation, and breakdown of the transformer will inevitably follow. It has been agreed almost universally that the maximum temperature allowable for continuous operation is 105° C., and, further, that the permissible difference between the maximum copper-temperature and the mean copper-temperature obtained by resistance is 10 deg. C. It has also been assumed that the ambient temperature should be 40 deg. C., thus leaving an allowable temperature-rise by resistance of 55 deg. C. The temperature-rise limits allowed by the British Engineering Standards Association for oil-immersed transformers are:—(1) 50 deg. C. measured by thermometer in the hottest oil, and (2) 55 deg. C. measured by the increase in the winding resistance.

It is evident that in actual service conditions the air temperature will seldom approach, and rarely, if ever, be maintained at 40° C. With certain favourable operating conditions and an accurate knowledge of the internal temperature conditions it is therefore possible to obtain safely a larger kVA output and even to exceed the above temperature-rise limits, without violating the intentions of the B.E.S.A.

There are three main methods of ascertaining the temperature of a transformer, viz. by reading a thermometer placed in the hottest oil, by noting the increase in the resistance of the windings, and by employing embedded temperature-detectors. To understand the limitations of each of these methods and to be able to interpret the results of such tests requires an understanding of the temperature distribution and the factors controlling the heat flow from the heated body to the surrounding cooling medium. The usual temperature-rise limit in transformers is the temperature-rise by resistance, and since the resistance of copper varies in direct proportion to the absolute temperature of the copper the ratio of the hot to the cold temperature of the windings may be obtained from the ratio of their hot to their cold resistances. Complete formulæ based on this fact are given in B.S.S. No. 171—1927.

The temperature-rise thus obtained is the average temperature-rise of the windings, and is the sum of the average winding-gradient and the mean oil-temperature, the hottest-spot temperature being the sum of the hottest-oil temperature and the maximum winding-gradient. The hottest-oil temperature and the winding gradient are quite independent of each other, and, within limits, each may be given any desired value. A measurement of the hottest-oil temperature therefore gives very little indication of the actual temperature of the transformer windings, and is thus no guide to the safe loading of the transformer. The ideal method of obtaining the true rating of a transformer is to measure it in terms of the hottest-spot temperature, and this is the function of a temperature-indicator. Some of the more important advantages of knowing the temperature of a transformer during operation are:—

(1) Insurance against damage from overloading, which should prolong the life of the transformer.

(2) Reduction in the installed kVA capacity of the transformer plant by the ability to increase the output of the transformer when the ambient temperature is below normal, when short-time overloads are required, and when the difference between the hottest-spot temperature and the average temperature is negligible.

(3) The possibility of conserving the cooling water for water-cooled transformers when the temperature of the ingoing water is below 25° C., and when the load is below normal.

There are a number of well-known schemes for observing the hottest-spot temperature of transformers. The essential requisites of any temperature-indicator are freedom from danger to the operator, simplicity of operation, and ability to indicate continuously, correctly and permanently the maximum temperature of the windings, under any condition of loading.

The most popular type of temperature-indicator in this country at the present time consists essentially of a dial thermometer the bulb of which is immersed in the hottest oil. Surrounding the bulb is a small resistance coil which is connected to the secondary of a current transformer through the primary winding of which the load current flows. The temperature of the resistance unit is so adjusted that it increases the temperature of the bulb by an amount equal to the maximum winding-gradient.

The resistance unit, being insulated from the main transformer winding, does not subject the operator to the danger of high potentials. If proper attention is given to the thermal design of the transformer there will be no need to have a separate resistance unit and current transformer for the high- and low-tension windings respectively. It is a popular misconception that the high-tension winding reaches a higher temperature than the low-tension winding. This is not so; it is purely a matter of design, and the relative temperatures of the windings may be varied at will by the designer.

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* A Students' Premium was awarded by the Council for this paper, and it is the practice of the Council in such cases to publish the paper, in full or in abstract, in the *Journal*.

Since the thermal time-constant of the resistance unit is very small (2 or 3 minutes), its temperature very rapidly follows any changes in the loading, and the indications of the instrument follow these changes with practically no time-lag—an important feature if the transformer is subjected to sudden and heavy overloads. The instrument can be calibrated directly in hottest-spot temperatures or in percentages of the maximum load the transformer will safely carry, and may be fitted with a warning or tripping device to operate when the transformer reaches a dangerous temperature.

One possible objection to thermal loading is the resultant poor voltage regulation. An examination of this objection shows that, assuming the very worst conditions, the effect of loading transformers at their true thermal rating should not give an increased voltage-drop of more than 1 per cent. Considering the investment represented by the transformers on a large supply system, it is evident that a means of loading transformers to the limit of their true rating is necessary if the capital invested is to be reduced to a minimum and the transformers kept in good operating condition throughout their useful life. It is impossible to stress too much the importance of replacing transformers as soon as their thermal capacities have been exceeded.

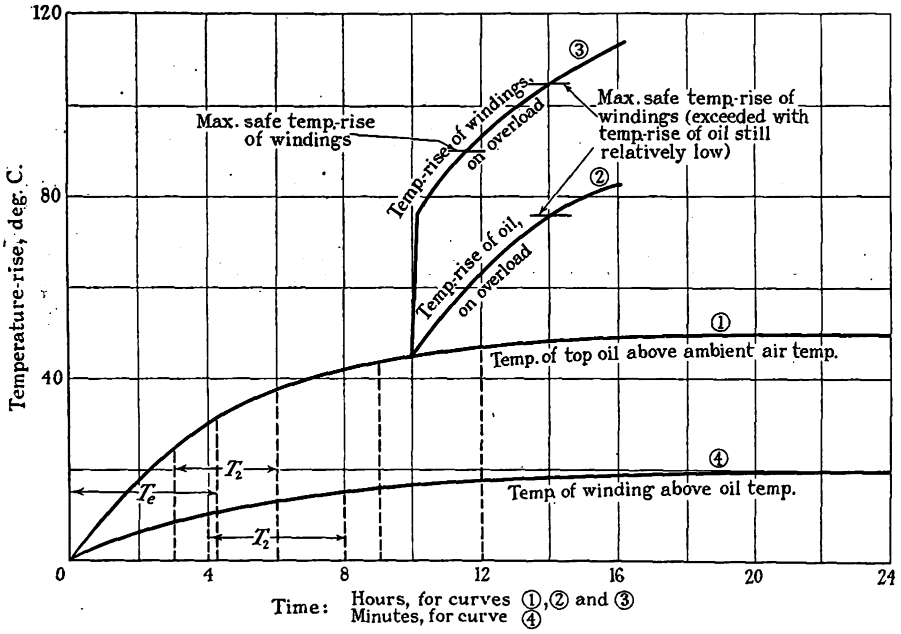
The author wishes to acknowledge his indebtedness to Messrs. Ferranti, Ltd., for allowing him to prepare the paper, and to members of the staff of the company, and of the English Electric Co., Ltd., for their valuable help and suggestions while it was in the draft stage.

APPENDIX.

LIST OF SYMBOLS.

θ = ultimate temperature-rise in deg. C. above ambient temperature.
t = time in hours or minutes from start of temperature-rise test.
ϕ = temperature-rise in deg. C. above ambient temperature.
ϕ_1 = temperature-rise in deg. C. after time t_1.
ϕ_2 = temperature-rise in deg. C. after time t_2.
ϵ = 2·718.
T_e = exponential thermal time-constant.
T_2 = binary thermal time-constant.

Some of the more useful relations of a heating curve (see Figure) are given here for reference purposes. Owing to the complexity of thermal relations among the different elements of a machine the temperature-rise may depart somewhat from a simple exponential curve, but in many cases it conforms to such a curve sufficiently closely for practical purposes. When the temperature-rise of a machine follows a known law it is easy to predict the course of the change in temperature if the load is changed abruptly from one long-continued steady value to another. If the load is changed in a less simple way, so that the one thermal transient is started before the preceding transient or transients have substantially terminated, the predetermination of the corresponding temperature becomes very complex. An instrument such as a winding-temperature indicator will automatically take into account the preceding loading history of the transformer when indicating the safe load which may be taken from the transformer.



Typical temperature-rise/time curve of a transformer, showing the relative winding and oil temperatures with 25 per cent overload.

Ambient air temperature = 15° C. (59° F.)
Winding temperature-rises above ambient air are obtained by adding the winding rise above oil to the oil rise.

The exponential thermal time-constant (T_e) is that interval of time during which the temperature-rise comes within $1/\epsilon$, or $1/2 \cdot 718$, or $36 \cdot 8$ per cent of the final temperature-rise, i.e. the time taken to reach $63 \cdot 2$ per cent of the ultimate rise. In a period $2T_e$ the rise will come within $1/\epsilon^2$, or about 13 per cent, and in a period $3T_e$ within $1/\epsilon^3$ or about 5 per cent of the ultimate rise.

The binary thermal time-constant T_2, suggested by Kennelly, is now used largely in America although it does not appear to have gained much popularity in this country. It is claimed that the binary time-constant is the obvious practical constant presenting itself for use, as it is an easy constant to remember and explain, and bears a fixed relation to the exponential time-constant; the difference being that it has a base of 2 instead of $\epsilon(2 \cdot 718)$. The binary time-constant T_2 may be defined as that interval of time during which the temperature-rise comes within one-half or 50 per cent of the final rise. In a period $2T_2$ the rise will come within $(\frac{1}{2})^2$, or 25 per cent, and in $3T_2$ within $(\frac{1}{2})^3$ or $12\frac{1}{2}$ per cent of the ultimate temperature-rise. The two time-constants are always connected by the relation

$$T_2 = 0 \cdot 69315\, T_e, \text{ or } T_e = 1 \cdot 4427\, T_2.$$

The general formula for a heating curve is

$$\phi = \theta(1 - \epsilon^{-t/T_e})$$

Therefore

$$1 - \phi/\theta = \epsilon^{-t/T_e} = 2^{-t/T_2} \quad . \quad . \quad . \quad (1)$$

This may be plotted as a straight line on semi-log paper. $(\theta - \phi)/\theta$ is the deficiency, and ϕ/θ the attainment. A temperature-rise (ϕ, t) curve having been obtained by test, it is easy to determine by inspection whether the curve follows equation (1). The ambient temperature should, of course, be kept constant during the heat run, or if it has slightly varied the curve should be corrected. The final temperature-rise is also necessary, either from test-results or by extrapolating from the curve. The time from 0 to $\frac{1}{2}\theta$ is measured along the time axis of the curve. This should be the binary time-constant T_2. In another such period of time the further temperature-rise should be $\frac{1}{4}\theta$, in a third such period of time the further temperature-rise should be $\frac{1}{8}\theta$, and so on. If these relations hold satisfactorily the curve may be regarded as exponential, from a practical standpoint.

The formula for deriving the ultimate temperature from an incomplete temperature-rise curve is

$$\theta = \frac{\phi_1}{2 - (\phi_2/\phi_1)} \text{ deg. C.}$$

where ϕ_1 is the temperature-rise at the end of t_1 hours, and ϕ_2 is the temperature-rise at the end of t_2 hours, t_2 being $2t_1$ hours. It is assumed that the curve is exponential, that $\phi = 0$ at the start, and that the ambient temperature remains constant throughout, or has been corrected for. Thus, if $\phi_2 = 1 \cdot 5\phi_1$, it follows that $\theta = 2\phi_1$, and $t_1 = T_2$.

DISCUSSION ON
"THE ROTOR BEARINGS OF ELECTRICITY METERS."*

Mr. E. G. Sandmeier (*communicated*): The author recognizes the obscurity of the problem of worn bearings, and points out that the evidence provided by life statistics of jewels is so contradictory that no conclusion as to the cause of wear can be drawn from them. The following observations may perhaps help to throw some light on this rather complex question. They are based upon systematic researches, extending over several years, which aimed at producing a suitable rough material and making from it a reliable jewel bearing for use in electricity meters and other sensitive measuring instruments. The investigations were concerned only with ruby and sapphire bearings, and dealt exclusively with defects directly connected with the raw material and the manufacture of jewels. All other causes of rapid wear, such as inappropriate pivots, badly mounted jewels, defective protection of the bearing against dust, jewels damaged by the obsolete needle test, or dirt in the cup of the jewel when a new meter is installed, were ignored. When tracing the causes of defects or over-rapid wear in bearings, an important factor is generally left out of consideration. Little or no attention is given to the fact that the sapphire is not an amorphous material, having the same properties in all directions, but is endowed with a crystalline structure which plays an important part in qualifying it to act as a long-life jewel bearing. In most of the ordinary meter jewels, natural and synthetic, the position of the cup was, until a short time ago, fixed regardless of the structure of the material. What this means can be seen clearly in the photo-micrographs of Fig. A (natural sapphire) and Fig. O (synthetic ruby). In these bearings the pivot rotates perpendicularly on a cross-section of the layers forming the stones. Because of the more or less pronounced difference in hardness between the layers of different colours, and since the angles formed by the crystal faces of the hexagonal prism (Fig. A) of a natural sapphire are harder than the flat sides, such jewels will very quickly wear out the pivot. It was therefore of interest to ascertain whether the faulty bearings mentioned in the paper confirmed the results obtained with other worn jewels. By the courtesy of the author I was able to examine 36 of the defective jewel bearings referred to in Table 1 of the paper. A first inspection of these jewels revealed the fact that all were of a rather poor quality, the majority being polished in an inferior fashion, and not a few of the stones exhibiting serious flaws. None was entirely free from defects of material or workmanship, each having at least one of the capital defects mentioned in the table, and in general they gave the impression of being of the so-called "War" quality. As far as can be judged by the condition of these used jewels, all of which show more or less deep abrasions, the real causes of failure are, first, a very defective polish on the surface of the cup, and secondly defects of material, in some cases so serious that they should have led to the rejection of the jewels concerned. A third cause of wear may have been the broken edges of the cup, the minute particles of material from which form an excellent grinding medium. The possible sources of wear are so numerous that it is rather difficult to say exactly what caused the failure in each particular case. It is highly probable that a combination of the various defects helped to shorten the life of the respective jewels. Figs. B to O are reproductions of photo-micrographs of some of the jewels whose principal defects of material and workmanship are set out in the table. Fig. B represents inclusions of a natural sapphire, probably consisting of rutile-needles. Fig. C shows big inclusions of another nature in a natural sapphire. Fig. D is a side view of a natural sapphire full of liquid inclusions. Fig. E shows a striated natural sapphire, the cup of the jewel being placed on a cross-section of striæ. The black spot on the left is a hollow cut out by the surface of the bowl and filled up with rust from the pivot. Fig. F represents another typical striated natural sapphire exhibiting signs of internal strain. Figs. G and H show the same natural sapphire, the first being a reproduction of the abrasion, and the second showing a field of fine bubble-like inclusions. Fig. J illustrates a central circular abrasion, as well as minute inclusions. The black half-moon on the right of the abrasion is a crack running almost horizontally into the stone, and filled with rust from the pivot. Fig. K shows the very badly polished surface of the cup of a natural sapphire, with a deep central abrasion. The radial, slightly curved scratches are typical of the first polishing operation. They have not been removed entirely by the following process of giving a high polish to the cup. Fig. L shows a synthetic ruby full of small gas bubbles, whilst Fig. M shows the same jewel. The edge of the cup is completely smashed. Fig. N represents a synthetic ruby containing big gas bubbles. Fig. O is a photo-micrograph of a synthetic ruby, showing the slightly curved layers, i.e. the typical

TABLE.

	Total	Natural sapphire	Synthetic ruby
Number of jewels examined ..	36	19	17
Defects of material—			
1. Flaws, inclusions, striations, and internal strains ..	27	18	
2. Inclusions, gas bubbles, etc.			9
Defective polish. Badly polished surface of cup, scratches, etc.	34	18	16
Chipped or broken edge of cup, cracks in cup, etc.	25	10	15

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* Paper by Mr. W. Lawson (see vol. 67, p. 1147).

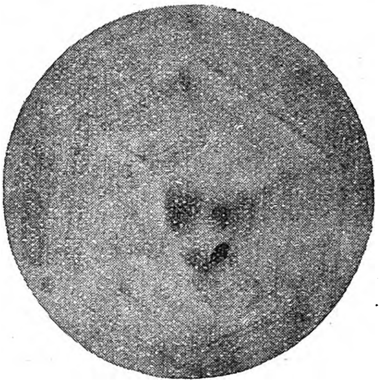

FIG. A.

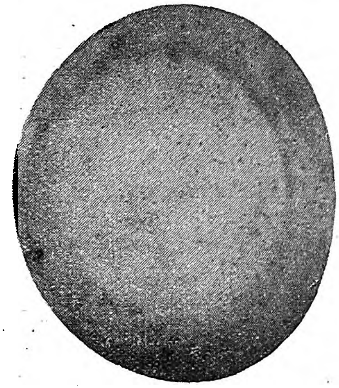

FIG. B.

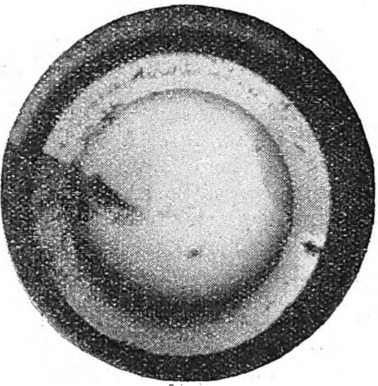

FIG. C.

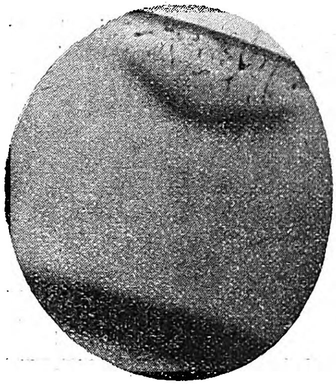

FIG. D.

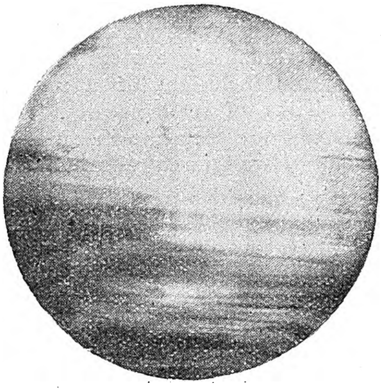

FIG. E.

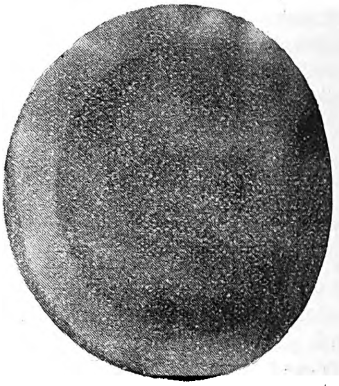

FIG. F.

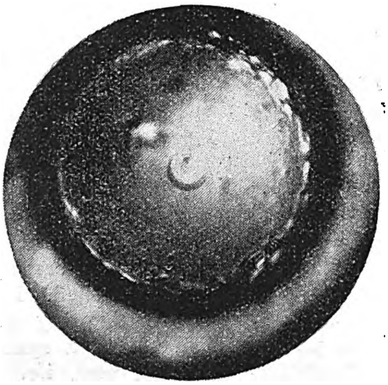

FIG. G.

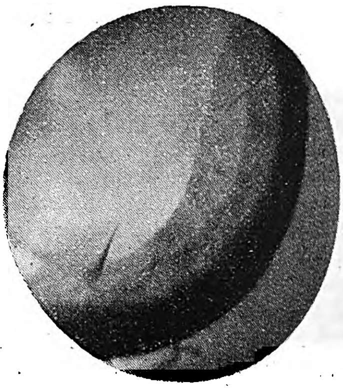

FIG. H.

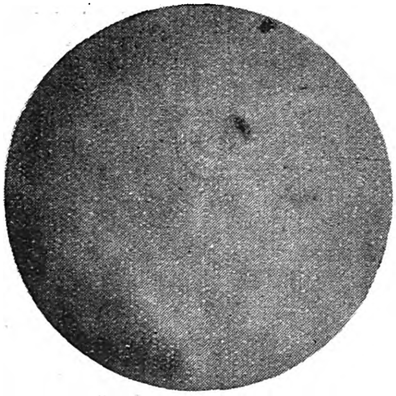

FIG. J.

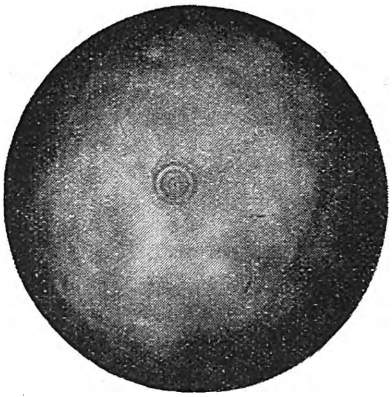

FIG. K.

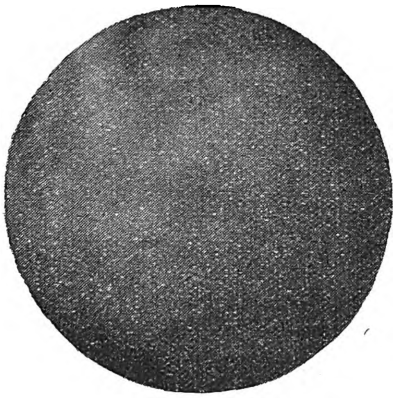

FIG. L.

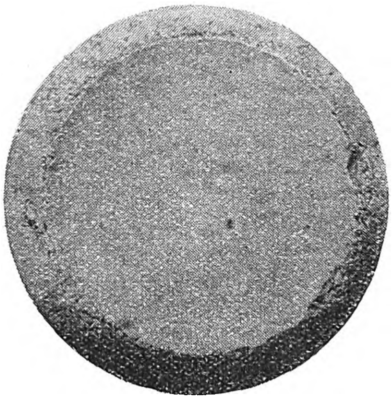

FIG. M.

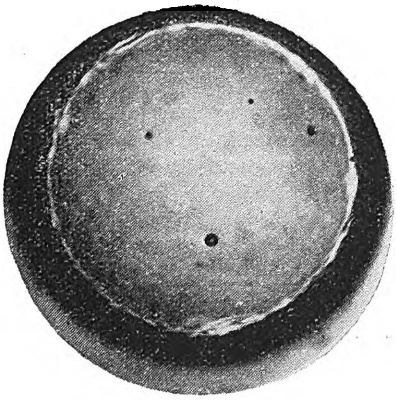

FIG. N.

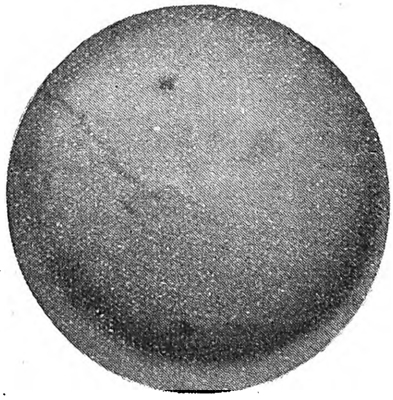

FIG. O.

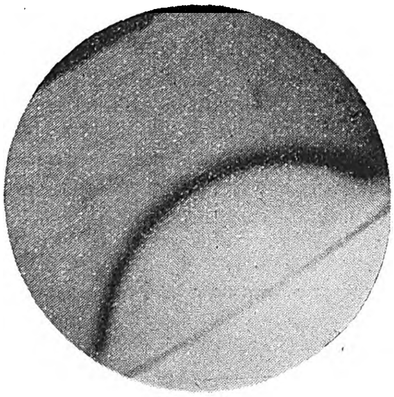

FIG. P.

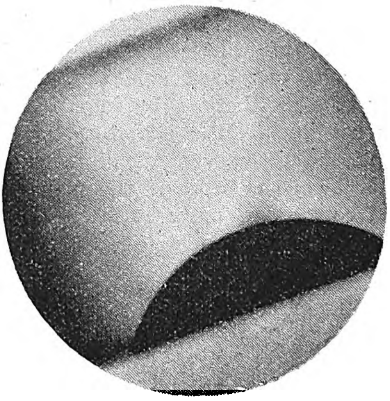

FIG. Q.

structure of the synthetic coloured corundum, the cup being placed on a cross-section of the material. The nature of the various defects of the 36 faulty jewels can be so easily established, and the flaws are so serious, that it seems impossible to ascertain whether the fact of placing the cups without regard to structure was another cause of over-rapid wear. However, it is noteworthy that the jewels with the deepest abrasions are in general those in which the cup is placed on a cross-section of the structure. Inspection of the 36 defective jewels leads, in the first place, to the conclusion that these stones cannot be taken as a basis for judging the suitability of ruby or sapphire for meter bearings. The examined jewels had to break down, and it would have been surprising if they had done anything else. Secondly, the investigation gave evidence of the considerably higher risk of failure in the case of natural sapphires, nearly 95 per cent of the natural stones examined being infected with flaws of material, inclusions, striæ and other areas of weakness which rendered them undesirable as material for bearings. The synthetic rubies show 53 per cent of defects of material, all of which can easily be avoided to-day because the quality of the synthetic stone has been greatly improved since its first appearance on the market. In this connection it is interesting to note that Lieut. R. J. Bray, in his standard work on "Pivots and Caps in Compasses," published in 1917, foresaw the possibility of improving the quality of synthetic corundum and making it the "ideal material for mechanical purposes." During the last few years these improvements have been achieved, at least so far as they concern the products of the factory with which I am associated. Indeed, if the synthetic rubies known until 1917 were full of striæ and inclusions, and inclined to split and shatter, the special-quality synthetic sapphire of to-day has no inclusions whatever. This new material has the hardness of the natural sapphire, but not its defects; it is much tougher, less brittle, and not liable to the failures to which the native product may give rise. The uniformity in hardness and in toughness is obtained partly by directing the operation of fusing and crystallizing in such a manner that the creation of internal strains in the growing crystal is avoided or reduced to a harmless minimum, and partly by selecting specially prepared pure alumina containing no colouring agents whatever and giving a transparent, colourless sapphire. The tendency of the synthetic ruby to split and shatter, referred to by Lieut. Bray, is due more to internal strains than to inclusions. By locating the cup according to the structure of the material a further improvement, and one that could not have been foreseen 12 years ago, has been achieved. Fig. P is an internal view of a synthetic ruby in which the cup is orientated according to the structure. The slightly curved layers forming the synthetic stone can be plainly seen. In this jewel the head of the pivot turns on a plane formed by one or more surfaces of the layers, but never on the edges of the latter. In the case of the natural sapphire also it is theoretically possible to locate the cup according to the crystalline structure of the stone, but this could hardly be done in practice because it would be difficult to find enough natural sapphires without flaws or striæ. Furthermore, the price of a natural jewel selected in this way by scientific research would be much too high, because a great number of stones would usually have to be examined before one capable of passing all the tests could be found. On the other hand, industry disposes to-day of the white or colourless specimen of synthetic sapphire, as shown by Fig. Q. This photo-micrograph is an internal view just below the cup, of a synthetic jewel, made of a special-quality white sapphire. No characteristics of structure can be distinguished, the material containing no colouring agent whatever, being absolutely uniform, and without any flaws. The cup is nevertheless correctly located according to the structure, and this type of jewel is therefore the best at present available, the diamond excepted, for use as a long-life bearing. It has been perfected as the result of a thorough study of faulty bearings and the possible causes of wear, and this is perhaps the only way which will lead to a solution of the problem of the apparent contradiction to be found in life statistics of jewels belonging to the same class of minerals.

Mr. W. Lawson (*in reply*): It is disturbing to read Mr. Sandmeier's conclusion that none of the jewels which I submitted to him was originally free from defect of either workmanship or material. The fault is clearly with the meter manufacturers, and although the majority of these bearings were purchased during the War period they were not necessarily of the so-called "War" quality, because my statistics show that the pre-War jewels associated with the same make of meter had approximately the same percentage of defectives.

Before the meters were calibrated and put into service the jewel cups were carefully cleaned and subjected to the needle test. Unfortunately it was not then my practice to have new jewels examined under the microscope, otherwise some of the flaws, inclusions, and the inferior polish which, Mr. Sandmeier states, characterized these jewels may not have passed entirely unnoticed. Mr. Sandmeier would appear to have made out a strong case for adopting the synthetic stone, but I am able to say that good results are being obtained from natural stones in single-phase meters at the present time. I appreciate the very thorough way in which Mr. Sandmeier carried out his investigations on the jewels I submitted to him and I consider that he has provided us with much valuable knowledge. I have no doubt that if the greatest possible care is exercised in selecting the material of both the jewel and pivot and if they are shaped with the utmost precision and given the highest possible finish we shall in the future hear very little of the failure of meter bearings.

DISCUSSION ON

"AN INVESTIGATION OF FREQUENCY VARIATIONS IN INDUCTION WATT-HOUR METERS."*

Dr. A. Callsen (*communicated*): The paper contains a great deal of experimental data relating to the frequency variations of induction meters, but the authors' theoretical explanations of the origin of torque fluctuations with frequency fluctuations, and the conclusions which they deduce therefrom as to the disc inductivity are, however, open to question. The authors assume that the torque is proportional to $\cos^2 \theta$, where θ is the angle of lag of the disc current in relation to the disc e.m.f., and ascertain the torque error at various frequencies for a time-constant $\alpha = 0 \cdot 0005$ ($\theta_{f=50} \sim 9°$) and $\alpha = 0 \cdot 001$ ($\theta_{f=50} \sim 17 \cdot 5°$). As θ increases with higher frequencies ($\tan \theta = 2\pi \times f \times \alpha$) they obtain with higher frequencies a decrease of torque proportional to $\cos^2 \theta$, and they make use of this observation to determine the time-constant α by measuring the torque at two different frequencies. In this connection I wish to make the following observations:—

(1) The torque of the induction meter is proportional not to $\cos^2 \theta$ but to $\cos \theta$, as can be deduced from the torque formula of the meter

$$\begin{aligned} D = {} & C' \times \Phi_I \times \Phi_V \times f \times \sin (\psi - \theta_I) \\ & + C'' \times \Phi_I \times \Phi_V \times f \times \sin (\psi + \theta_V) \end{aligned}$$

where D = torque; Φ_I and Φ_V = the current flux and voltage flux respectively; ψ = angle between Φ_I and Φ_V; and θ_I and θ_V = angle of lag of the disc current with the disc e.m.f. If in this equation $C' = C''$ and $\theta_I = \theta_V$ then we get

$$D \propto 2 \times \sin \psi \times \cos \theta \text{ and}$$
$$D \propto \cos \theta \text{ if } \psi \text{ is constant}$$

(2) The calculation of the frequency error on the basis of the alteration of the angle θ does not take into account the real causes of the frequency errors. Exhaustive calculation only shows that the influence of the disc inductivity with the variations of the frequency is very small, at the most 1 per cent with change of frequency from 50 to 100 cycles per sec. with an aluminium disc 1·2 mm thick. The prime cause of frequency error is rather the change of the voltage damping in the reverse action of the disc current on the magnetic circuit of the voltage and current fluxes. The reverse action occasioned through the loading of the fluxes by the secondary current in the disc and short-circuited windings on the poles causes a diminution of the driving fluxes at higher frequencies. This phenomenon has long since been theoretically explained † and has also more recently been treated mathematically.‡ These deductions are confirmed by Figs. A and B, which are experimentally developed frequency-error curves. These curves, which were obtained in the meter research laboratory of Siemens-Schukertwerke, refer to a single-phase meter with a phase displacement of 90° produced by a magnetic shunt on the voltage iron. As the 90° displacement was obtained without any short-circuit winding on the voltage pole, the flux changes are caused *solely* by the reverse action of the disc. The errors of the voltage-driving flux Φ_V and of the current-driving flux Φ_I are measured by the alternating-current compensator. The brake factor of the voltage-driving flux was experimentally obtained and the brake curve ΔB_r calculated on the basis of this factor. Fig. B shows the sum of these errors and, for comparison, the error curve as actually ascertained from measuring the meter revolutions.* A similar method was adopted for a second meter in which the 90° displacement was produced not by a magnetic shunt on the voltage iron but only by strong short-circuiting rings at the voltage pole. The resultant error curve, together with the measured-error curve, is shown in Fig. C. The steep bend at frequencies below 50 cycles per sec. is due to increased voltage damping and the effect of the ohmic voltage-drop in the voltage coil. As no magnetic shunt is present in the voltage iron the magnetization current i_m and hence also the ohmic drop are so large that at lower frequencies ($i_m \propto 1/f$) an appreciable decrease of the e.m.f.—and

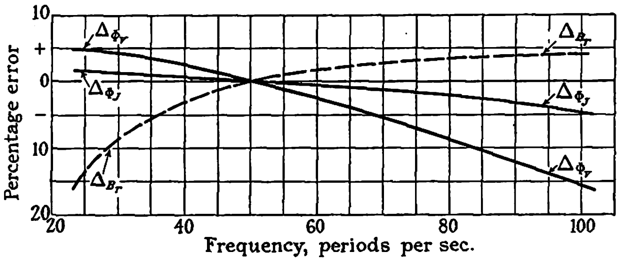

FIG. A.—Individual frequency errors of an individual meter with 90° phase displacement obtained by magnetic shunt on the voltage iron. Constant terminal voltage V.

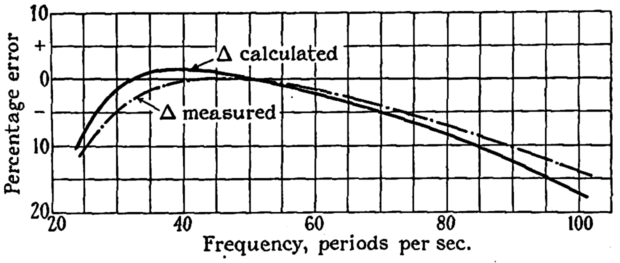

FIG B.—Error curve (compounded from the individual errors of Fig. A) of the meter with $\cos \phi = 1 \cdot 0$, in comparison with an observed frequency curve with $\cos \phi = 1 \cdot 0$. Constant terminal voltage V.

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[*] Paper by Messrs. A. E. MOORE and W. T. SLATER (see page 1023).

[†] MOLLINGER: "Wirkungsweise der Motorzahler und Messwandler," 2nd ed., p. 102; also SCHMIEDEL: "Wirkungsweise und Entwurf der Motor-Elektrizitatzahler," p. 24.

[‡] A. CALLSEN: *Archiv für Elektrotechnik*, 1929, vol. 23, p. 40.

[*] In summing the errors the effect of the angle error on the torque was also considered. With $f = 100$ this error was about $- 0 \cdot 2$ per cent.

consequently of the total flux—results. At higher frequencies smaller errors were found than in the case of the meter considered in Figs. A and B. This again is partly due to the voltage damping and the ohmic voltage-drop but also partly to the fact that in a magnetic circuit without any magnetic shunt the reverse action of the secondary current is smaller. In spite of the strong short-circuiting rings the effect of the flux is smaller than in the case of the first meter. In both cases the agreement between the error curve compiled from individual errors and the curve resulting from measuring the revolutions is proportionately good. At most of the frequencies the error ascertained by measuring the revolutions is smaller than the sum of the individual errors, which goes to show that the influence of disc inductivity lies within the limits of errors of measurement.

(3) From the foregoing it follows that the determination of disc inductivity by measuring the torque at two different frequencies according to the authors' method must produce much too high a value; for the decrease of torque at higher frequencies is due almost exclusively to the diminution of the driving fluxes in consequence of the strengthened disc reverse action, and in a very small degree to the disc inductivity. Nevertheless this method of determining the disc inductivity would be free from objection if, when measuring the torque, the change in the driving fluxes is also taken into account by measuring the flux. As, however, the differences would be very small this determination of the angle θ might be inaccurate.

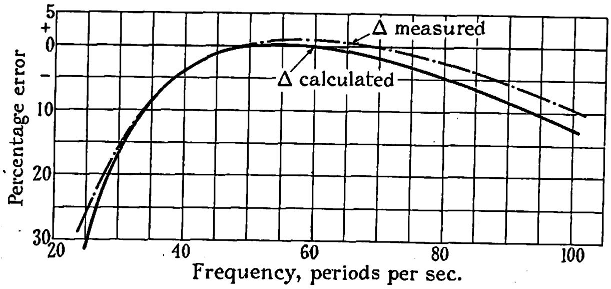

FIG. C.—Corresponding curves as in Fig. B, but for a meter without magnetic shunt on the voltage iron and with 90° phase displacement obtained by short-circuited windings on the voltage pole. Constant terminal voltage V.

Messrs. A. E. Moore and **W. T. Slater** (*in reply*): The torque formula given by Dr. Callsen for the meter is incomplete. It takes account of the magnitudes of the fluxes and the phase of the eddy currents, but it omits the magnitude of the eddy currents. The magnitude of the voltage eddy current is $e_V/Z = e_V/R \cos\theta$, where Z is the impedance and R the resistance of the eddy-current path. Thus the torque formula should contain another $\cos\theta$ factor. The same formula obtains in the case of the induction motor, and the torque in that case is also proportional to $\cos^2\theta$.

In the second part of his remarks Dr. Callsen states, firstly, that the inductivity of the disc is so small as to have practically no effect, and then proceeds to say that the eddy currents induced in the disc have a powerful demagnetizing effect on the poles. These two statements appear to us to be contradictory. If the inductive effect of the disc is negligible then the eddy currents are in quadrature with the inducing fluxes, and the demagnetizing components are negligible. If, however, the demagnetizing components are appreciable then the eddy currents must lag considerably behind the induced e.m.f.'s, since the induced e.m.f.'s are in quadrature with the inducing fluxes. We submit, therefore, that the explanation put forward by Dr. Callsen is a confirmation of the theory which we ourselves have given. The point is further illustrated by the vector diagram, Fig. D, which is drawn for unity-power-factor conditions on the assumption that the effect of the disc inductivity is negligible. Referring to the diagram, e_I and i_I are in phase with each other and produce a flux Φ_{EI} also at the same phase position. Similarly e_V, i_V and Φ_{EV} all have the same phase. The resultant voltage flux Φ_{VT} is therefore composed of Φ_V and Φ_{EV} and differs in phase from Φ_V by an angle δ. The torque of one pair of components is therefore proportional to

$$i_I \times \Phi_{VT} \times \cos\delta = i_I \times \Phi_V$$

for Φ_V and Φ_{EV} are at right angles, since the time-constant of the disc is zero by assumption, and therefore $\Phi_{VT} \cos\delta = \Phi_V$. Hence, no matter how much the flux is altered

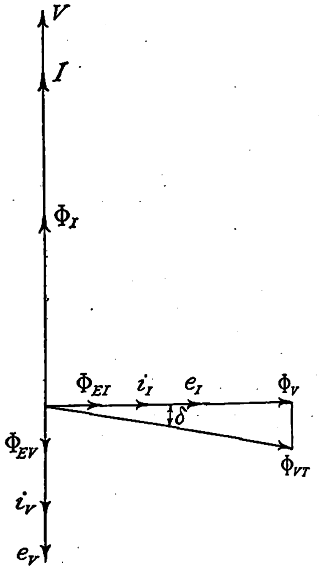

FIG. D.

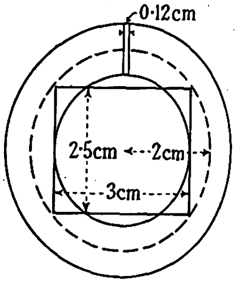

FIG. E.

by the corresponding eddy current, the resultant effect on the torque is nil, so long as the disc is assumed to have zero time-constant. We have examined a meter made by Messrs. Siemens-Schuckert and from the details of the meter have arrived at the following approximate result. Taking the voltage poles (Fig. E), area of pole-faces $= 2\cdot 5 \times 3 = 7\cdot 5$ cm^2, and length of air-gap $= 0\cdot 3$ cm. Assuming the iron circuit to have a negligible reluctance compared with the air-gap, and assuming that the eddy-current path is defined by, say, a ring in the disc, the ring having a mean radius of 2 cm and a cross-section of 1 cm × 0·12 cm, the time-constant of the disc, if of copper, works out as follows:—

$$L = \frac{4\pi \times 7\cdot 5}{0\cdot 3 \times 10^9}$$

$$R = \frac{1\cdot 7 \times 2\pi \times 2}{0\cdot 12 \times 10^6}$$

$$L/R = 0\cdot 002 \text{ (approx.)}$$

For an aluminium disc of the same dimensions L/R would be approximately 0·0012. These figures for the time-constant, though only very approximate, appear to indicate that the values for the time-constants which we obtained experimentally are not excessive. The air-gap between the current poles is generally larger than that between the voltage poles, and the time-constant of the disc when between the current poles would be less than when between the voltage poles. The figures obtained experimentally for the time-constants probably approximate to the mean values of the two.

In this connection we should like to revert to Mr. Fawssett's contribution to the discussion (page 1033). We think that the experiment which Mr. Fawssett describes gives results for that part of the disc which is between the current poles, and if he repeated the experiment with the rotor current embracing the voltage flux instead of cutting it the results would be interesting.

THE BENEVOLENT FUND.

32ND ANNUAL GENERAL MEETING, 15TH MAY, 1930.

Col. Sir Thomas F. Purves, O.B.E., took the chair at 5.30 p.m.

The notice convening the meeting was taken as read.

The minutes of the 31st Annual General Meeting held on the 9th May, 1929, were also taken as read and were confirmed and signed.

The Report of the Committee of Management (see below) and the Statement of Accounts for the year 1929 (see page 768) were presented and, on the motion of the Chairman, seconded by Mr. P. Rosling, were unanimously adopted.

On the motion of the Chairman, it was resolved that Mr. J. Attfield, F.C.A., be appointed Honorary Auditor for the year 1930.

The Chairman reported that, under Rule 15, the Council had appointed the following Committee of Management for the year 1929–30:—

The President (*ex-officio*).

Major B. Binyon, O.B.E., M.A., Mr. H. Marryat, Col. R. K. Morcom, C.B.E., M.A., Mr. F. W. Purse, Lieut.-Col. W. A. Vignoles, D.S.O., Mr. H. T. Young,	representing the Council;
Mr. A. F. Harmer, Mr. S. R. Mullard, Mr. P. Rosling,	representing the Contributors;

and the Chairmen of the Local Centres in the United Kingdom and Ireland.

REPORT OF THE COMMITTEE OF MANAGEMENT OF THE BENEVOLENT FUND FOR 1929.

CAPITAL.

The Capital Account stood on the 31st December, 1929, at £14 242 8s. 4d., which is invested.

RECEIPTS.

The Income for 1929 from dividends, interest and annual subscriptions was as follows:—

	£	s.	d.
Dividends on investments ..	681	15	6
Interest	32	16	10
1 056 Annual Subscriptions ..	606	11	0
	£1 321	3	4

In addition to the foregoing, the Fund benefited during the year by the following amounts, many of which are non-recurring donations:—

	£	s.	d.
South Midland Electrical Engineers' Ball Committee	78	15	0
Electrical Engineers' Ball Committee	50	0	0
Liverpool Centre, Golf Tournament	38	14	4
"Twenty-Five Club"	26	5	0
Henley's Telegraph Works Co., Ltd.	25	0	0
Meter Engineers' Technical Association	22	15	0
T. L. Eckersley	20	0	0
Western Centre	19	9	8
Scottish Centre, Golf Tournament	17	18	6
North Midland Electrical Engineers' Ball Committee	15	0	0
General Electric Co.	10	10	0
Incorporated Municipal Electrical Association	10	10	0
Messrs. Kennedy and Donkin	10	10	0
F. R. Marsh	10	10	0
F. Bailey	10	0	0
J. D. Dallas	10	0	0
H. Marryat	10	0	0
S. R. Mullard	10	0	0
P. Rosling	10	0	0
Sir George Sutton, Bart.	10	0	0
West Insulating Co., Ltd.	10	0	0
North Midland Centre	7	13	0
Electrical Contractors' Association	7	12	8
A. J. Mavor	7	5	0
A. M. Sillar	5	17	6
Anonymous	5	5	0
W. B. Esson	5	5	0
Sir Hugo Hirst	5	5	0
T. B. Mackenzie	5	5	0
National Register of Electrical Installation Contractors	5	5	0
E. J. Wade	5	5	0
R. O. Wright	5	5	0
T. H. U. Aldridge	5	0	0
S. G. Brown	5	0	0
"C2"	5	0	0
Captain J. M. Donaldson, M.C.	5	0	0
E. Fawssett	5	0	0
H. R. Lloyd	5	0	0
H. E. Morrow	5	0	0
W. J. Robertson	5	0	0
E. A. Short	5	0	0
E. B. Vignoles	5	0	0
2 429 donations of under £5	948	13	7
	£1 489	14	3

The accumulated balance of the Income and Expenditure Account amounted on the 31st December, 1929, to £2 258 9s. 7d., of which £1 552 16s. 4d. was invested and £500 was on deposit with the Institution Bankers.

DONORS AND SUBSCRIBERS.

Lists of the names of donors and subscribers are issued to members of the Institution annually.

The Committee of Management desire to acknowledge their indebtedness to the donors and subscribers, and to intimate that, apart from donations, the Committee will be grateful for annual subscriptions of any amount. The Committee are anxious that the Capital Account should be steadily augmented, so as to strengthen the financial position of the fund.

LEGACIES.

The Committee have to report legacies of £100 each from the late Dr. C. S. du Riche Preller (Member) and the late Mr. H. Louis Leach (Member), which amounts have been invested.

GRANTS.

Applications for assistance were made by or on behalf of 35 persons during 1929, and the Committee, after due consideration, made grants in 32 cases.

The total amount of the grants was £1 538 15s. 0d.

WILDE FUND.

The Capital Account stood on the 31st December, 1929, at £3 049 16s. 2d., all of which is invested and brings in an annual income of about £112 5s. 0d.

The balance standing to the credit of the Income Account (from which, under the Trust Deed, full Members only can benefit) on the same date was £87 17s. 5d.

Grants amounting to £92 were made from this Fund during the year.

PROCEEDINGS OF THE INSTITUTION.

800TH ORDINARY MEETING, 27TH FEBRUARY, 1930.

Col. Sir Thomas F. Purves, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 13th February, 1930, were taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

The President drew attention to the portrait of Sir Joseph Swan by Mr. Wal Paget, which had been presented to the Institution by Sir Charles Parsons and had been hung in the Lecture Theatre. He asked the donor to say a few words about the portrait and its subject.

Sir Charles Parsons: It is my pleasant duty to say a few words about my old friend Sir Joseph Swan. So much has lately been said about him on the occasion of the jubilee of the incandescent electric lamp, that it is superfluous for me to say very much on this occasion. In the Institution *Journal* for February, 1929,* will be found an account of the proceedings in connection with the jubilee of the invention of the carbon incandescent electric lamp by Sir Joseph Swan in 1878. The same issue of the *Journal* also contains † an address by Mr. Swinburne, entitled " Sir Joseph Swan's Electrical Work." Mr. Swinburne was employed in his younger days by Mr. Swan (as he then was) at Newcastle-upon-Tyne, just at the time when Swan was developing his electric lamp, and they were close friends. Mr. Swinburne elaborates the many and considerable difficulties met with by this pioneer at that time, and the great technical skill and patience which Swan employed and which brought about the success of the invention. In the same publication ‡ Sir Ambrose Fleming gave some brief personal recollections of Swan's part in the invention of the carbon incandescent electric lamp, and stated that it is beyond question that Sir Joseph Swan was one of the great pioneers whose investigations and inventions gave us the incandescent electric lamp in its earliest practical form, and that the credit for that epoch-making invention cannot be claimed for Mr. T. A. Edison alone. In the late seventies, while serving an apprenticeship at the Elswick works of Sir William Armstrong, Mitchell and Co., I became acquainted with the future Sir Joseph Swan, and we had many interesting discussions then and at subsequent periods. In the early eighties he often inquired how the steam turbine was getting on, always in the most kindly, sympathetic and encouraging way. Swan had an interest in many things besides his lamp, among them rapid photographic dry plates, of which I believe he was to some extent the inventor. We also talked about improvements in the navigation facilities of the Tyne, and he was very interested in, and often used to speak about, the building of the High Level Bridge over the Tyne by Robert Stephenson. Swan's kindly face is admirably reproduced in this portrait by Mr. Wal Paget, and I venture to think that the members of this Institution will agree with me in suggesting that the Council are to be congratulated on having secured the services of so excellent an artist and one, moreover, who had the advantage of being personally acquainted with Sir Joseph Swan.

The President: In a case of lavish generosity such as this, Sir Charles Parsons is hardly the kind of person who would either expect or enjoy any elaborate protestations of gratitude. I will ask you to express in the usual manner your hearty thanks to Sir Charles Parsons.

The vote of thanks was carried with acclamation.

The Faraday Lecture was then delivered by Captain P. P. Eckersley, Member, the subject being " Broadcasting by Electric Waves."

On the motion of the President, a vote of thanks to the lecturer was carried by acclamation and the meeting terminated at 7.15 p.m.

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* Vol. 67, page 313. † *Ibid.*, page 291. ‡ *Ibid.*, page 293.

801ST ORDINARY MEETING, 13TH MARCH, 1930.

Col. Sir Thomas F. Purves, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 27th February, 1930, were taken as read and were confirmed and signed.

Messrs. L. G. Bolton and D. P. Sayers were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the President reported that the members whose names appeared on the ballot lists had been duly elected and transferred.

The President announced that, during the month of February, 621 donations and subscriptions to the Benevolent Fund had been received, amounting to £270. A vote of thanks was accorded to the donors.

A paper by Messrs. H. A. Humphrey and D. M. Buist, Members, and J. W. Bansall, Associate Member, entitled " The Steam and Electric Power Plant of Imperial Chemical Industries, Ltd., at Billingham " (see page 1233), was read and discussed.

The meeting terminated at 7.55 p.m. with a vote of thanks to the authors, which was moved by the President and carried with acclamation.

802ND ORDINARY MEETING, 20TH MARCH, 1930.

Col. Sir Thomas F. Purves, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 13th March, 1930, were taken as read and were confirmed and signed.

A paper by Mr. Bernard Leggett, M.R.C.S., L.R.C.P., Associate Member, entitled "The Medical and Surgical Applications of Electricity," was read and discussed.

The meeting terminated at 7.55 p.m. with a vote of thanks to the author, which was moved by the President and carried with acclamation.

803RD ORDINARY MEETING, 27TH MARCH, 1930.

Mr. P. V. Hunter, C.B.E., Vice-President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 20th March, 1930, were taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

A paper by Mr. H. H. Harrison, Member, entitled "Developments in Machine Telegraph Systems and Methods of Operation" (see page 1369), was read and discussed.

The meeting terminated at 8 p.m. with a vote of thanks to the author, which was moved by the Chairman and carried with acclamation.

804TH ORDINARY MEETING, 10TH APRIL, 1930.

Col. Sir Thomas F. Purves, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 27th March, 1930, were taken as read and were confirmed and signed.

Messrs. R. S. Herbert and W. C. Kennett were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the President reported that the members whose names appeared on the lists had been duly elected and transferred.

The President announced that, during the month of March, 334 donations and subscriptions to the Benevolent Fund had been received, amounting to £170. A vote of thanks was accorded to the donors.

A paper by Messrs. S. W. Melsom, Member, A. N. Arman, B.Sc., and W. Bibby, B.Sc., Associate Members, entitled "Surge Investigations on Overhead Lines and Cable Systems" (see page 1476), was read and discussed.

The meeting terminated at 8 p.m. with a vote of thanks to the authors, which was moved by the President and carried with acclamation.

805TH ORDINARY MEETING, 1ST MAY, 1930.

Col. Sir Thomas F. Purves, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 10th April, 1930, were taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

Messrs. D. J. Bolton, R. S. H. Boulding, O.B.E., and H. W. Gregory were appointed scrutineers for the ballot for the election of new members of Council.

The President announced that, during the month of April, 193 donations and subscriptions to the Benevolent Fund had been received, amounting to £102. A vote of thanks was accorded to the donors.

The President then presented the Faraday Medal for 1930 to Sir Ernest Rutherford, O.M., F.R.S.

Mr. R. H. Fowler, F.R.S., then delivered the Twenty-First Kelvin Lecture entitled "Some Recent Advances in the Electron Theory of Metals" (see page 1469).

A vote of thanks to the Lecturer, moved by Dr. W. H. Eccles, F.R.S., and seconded by Lieut.-Col. K. Edgcumbe, T.D., R.E.T.(Ret.), was carried with acclamation.

The meeting terminated at 7.30 p.m.

58TH ANNUAL GENERAL MEETING, 15TH MAY, 1930.

Col. Sir Thomas F. Purves, O.B.E., President, took the chair at 6 p.m.

The notice convening the meeting was taken as read. The minutes of the Ordinary Meeting held on the 1st May, 1930, were also taken as read and were confirmed and signed.

Messrs. G. R. Shepherd and H. C. Wilkinson were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the President reported that the members whose names appeared on the list (see page 1088) had been duly elected and transferred.

The Premiums (see page 795) which had been awarded by the Council for papers during the session were announced.

The President then summarized the Annual Report of the Council (see page 751) and moved its adoption.

Mr. J. O. Girdlestone seconded the motion.

Mr. F. W. Purse: I have one point of criticism. It is in regard to the membership, which is dealt with on the tenth page (see page 760) of the Report. We started the year with 1 959 full members, during the year we increased the total membership by 639, and we now have a membership of 14 200; and yet the deaths and resignations among the full members just balance the additions to that class. I cannot imagine an Institution of this character and size which during a period of 12 months cannot effectively increase its full membership. I think it must be due to lack of interest on the part of members who can transfer, and of others who are eligible and do not come forward, that we have not 2 000 full members. I raise the point in the hope that the technical Press will emphasize it and call attention to the fact that there are men who are not doing their best for the Institution and the profession.

The President: It is certainly a very important point. The present state of affairs is due entirely to the fact that proposals are not coming forward for full membership. I think it will be a good thing to turn over in our minds how we can best increase the number of full members, who, after all, are the most important section of the Institution.

Mr. W. C. P. Tapper: May I suggest that the Institution should keep a record of those who want copies of the Annual Report. We could register our names on a list, and copies would be sent to those who desire them. Then we shall have an opportunity of reading the Report before we get to the meeting and may be able to make useful suggestions.

The President: I would point out that in the notice convening the meeting, which was sent out on the 13th March, it is clearly stated that copies of the Report and Accounts can be obtained from the Secretary before the meeting. Nevertheless, I think that the suggestion of a list of members who desire to have copies of the Report is quite a practicable one. I will look into that with the Secretary and see if we can arrange machinery of that kind.

The resolution was then put to the meeting and carried unanimously.

Captain J. M. Donaldson: I should explain that I am speaking in place of the Hon. Treasurer who is undergoing medical treatment in Switzerland, and we are very glad to know that he is rapidly recovering and expects to be with us in August. I have to move "That the Statement of Accounts and Balance Sheet for the year ended 31st December, 1929, as presented be received and adopted." These Accounts you have in front of you, and I might also refer you to a very useful summary on the ninth page (see page 759) of the Report, which gives some of the vital points in considerable detail. Turning first of all to the Revenue Account, you will see on the left-hand side that the expenditure was some £34 356, as against £31 277 last year; in other words, we have spent a little over £3 000 more than we did last year. On the other hand, the income has increased by £1 689, which means, of course, that the surplus is a little less than last year. As a matter of fact, the surplus this year is £5 242, as against £6 041 in the preceding year. With regard to the increase of a little over £3 000 in expenditure, I would draw your attention to certain items which might be considered exceptional. One is an amount of £1 245 for the redecoration of this room. That, of course, will not happen again for many years. I think you will agree that the money was well spent. You will then see an item, "Structural Alterations £958 10s. 0d." That is, in the main, the cost of putting into use some rooms in the basement which were much needed. The other increases are not very great and are balanced by savings on some items. There is an increase of £620 in cost of management, which, of course, is natural with the increasing membership. More money has been spent on meetings because there have been more meetings. You will notice that the publication of the *Journal* actually cost £47 less than last year, although the volume was of larger size than in the preceding year. The explanation is that more money has been derived from advertisements. £144 has been saved on the rates of the building owing to the de-rating legislation. Travelling and legal expenses are less. The item of "interest on mortgage debt" now disappears because it has been cleared off. Another exceptional item of expenditure is on a bust of Faraday, which cost £37 and will not occur a second time. Another curious and interesting feature is that the cost of the Annual Dinner is £26 less than last year. On the Income side, we have about £1 250 more in subscriptions and £821 more in dividends and interest; there is a small falling off of about £100 in entrance fees. Publications show an increase of £59 and examination fees of £29, while there is a little drop in the subscriptions to *Science Abstracts*. On the other hand, of course, the item of £349 for the revenue from the Tothill Street property disappears; we have got rid of that property and I think that we have got out of it quite well. The Balance Sheet discloses a satisfactory state of things. You will notice how the Institution building and lease are dealt with. We paid for the building and lease some £73 000; I think that the lease has some 50 years to run; at the end of that period we shall have put by in the Depreciation Account £73 000, so that that asset will remain intact. We have transferred amounts from the Income and Expenditure Account to the General Fund and the Reserve Fund, and we have made further investments during the year, because we save, on an average, about £7 000 a year. The total of the securities held amounts to £97 000. That, of course, is the price at which they were purchased; their market value on 2nd May was £96 089; in other words, the depreciation is barely 1 per cent, which is not a serious matter. Taking the broad view of the situation, we have total assets of £186 343. The actual liabilities are £10 200, which is arrived at by adding up the second and the three following items on page 764; so that in point of fact we have a surplus of £176 143, which is about £8 000 better than the position last year. Those figures, I think, show that the prosperity of the Institution continues to be well maintained and that we are in a very strong financial position.

Mr. J. Harcourt Williams seconded the motion, which, there being no discussion, was put to the meeting by the President and unanimously carried.

Mr. T. E. Herbert: I have the honour to propose "That the best thanks of the Institution be accorded to the following officers for their valuable services during the past year: (*a*) the Hon. Secretaries of the Local Centres; (*b*) the Local Hon. Secretaries abroad; and (*c*) the Hon. Treasurer, Mr. E. Leete."

Mr. W. C. P. Tapper seconded the motion, which was carried unanimously.

Mr. S. Harcombe then moved "That Messrs. Allen, Attfield and Co. be appointed auditors for the year 1930-31." The motion was seconded by **Mr. Alan Williams** and was carried unanimously.

The meeting terminated at 6.30 p.m.

INSTITUTION NOTES.

Scholarships.

The following scholarships have been awarded for 1930–1931:—

Ferranti Scholarship (*Annual Value* £250; *tenable for* 2 *years*).

E. Wilkinson (Liverpool University).

Duddell Scholarship (*Annual Value* £150; *tenable for* 3 *years*).

T. R. Stretton (Cardiff Technical College).

David Hughes Scholarship (*Value* £100; *tenable for* 1 *year*).

H. A. Wainwright (Sheffield University).

Salomons Scholarship (*Value* £100; *tenable for* 1 *year*).

E. Bell (Armstrong College, Newcastle-on-Tyne).

War Thanksgiving Education and Research Fund (*No.* 1).

Grants of £50 each to:—

F. J. Clark (East London College).
Miss W. Hackett (Birmingham University).

Thorrowgood Scholarship (*Annual Value* £25; *tenable for* 2 *years*).

J. F. H. Tyler (Southern Railway Company).

Page Prize.

The above Prize for the session 1929–30 has been awarded to Mr. G. T. Winch for his thesis entitled "A Direct-Reading Photo-electric Photometer for the Commercial Measurement of Incandescent Electric Lamps" (see page 533).

Discussion on "Electric Lighting Fixtures and Modern Lighting."

A meeting of the Design and Industries Association will be held in the Institution Lecture Theatre on Tuesday, 25th November, at 8 p.m. (light refreshments 7.30 p.m.), when there will be a discussion on the above subject. The discussion will be opened by Mr. R. D. Best and Mr. Raymond McGrath.

Members of the Institution are cordially invited to the meeting and to take part in the discussion.

Model General Conditions for Contracts.

The Council desire again to call the attention of members to the work that has been done by the Institution in preparing and publishing model general conditions applicable to various classes of contracts.

In the past, a certain amount of friction and confusion has existed over general conditions of contract, buyers or consulting engineers using conditions which obviously put the contractor in a position where he was subject to disabilities which were hardly equitable; and, on the other hand, contractors putting forward conditions which relieved them of responsibilities which the purchaser had a right to expect them to assume.

It was for this reason that several years ago a committee was appointed by the Council, which included consulting engineers, manufacturers, contractors, representatives of municipal and company supply undertakings, etc., and, as a result, the document "Model Form of General Conditions, A (Home—With Erection)" was produced.

These conditions were intended for use in connection with central station contracts, and proved so useful that further sets of conditions have since been produced, applicable to specific classes of transactions (see list below).

In view of the large amount of work involved in producing these "Conditions," and the general agreement between all interests which they represent, the Council desire to call attention to the fact that they are "*recommended* by the Institution of Electrical Engineers," and to urge members of the Institution to make use of them as far as possible in their work, and to bring them to the attention of those who are outside the Institution membership.

List.

		Price (post free)
A.	Model Form of General Conditions (Home—With Erection)	2s. 2d.
B1.	Model Form of General Conditions (Export Delivery F.O.B.)	1s. 0d.
B2.	Model Form of General Conditions (Export, Including Complete Erection or Supervision of Erection)	1s. 0d.
C.	Model Form of General Conditions: Goods other than Cables (Home—Without Erection)	6d.
D.	Model Form of General Conditions: Cables (Home—Without Erection)	6d.
E.	Model Form of General Conditions: Cables (Home—With Erection)	(In preparation)

Copies can be obtained from the Institution or from Messrs. E. and F. N. Spon, Ltd., 57 Haymarket, London, S.W.

The Benevolent Fund.

An appeal for subscriptions, donations and legacies to the Benevolent Fund will be found on the last page of the cover of this issue of the *Journal.*

Discussions at Meetings.

The Council wish again to remind members that the remarks of speakers at the meetings should not be read from manuscript, the view being held that the presentation of remarks in this manner is contrary to the true spirit of a "discussion" and that contributions in manuscript should more appropriately be sent to the Secretary for publication in the *Journal* as "communicated remarks."

OBITUARY NOTICES.

GILBERT ARCHER was born in London on the 13th August, 1867, his father, Thomas Archer, being a well-known writer and an original member of the Savage Club. He was educated at Cowper Street School and studied electrical engineering at Finsbury Technical College under the late Prof. Silvanus Thompson. After a period of practical training with the Hammond Electricity Co., Brighton, he took up his first appointment in 1888, with the Brighton supply undertaking, when Mr. Arthur Wright was in control. In 1894 he went to Dublin as senior assistant to Mr. Mark Ruddle, of the Dublin Corporation Electricity Department, becoming chief assistant two years later. At that time the Dublin generating station was in Fleet Street, and the supply was single phase at 2 000 volts with house transformers and Callender bitumen cables. Ten years later, the late Mr. Robert Hammond installed the then new 3-phase 4-wire system of distribution and erected the generating station at Pigeon House Fort. Mr. Archer had a very extensive knowledge of 3-phase working in all its aspects, and more particularly on the distribution side. In 1918 he became deputy city electrical engineer of Dublin, a position which he held until his death. He was a tireless worker and was more a father than a chief to the members of his staff, by whom he was held in great affection and esteem. He was a man of many interests, and in a busy life found time for a vast amount of social and philanthropic work. The taking-over of the Dublin electricity undertaking in 1929 by the Free State Electricity Supply Board involved him in work which proved too much for his health, and he died in his office with tragic suddenness on the 13th December, 1929. A widow and two sons survive him. He was elected a Member of the Institution in 1927.

L. J. K.

THOMAS BAXENDALE died on the 6th December, 1929, in his 52nd year, after a comparatively short illness. He received his early education at the Bolton Church Institute, and later attended evening classes in engineering at the Technical Schools of Bolton and Manchester. The greater part of his career was spent in the service of the Manchester Corporation Electricity Department. He was appointed charge engineer at Stuart Street power station in 1902, in which year the supply of high-tension alternating current was inaugurated in Manchester. He became assistant resident and constructional engineer in 1913, and resident engineer in 1919. When Barton power station was laid down in 1923, he was transferred there, and, as resident engineer, he was in control during the difficult early years of the running of new plant which created a record for high thermal efficiency previously unattained in this country. In 1927 he became superintendent of power stations, a position he was destined to hold for but a short period before he became affected by heart trouble, which eventually brought about his death. A capable engineer, his disposition was kindly, and he was held in esteem and affection by his colleagues. In his humour there was often a vein of mild sarcasm, which, however, contained no barb and was largely discounted by an unfailing geniality. He was elected an Associate Member of the Institution in 1906 and a Member in 1922. He was also a member of the Committee of the North-Western Centre.

W. H. S.

SYDNEY WILLIAM BAYNES, a pioneer of the electrical industry, died on the 6th February, 1930, at the age of 69. His mechanical training was obtained as an apprentice to the late Mr. A. P. Lundberg, whom he followed into the service of Messrs. Crompton in 1878. While yet a mere boy, he showed such aptitude and keenness that his firm put him in charge of arc-lighting systems when these were first installed, and he had in most cases to teach the workmen the use of their plant. The charge of portable arc-lighting equipment took him into all parts of the kingdom and abroad, and on the recommendation of the head of the firm he took charge of similar plant at the Forth Bridge works. He was actually in charge for Messrs. Crompton when Swan's lamps were used in public for the first time at the Glasgow Exhibition in 1880. In 1888 he was appointed electrical engineer to the Bradford Corporation, the first municipal electricity undertaking in Great Britain, and in 1895 he entered the service of the Metropolitan Borough of St. Pancras, the first municipal electricity undertaking in London, as chief electrical engineer. He immediately set to work to double the pressure of supply, and in 1896 he was the first engineer to declare a 440-volt, 3-wire direct-current distribution with 220 volts to the middle wire. He was also one of the first supply engineers to foresee the immense possibilities of a cheap supply of electricity for manufacturing purposes. In 1903 he again led the way with a scheme for a 3-phase, 5 000-volt, 50-cycle alternating-current transmission to substations in remote parts of the area of supply, and in 1905 he was one of the first to adopt Parsons turbines to replace reciprocating engines. In 1912 he persuaded members of the Electricity Committee of the Borough Council to accompany him on a visit to Stockholm in order to investigate the Ljungström turbine, which was then being introduced to the electrical world. The first Brush-Ljungström turbine set (1 500 kW) made in England was installed in the St. Pancras power station. He was early interested in pulverized fuel, and St. Pancras was one of the first municipal undertakings to adopt this system of firing. Owing to ill health he retired from the service in December 1927, the Borough Council accepting his resignation with regret and placing on record their recognition and appreciation of the distinguished services he had rendered to the borough in connection with the development of the Council's electricity undertaking during his 32 years' service. Unfortunately his health remained indifferent, and he was unable in the remaining years of his life to secure the enjoyment that his strenuous efforts to cheapen the production of electrical energy had earned for him. He joined the Institution as an Associate in 1889, and became a Member in 1891.

J. T. B.

CHARLES ALBERT BLASCHECK was born in London on the 19th April, 1874, and died at Canterbury on the 26th November, 1929. In 1892, after two years as a pupil in the mechanical workshops of Messrs. Klein, Nuremberg, he entered the Frankfort works of Messrs. Schuckert and Co., leaving the following year to take up a course of training in electrical engineering at the Royal Technical College of Hanover. He left the College in 1895, and returned to England as an assistant with Messrs. Nicholson and Tyler. In 1896 he was engaged as an improver by the St. James and Pall Mall Electric Light Co., and from 1897 to 1899 he was assistant engineer in charge of a regular shift with the same company. From 1899 to 1902 he was chief assistant with the Norwich Electricity Co., and in 1902 he was appointed chief engineer of the Canterbury Corporation Electricity Works, a position which he held until his sudden death after an operation. His work and personality were greatly appreciated throughout his career. He was devoted to his work and will be missed by a wide circle of friends. He was elected an Associate Member of the Institution in 1902 and a Member in 1912.

A. D. B.

SEBASTIAN ZIANI DE FERRANTI, D.Sc., F.R.S., was born at Liverpool on the 9th April, 1864, and died at Zurich on the 13th January, 1930. He was educated at St. Augustine's College, Ramsgate, and for a short time he attended evening classes at University College, London, but his scientific knowledge was a matter of self-education, by reading books, by studying what others had done and by making his own experiments. His scientific bent was shown early in life; before he went to school he had constructed a battery and produced an arc light, and when he was at Ramsgate in 1878 at the age of 14 he constructed a dynamo. After he left college he had some small experience on the staff of Siemens Brothers and Co., but in 1882 he started in business for himself with Alfred Thomson and F. Ince as his partners, the latter being a solicitor by profession. This combination was formed to exploit the "Ferranti dynamo," a machine with flat coils having no iron in their cores, these being mounted on a hub and revolving between the poles of a ring of electromagnets. The magnets were relatively more powerful than those of its progenitor, the Siemens flat-coil alternator; the revolving coils were fixed to the supporting hub by a highly efficient mechanical method, and the disc thus formed was dynamically stiffened by its rotation. It achieved an instant success, having an output for its size greatly in advance of that of existing machines, but legislation had shut out all possibility of financing public supply undertakings, and other business was limited. Thus the new partnership was not successful, and after a period Ferranti started in business independently, being financed by Mr. Francis Ince. He turned his attention to the metering of electricity, and it was this that brought him in contact with the Grosvenor Gallery Electric Supply Corporation formed by Sir Coutts Lindsay and others to supply the Grosvenor Gallery and neighbourhood with electric light, using overhead mains. Ferranti had seen the Gaulard and Gibbs series transformer system which was at work at the Grosvenor Gallery installation, and he had also seen the Zipernowski transformers which were worked in parallel. He had made small transformers of a greatly improved mechanical construction, and had used them across constant-potential mains; thus when he learned of the trouble then being experienced with the regulation of the lamp pressure on the Gaulard-Gibbs system he was able to convince the directors of the Grosvenor Gallery of the superior advantages of his own system—comprising dynamo, transformer and meter—and at the age of 22 he was appointed engineer to the company. The success of the system which he installed decided the directors to put in hand the electrification of London, for which purpose Ferranti proposed to use the marine type of engine, which was known to work economically for long periods without stoppage. As it was then believed that alternators could not be run in parallel, units of 10 000 h.p. were decided upon, plans for a great central station at Deptford were completed, and construction was commenced. But meantime (1888) Parliament had revised the Electric Lighting Acts, and applications for provisional orders were made by various groups. The Board of Trade allotted so small an area to the Deptford undertaking that the construction of these large sets was stopped and smaller sets were installed. The plans for this central station were at the time entirely novel and opposed to all the existing ideas of other engineers, who sought to put the generating station as near the centre of the area to be supplied as possible. Ferranti conceived and put into operation the main principles on which all modern generation of electricity by steam power is based, viz. large generating stations near to ample supplies of cooling water, with facilities for bringing coal and removing ashes by water transport. Transmission to the point to be supplied was by means of high-pressure alternating current and transformers using high-pressure cables with impregnated paper insulation. After the completion and putting into operation of this generating station, Ferranti returned to electrical manufacturing, producing transformers, meters, rectifiers for arc-lamp lighting, oil breaker switches or fuses, and finally direct-driven steam generator sets. His modifications of the marine type of engine in which he endeavoured to improve the steam distribution by using slide valves moved by cams instead of eccentrics was not successful. Ferranti joined the Institution as a Member in 1891, and in the early days took part in the discussions at the meetings fairly frequently. He became a Member of Council in 1895 and President in 1910 and 1911. He was elected an Honorary Member in 1925. His presidential address was a new starting point for the electrical industry. He urged the universal application of electricity for all services.

Lighting, heating, motive power on every scale and for every purpose—whether domestic, factory or transport—was all to be electrical. He stressed the possibility of cheap supply under these conditions. From that date onwards, interrupted only by the War period, he pressed this ideal, and his reasoned argument, his enthusiasm in the propaganda, and the practical example which he set in his own home and elsewhere have been great factors in the remarkable expansion of the use of electricity since the War. His last appearance at the Institution was on the 19th December, 1929, less than a month before his death, when he opened the discussion* on Mr. T. G. N. Haldane's paper on an electrical heat pump. He will always be remembered in electrical work for these two great achievements, the production and transmission of electrical energy at high pressure and its distribution at low pressure, and the universal use of electricity for all purposes. Ferranti's activities were not confined to electrical work, for from 1895 onwards he worked on the gas turbine. He started his work with a patent for a combination of turbine, compressors and regenerators, working on the Carnot cycle, that is adiabatic compression and expansion—heat being taken in and given out by the working fluid (gas or steam) at constant pressure. He gradually realized, however, that this cycle—though theoretically the most efficient—leads to a small output from a given size of machine, and in 1902 he took out a patent for working on an isothermal expansion cycle, heat being supplied at stages during the expansion by the use of superheaters. This procedure has become standard practice in steam turbine work. Further, he developed the idea of abstracting some of the steam at successive stages for the purpose of raising the temperatures of the feed water to the temperature of the boiler, realizing that steam so abstracted after it had done some work was really operating at 100 per cent efficiency. This procedure again has passed into general practice. These studies and experimental work were preliminaries, so to speak, to work on the gas turbine, but enabled a great increase in efficiency to be realized, some particulars of which he gave in his presidential address already referred to, and also at the World Power Conference in 1924. He was eventually able to realize his project of burning gas at high pressure and temperature and expanding it through nozzles until it was cool enough to come in contact with the blades of the turbine, being still nearly red hot. But this cycle of operations calls for compression of the fuel gas and the air for combustion to the operating pressure, and even if liquid fuel is used the air has still to be compressed. The power required to do this, even with the most efficient types of pump, absorbs so large a part of the output of the turbine that the machine as a whole becomes uneconomic. From 1906 to 1930 Ferranti was occupied with the problem of increasing the speed of production and the quality of spun textile yarns. The process of twisting threads which had already been combed parallel was originally carried out by hand with the aid of a spinning wheel. It had been mechanized in two types, discontinuous spinning, that is a certain length at a time, by Hargreaves and Crompton, and the continuous process by Arkwright. The latter process enabled high speeds to be aimed at, but the limit had been reached due to unbalanced revolving parts, centrifugal forces acting on the thread as it was spun round at the bobbin, and irregular speeds owing to slipping of the bobbin driving bands. With his great power of analysis of a problem, and his equally great synthetic power—enabling him to integrate a new process leading from the same beginning to the same end—Ferranti removed the obstacles and greatly increased the speed of production, obtaining at the same time superior qualities of spun or twisted yarn. These experiments were still being carried out at the date of his death, and time only will show whether his new technique of this mechanical operation is a complete solution. Ferranti's retiring nature and modesty as to his own work were responsible for the slow recognition, except in specialist circles, of what he had done. He received the honorary degree of Doctor of Science of the University of Manchester in 1911; in 1924 he received the Faraday Medal of the Institution; and in 1927 he was elected a Fellow of the Royal Society. Ferranti married in 1888 Gertrude Ruth, second daughter of the late Mr. Francis Ince, whom he first met in 1882 at her father's house in Hampstead. He had three sons and four daughters. LL. B. A.

MICHAEL BIRT FIELD was born in London in May 1874, and died as the result of a street accident in February, 1930. He was educated at Highgate Grammar School and at Finsbury Technical College, where he studied under the late Professors Silvanus Thompson and John Perry, becoming personal assistant to the latter. In 1893 he entered the workshops of Messrs. Johnson and Phillips, and then joined Prof. Gisbert Kapp as assistant in 1894. The following year he went to Messrs. Brown, Boveri and Co., Baden, for whom he worked for three years in Switzerland and also in Spain. He joined the British Thomson-Houston Co. in London in 1898, but in 1900 went to Glasgow, where he was appointed chief electrical engineer to the Corporation Tramways and took charge of the newly-installed electrified system. During this period he read several papers before the Institution and was awarded a premium for one on "The Testing of Tramway Motors," which is a standard work on the subject. In 1903 he was appointed chief engineer to Messrs. Ferranti, of Hollinwood, where, after a visit to the United States for the purpose of studying American developments, he organized a switchgear department and prepared for the firm a catalogue on switchgear which was, in effect, an original and illuminating treatise on the subject. In 1911 he returned to Glasgow, being appointed chief engineer and general manager, and, afterwards, managing director to Messrs. Kelvin, Bottomley and Baird, the makers of Lord Kelvin's instruments. During the War period this firm was engaged in highly specialized work for the Admiralty, and Mr. Field was largely occupied in pioneer work on the design and construction of modern submarine periscopes. His attention had long been concentrated on navigational instruments, and in 1919 he delivered a lecture before the Institution on "The Navigational Magnetic Compass considered as an Instrument of Precision," which was awarded the Institution Premium. In the following year he contributed a paper on "Multiple-Unit Shunts for the Measurement of Very Heavy Currents" which was also awarded a Premium. Latterly his interests were concerned with aerial and marine navigational instruments, and before his death he was chiefly engaged on problems relating to acoustic depth-sounding. He was a man of outstanding ability as an engineer, a scientist, and a mathematician, and his untimely death is a very real loss to the profession and industry of engineering. He was elected an Associate of the Institution in 1894 and a Member in 1901.

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* See page 676.

W. W. L.

ALFRED ERNEST GREEN, who died on the 1st September, 1930, was born in 1872 and was educated at Oliver's Mathematical College, Portsmouth. He entered the naval service as an engineering cadet in 1887, and was trained at the Royal Naval Engineering College, Keyham, Devonport. After two years' service at sea he resigned his commission in the Royal Navy, and accepted the position of engineering instructor to the Chinese Navy. This appointment, which at first entailed looking into the progress of certain armament contracts that the Chinese Government had placed in this country, did not last very long. He was then for some time at the Maxim Nordenfelt Works, Erith, Kent, and afterwards on the staff of the British Thomson-Houston Co. In 1898 he became chief draughtsman in the late Sir James Clifton Robinson's offices at Stockton-on-Tees and Chiswick, London, but resigned in 1899 to join the staff of Messrs. Dick Kerr and Co., Preston, as chief engineer of the electrical erecting staff. Here he was responsible for the equipment of electric tramcars and electric rolling stock, for the installation of heavy generating machinery for power houses, etc., and for electric equipment for industrial purposes generally. When the company became merged in the English Electric Co. he retained his original position. He was elected a Member of the Institution in 1912.

J. C.

JOHN PUGH GREGORY, manager of the contract department of the British Thomson-Houston Co., died at Rugby on the 6th August, 1930. Born at Carnarvon in 1876, he was educated privately and at the High School, Oswestry. After serving an apprenticeship with Messrs. De Winton and Co., marine and general engineers, of Carnarvon, he left their works in 1896 to take up a position in the drawing office of Messrs. Ferranti, where he was for two years engaged upon work in connection with the steam side of electrical engineering. He subsequently studied at the Central Technical College, London. In 1899 he joined the testing department of the General Electric Co. of Schenectady, and later became one of their assistant engineers on power and mining work. After a year in America he was transferred to the London office of the company, resigning his position in 1901 to become assistant to the managing engineer at the British Thomson-Houston Co.'s new Rugby works. Shortly afterwards he was appointed manager of the power and lighting engineering department of the company, which ultimately became the present contract department. His duties brought him into contact with large numbers of electrical engineers all over Great Britain, many of whom became his personal friends. The British Electrical and Allied Manufacturers' Association owes much to his initiative and he was an active member of several of its committees. He was elected an Associate of the Institution in 1889 and became a Member in 1908.

FEARNSIDE IRVINE was born at Arbroath in 1856. He was educated at Glasgow University and received his early engineering training with Messrs. Alexander Shanks and Son, at Arbroath, Messrs. J. and G. Thomson, and Messrs. P. and W. McLellan, at Glasgow. His first appointments were those of assistant engineer to the Eastern Extension and Maintenance Cable Co., at Singapore, and assistant inspector of machinery for the Indian Government. Later, he acted as assistant engineer at Calcutta Water Works, engineer to the Cape Government Railways and Southern Mahratta Railways, and engineer to the African Gold Recovery Co., for whom he designed and equipped the first cyanide gold-recovery plant in the Transvaal. His appointment as engineer and manager at Johannesburg of several gold-mining companies, including the New Modderfontein Gold Mining Co., brought him the responsible task of equipping the Heriot, Henry Nourse, City and Suburban, Robinson, Paarl Central, Gold Reef, and New Modderfontein gold mines. From 1910 to 1913 he was engaged in re-equipping the Prestea Block A gold mines, Gold Coast Colony, the work including the design and installation of a complete modern power-station plant. He will be best remembered for his 30 years' association with the Capetown Tramways, Port Elizabeth Electric Tramways, and Lisbon Electric Tramways, for which systems he held the position of consulting engineer in London up to the time of his death on the 2nd November, 1929. He was elected a Member of the Institution in 1896.

ADMIRAL OF THE FLEET SIR HENRY BRADWARDINE JACKSON, R.N., G.C.B., K.C.V.O., F.R.S., was born at Barnsley in 1855. He served in the Zulu War in 1878 and was appointed to the torpedo school on the "Vernon" in 1879. Later his interest became concentrated upon the development of naval signalling. It is on record that in 1891 he urged the trial of Hertzian waves for short-range signalling; it is known that in 1895, when in command of the torpedo-school ship "Defiance," he successfully transmitted signals several hundred yards by reflector apparatus like that of Hertz, but with a Bose type of coherer at the receiving end and a tapper for causing decoherence after the receipt of each morse signal. Sir Oliver Lodge, by means of similar apparatus, had transmitted and received morse signals the preceding year but had made no attempt at application. Sir Henry Jackson was probably the first to make practical use of Hertzian waves, and he was certainly the father of marine wireless communication. In 1899 he assumed command of the "Vulcan" and in November 1901 reported to the Admiralty that by careful tuning he had established communication between two points in the Mediterranean separated by 134 miles. He had developed in 1900–01 a transmitter of his own design, in which a tuned primary circuit was coupled to a tuned aerial circuit by both condenser coupling and mutual inductance. The aerial was not earthed directly, but indirectly through the coupling condenser—a desirable arrangement on a ship. This transmitter operated on 600 m and 240 m; the inductances and condensers were carefully calculated with the aid of formulæ, and the capacities of typical forms of antenna were measured by laboratory methods. The fruits of a long series of measurements of the range of wireless stations over water and over various kinds of land formation and under miscellaneous atmospheric conditions were given in May, 1902, to the Royal Society, soon after he had gained the Fellowship. Until 1905 he was responsible for the whole development of naval signalling, and official equipment made excellent progress during his period of office. In 1905 he was appointed Third Sea Lord and Controller, and gradually lost touch with practical radio-telegraphy. At the beginning of the War he was appointed to the War Staff at the Admiralty and in May, 1915, became First Sea Lord. At the end of 1916 he left the Admiralty and was made an Admiral of the Fleet. In 1920 he resumed his active participation in wireless by accepting the Chairmanship of the Radio Research Board. In 1924 he acted as Chairman of the Transatlantic Telephony Committee. His success in these important offices was largely due to his receptiveness for new ideas. This modernity was strikingly shown by the way he followed up the amateur short-wave movement from 1922 onwards. He died on the 14th December, 1929. In his work for wireless he was conspicuous for his unselfish, far-seeing, scientific efficiency and his avoidance of controversies about priority. He was elected an Associate of the Institution in 1883 and a Member in 1902. W. H. E.

WALTER JUDD was born in October, 1852, and died at Bracknell, Berkshire, on the 20th February, 1930. He entered the service of the Eastern Extension Australasia and China Telegraph Co. in July, 1870, being rapidly promoted to the position of local manager in 1874. He served in this capacity at all the principal stations of the company, including Singapore, Shanghai, Hong-Kong and Penang, and in 1886 he was appointed manager in the Far East. In April, 1897, he became assistant electrician-in-chief in London to the Eastern Telegraph Co. and its associated group of companies, succeeding Mr. H. A. C. Saunders as electrician-in-chief in January, 1905, upon the latter's retirement. Mr. Judd's association with the electrical department of the associated companies signalized the beginning of reorganization and development of improved methods of working, and to his marked ability, untiring energy, and devotion to the companies' interests great advances were due. The primitive methods which survived from earlier days were soon modified in accordance with the more up-to-date principles upon which the present system has developed. The use of more delicate and intricate apparatus, for the design of which he was responsible, permitted the great increase in traffic to be carried. A vast amount of research in the manufacture and balancing of cables was also necessary in order that full advantage might be taken of the benefits accruing from the improved apparatus. The combined results of the investigations carried out under his direction laid the foundation for the present-day methods of working, which have practically revolutionized the art of cable and submarine telegraphy, and with which his name will always be associated. During the War a great strain was thrown upon Mr. Judd and the technical department of the companies, by the necessity for maintaining the all-important cable communications, and for assisting the Government by meeting their many requirements for urgent strategic connections in all parts of the world. With the declaration of the Armistice Mr. Judd intimated his retirement, which took effect in March, 1919, after he had completed 49 years of cable service. He possessed a strong personality, which imbued his staff with confidence and a desire to emulate their leader. He became an Associate of the Institution in 1875, and a Member in 1877. He served on the Council for many years between 1905 and 1919, including a period of office as Vice-President from 1912 to 1915. J. C. B.

JOHN WILLIAM LIEB died at New Rochelle, New York, on the 1st November, 1929, at the age of 69. Born in 1860, he received his early training in electrical engineering at the Stevens Institute of Technology, New Jersey. In 1881 he joined the staff of the Edison Electric Light Co. of New York as a draughtsman, and was soon afterwards engaged in experimental work under Mr. Thomas Edison. In the following year he was appointed chief electrician of the company, and in 1883 chief engineer and technical director of the Italian Edison Co., Milan. He returned to New York in 1893 as a vice-president and general manager of the Edison Electric Illuminating Co. and a vice-president and associate general manager of the newly-formed New York Edison Co., eventually becoming general manager of the latter. In 1928, after 25 years' tenure of these positions, he retired from active service and became senior vice-president of the companies. He was elected a Member of the Institution in 1911, and was also a past-president of the American Institute of Electrical Engineers.

Sir BENJAMIN LONGBOTTOM died at his home at Totteridge on the 1st May, 1930, in his 54th year. Educated at Heath Grammar School, he received his training in electrical engineering at Ilkley College, and was an articled pupil with Messrs. Andrews and Preece, Ltd., Bradford, from 1892 to 1895. He was subsequently with the Phœnix Dynamo Co., Bradford, as an improver, and in May, 1898, he became superintendent engineer in charge of outside power work for the General Electric Co., Manchester. During his last 15 months with the firm he was assistant works manager. At the age of 24 he became general manager and engineer of Electromotors, Ltd. (now Laurence, Scott and Electromotors, Ltd.), a company which owed much of its subsequent success to his organizing ability. Under his leadership the firm began to manufacture in bulk a complete range of component parts suitable for d.c. motors of from $\frac{1}{2}$ to 20 h.p.; this was an entire departure from standard practice and enabled new machines to be assembled and delivered to order within a short and definite period of time. The immediate success of this policy was a tribute to his energy and foresight, and the long-continued prosperity of the firm bears witness to his consistent enthusiasm for good work. During the War he rendered valuable service to the Electrical Advisory Committee appointed by the Ministry of Munitions, and the Electrical Trades Committee. For some years he was a member of the Council of the British Electrical and Allied Manufacturers' Association, being chairman of that body from 1922 to 1925. During this period the Association organized one of the most successful exhibits in the Wembley Exhibition. His keen interest in public affairs found an outlet in the activity which he displayed on the board of the Manchester Chamber of Commerce. He was knighted in 1925. While still remaining manager of Electromotors, Ltd., he was also vice-chairman of Richard Johnson, Clapham and Morris, Ltd., and a director of Lo-Thermo Patents, Ltd. He was chairman of the executive committee of the World Power Conference. His death, occurring soon after that of Dr. S. Z. de Ferranti, was another severe loss to the industry as well as to a wide circle of friends to whom he had endeared himself by his genial and generous nature. He joined the Institution as an Associate Member in 1904, became a Member in 1909 and served on the Council from 1924 to 1927. C. R.

COLONEL EDWARD DONALD MALCOLM, C.B., R.E., one of the two surviving original members of the Society of Telegraph Engineers, now the Institution of Electrical Engineers, died in March, 1930, in his 93rd year. Born in 1837, he entered the Royal Academy, Woolwich, at the age of 14 and left to join the Royal Engineers in 1854. Returning to England after a distinguished military career, during the course of which he served in the Crimean War and took part in the suppression of the Indian Mutiny, he was appointed Inspector of Submarine Mining Defences at the War Office. He later took up the position of Officer Commanding the Royal Engineers on the staff in Scotland. On leaving the Army he became Commissioner Engineer in regard to piers and harbours in the crofting districts of the Highlands, for several years administering the Highlands and Islands Act of 1891. He was one of the three Commissioners appointed to rectify the boundaries of the counties and parishes in Scotland, a piece of work which owed much of its success to his tact, ingenuity, and intimate knowledge of local conditions. M. M.

ROLAND MARSHALL, who died on the 12th June, 1929, at the age of 56, received his early training at the Finsbury Technical College. He was for four years a pupil in the works of Messrs. Siemens Brothers, and was subsequently employed by them for many years as an engineer in charge of submarine cable laying and maintenance work, and also in carrying out contracts in connection with the laying of cables and the installation of plant for various electricity supply undertakings, including those at Londonderry, Hull and Ayr. He was also largely responsible for the erection of the overhead and station equipment for the Blackburn Corporation Tramways. He was then for three years chief assistant engineer at the Ayr Corporation Electricity Works, becoming chief engineer and manager in 1903. During his 23 years' service with the Corporation he was responsible for important additions to the generating plant and extensions of the mains. He was in recent years actively concerned in the project for harnessing the water power of Loch Doon in connection with the Ayr electricity supply. Outside his profession his main interests lay in music, golf and fishing. His qualities of head and heart endeared him to all with whom he came in contact. He joined the Institution as an Associate in 1898, and was elected an Associate Member in 1902 and a Member in 1909.

WILLIAM HENRY MAYSTON was born in 1885, and died in London on the 15th February, 1930. He was educated at the Brighton Grammar School and the Brighton Technical College. In 1899 he entered the service of the Eastern Telegraph Co. as a probationer, and in the course of the usual training at the company's school showed special aptitude for the technical and electrical side. He was subsequently appointed to the electrical staff at Porthcurnow, and thereafter served in this branch of the service from the rank of junior to the responsible position of senior electrician at the company's main line stations in the Mediterranean, Red Sea, on the east coast of Africa, in South Africa, and at Rodriguez and Seychelles, with intermittent periods in the electrical department at the company's head office in London. He was elected an Associate Member of the Institution in 1908 and a Member in 1921. J. C. B.

FRANCIS JOHN MUDFORD was born at Tiverton, Devonshire, in 1857, and died on the 13th November, 1929. He had a natural aptitude for the study and practical application of physical science, and from his school at Tiverton, where at one time he taught this subject, he gained a scholarship at the Royal College of Science, South Kensington. This was about the time when the telephone, the dynamo, and the incandescent lamp were invented, and when the Institution of Electrical Engineers was the Society of Telegraph Engineers. He turned his attention to electrical engineering, and after leaving the College became technical adviser to Messrs. Paterson and Cooper, one of the pioneer firms of the industry. Here he took part in the manufacture of the first (Gower Bell) telephones for the Post Office, and of the first ammeter, when this instrument for the direct measurement of current had been invented by Ayrton and Perry. Later, when in business on his own account, his exceptionally wide knowledge led him to undertake a variety of electrical work, much of it experimental, and at this he was generally successful and always happy. He treasured his contacts with Lord Kelvin, Professors Ayrton, Perry, Guthrie and Silvanus Thompson, and with his closer friend, S. A. Varley. He joined the Institution as an Associate in 1881 and became a Member in 1891. W. T.

GEORGE ARMSTRONG PEARSON, who died on the 20th October, 1929, was born in 1874 and was educated at Great Yarmouth College, the School of Electrical Engineering, Hanover Square, and the Finsbury Technical College. After two years' practical work, first with Messrs. Crompton and subsequently with the

British Insulated Wire Co., he became a charge engineer in the service of Messrs. Hartley and Co., Bradford. In 1897 he joined Messrs. Pearson and Co., of Bath, but after four years—during two of which he conducted evening classes in electrical engineering at the Bath Technical School—he decided to devote the whole of his time to lecturing and his practice as a consulting engineer. He became head of the department of electrical engineering at Bolton Technical Institute in 1901, and later occupied similar positions successively at Hull, Loughborough and Halifax Technical Colleges. His sportsmanship and genial sense of humour made him popular with his students and his colleagues. He was elected an Associate of the Institution in 1896, an Associate Member in 1899, and a Member in 1913. A. H. L.

PERCIVAL JOHN PRINGLE died in Switzerland on the 10th June, 1930, in his 60th year, while returning from Australia to England on a business visit. Born in 1870, after a short course of electrical training at the School of Electrical Engineering in Hanover Square he became a pupil of Messrs. Dubs and Co., Glasgow, and was subsequently engaged in research work with Prof. G. Forbes. In 1890 he joined the staff of Messrs. Drake and Gorham and was rapidly promoted to the position of manager of their Birmingham works. Later, in the service of the Brush Electrical Engineering Co., he was in charge of the erection of the Wandsworth central station and of extension plants for the Sheffield, Huddersfield, Leicester, and Watford undertakings. As a resident engineer in the employ of Messrs. Kincaid, Waller, Manville and Dawson he supervised the whole of the power scheme of the Midland Electric Power Corporation. He designed and patented the Pringle and Kent surface contact system of electric traction. In 1903 he took up the position of electrical engineer and tramways manager to the Burton-on-Trent Corporation. He resigned this position in 1911 to go to Australia as general manager and chief engineer of the Electric Supply Co. of Victoria, Ltd. As arbitrator in connection with tramway labour disputes he figured prominently in Australian public affairs. He was elected an Associate of the Institution in 1895, an Associate Member in 1899, and a Member in 1902.

ANDREW FREDERICK ROCK died at Rhos-on-Sea on the 29th March, 1930, at the age of 70. In 1872 he became a telegraph clerk in the employ of the North Staffordshire Railway Co. at Stoke-on-Trent, and after four years' service he was appointed an inspector in charge of the construction and maintenance of telegraph systems. He obtained a knowledge of the theoretical side of electrical engineering by attending technical classes in his spare time at Hanley and Stoke. In 1886 he took up the position of chief assistant to the late Mr. John Neale, whom he succeeded as electrical engineer and telegraph superintendent of the company in 1902. From that year until his retirement in 1924 he was in charge of the whole of the electrical equipment of the North Staffordshire Railway. During his period of service the personnel of his department increased from 40 to about 300, and the line also became the North Staffordshire Section, London, Midland and Scottish Railway. He was for eight years honorary secretary to the Railway Electrical and Telegraph Engineers Conference, and was also a member of the Council of the Institution of Railway Signal Engineers. He joined the Institution of Electrical Engineers as an Associate Member in 1902, and became a Member in 1908.

GUIDO SEMENZA was born in London on the 19th December, 1868, and died at Milan on the 7th November, 1929. He went to Italy at an early age and in 1893 graduated as an engineer from the Polytechnic High School of Milan, gaining an electrical engineering diploma at the Montefiore Electrotechnical Institute at Liége a year later. He devised and put into operation the first hydro-electric plant at Paderno for the Italian Edison Co. of Milan, this work being carried out shortly after the famous experimental three-phase transmission between Lauffen and Frankfort in 1891, and the first large-scale transmission system between Tivoli and Rome in 1892. Power was transmitted from the Paderno station at 13 600 volts, three-phase, and as no machinery which could work at such a pressure was then available, Semenza had himself to design suitable equipment. This pioneer work made his name famous in the electrical world, and his advice on similar problems of power supply was sought both in Italy and abroad. He also made a special study of electric communication and traction problems, and the Italian Government and many public and private bodies obtained the advantage of his experience. In addition to his engineering abilities he was a man of deep scientific insight and was also keenly interested in philosophy and music. He published many papers on important electrical engineering problems, and in 1924 he delivered the 15th Kelvin Lecture before the Institution, taking as his subject Kelvin's Conductor Law and its adaptation to the problems of the generation and distribution of electrical energy. As president of the Italian Electrotechnical Association he did much to extend its influence and to link it up with similar associations in other countries. From 1923 to 1927 he was president of the International Electrotechnical Commission, and during this period presided over the New York and Bellagio General Meetings of the Commission. In 1929 he was awarded the Faraday Medal of the Institution, and the same year he was the recipient of a presentation from the Italian Electrotechnical Association. Owing to failing health the last years of his life were devoted to literary rather than to scientific work. His death means to the electrical world the loss of a far-seeing pioneer and powerful driving force, and to Italy the passing of one of her most devoted citizens. He was elected a Foreign Member of the Institution in 1900, became a Member in 1903, and was for many years Local Hon. Secretary for Italy. L. L.

LIEUT.-COLONEL ALEXANDER SINCLAIR, T.D., was born at Aberdeen in 1861, and died at Swansea on the 18th February, 1930. He was educated privately and abroad, and he studied mechanical and electrical engineering in London. Under Messrs. Siemens Brothers of Charlton he took part in the manufacture and laying (in the " Faraday ") of the Mackay-Bennett cable to America, and he also served with Messrs. Goolden and

Trotter, of London. In 1885 he was appointed works manager to Messrs. Vivian and Sons, Swansea, from which position he retired in 1925. At these works he organized a complete and successful plant for the manufacture of copper shell bands. In 1897 he was elected a Councillor to the Swansea Corporation and was a member of the Council continuously up to the time of his death. During his 32 years on the Council he was twice elected an Alderman and was Mayor of the Borough for the year 1919–20. He was also a Justice of the Peace for the County Borough of Swansea. Whilst he rendered valuable service by his membership of several other important committees of the Corporation, it was as Chairman of the Electricity Committee over a period of 26 years that he served most admirably the interests of the town of Swansea, for during this time he played a great part in the development of the electricity undertaking. During the War period he was a member, and for a time Chairman, of the Local Tribunal; he was also Chairman of the Local Food Committee, and of the Road Transport Board for the West Glamorgan Area. He served on the District Joint Board for the Electricity Supply Industry in the South Wales and Monmouthshire area and was Chairman of that body for several years. He was for a considerable period a member of the Council of the Incorporated Municipal Electrical Association. In 1885 he joined the 1st Glamorgan Rifle Volunteers as a Lieutenant, and was later Second and temporarily in Command. When this regiment was disbanded in 1904 he transferred to the 3rd Glamorgan Rifle Volunteers, and after some years as Second-in-Command he retired in 1912, owing to ill health, with the rank of Major and Honorary Lieut.-Colonel. He was elected a Member of the Institution in 1887. J. W. B.

DANE SINCLAIR, one of the rapidly diminishing band of British telephone pioneers, died on the 6th May, 1930, at the age of 78. He was born in Caithness on the 6th June, 1852, and joined the telegraph department of the North British Railway in 1872. In 1875 he was selected to go to Japan in the capacity of inspector of telegraphs for the Japanese Government. On his return to this country, after four years in Japan, he was for a time in charge of the telegraph department of the Dundee and Arbroath Joint Railway, and in 1882 he became engineer to the National Telephone Co., in the Glasgow district. This period of his career was marked by a number of inventions connected with telephony. When the three principal telephone companies were amalgamated, forming the new National Telephone Co., he furnished the directors with a report on the system. His report formed the basis of an entire reorganization, and he was appointed London manager. In June, 1892, he became engineer-in-chief of the National Telephone Co., which position he continued to hold until 1902. He was the first British telephone engineer to apply automatic switching mechanism to public telephone service. This was carried out at Coatbridge, where an automatic switchboard of his own invention linked up a small number of subscribers to a distant main exchange over a single-junction circuit. An example of this switchboard is deposited in the Institution Museum. In 1902 he severed his connection with the National Telephone Co. at the invitation of the directors of the (then) British Insulated and Helsby Cables, Ltd., to become general manager of that company. He later became a director and, finally, chairman of the company, which expanded rapidly under his guidance. When the Automatic Telephone Manufacturing Co., Ltd., was formed in 1911 he was appointed managing director, a position which he held in addition to that of general manager of British Insulated and Helsby Cables, Ltd. He was also a director of the Associated Telephone and Telegraph Co., the International Automatic Telephone Co., the Midland Electric Corporation for Power Distribution, Ltd., Enfield Cable Works, Ltd., and the Electric Supply Company of Victoria, Ltd. He was a man of sterling character and, in spite of his heavy business cares, took a benevolent interest in the welfare of the large staffs which he controlled. His leisure hours were devoted to contemplative reading, his tastes being those of the literary student. He joined the Institution as an Associate in 1883, became a Member in 1893 and served on the Council from 1896 to 1898. H. H. H.

JAMES WILLIAM SPEIGHT died at Ormskirk on the 26th May, 1930, in his 65th year. In 1889 he joined the Bradford Corporation Electricity Department, remaining on the staff until 1896, when he was appointed outside superintendent in the Blackpool Corporation Electricity Department, later becoming deputy borough electrical and tramway engineer. In 1902 he entered into partnership as a consulting electrical engineer with Mr. Quin in London, and during a period of four years he laid down electric tramway systems at Dundee, Broughty Ferry, and Shipley (Yorks). He also supervised the erection of the electricity works at West Bromwich and was concerned with the Ilkley and Great Harwood undertakings. From 1906 to 1914 he lived at St. Annes, being largely responsible during that period for the Bispham-Norbreck electricity scheme for the Bispham Urban District Council. He was managing director and consulting engineer to the Penrith Electric Supply Co. from its formation in 1908 until his death, and held similar positions with the Ormskirk undertaking from 1912 until his retirement from the company in 1929, when the Lancashire Electric Power Co. purchased a controlling interest in its shares. He joined the Institution as an Associate in 1896 and became a Member in 1898. J. H. H.

ALAN ARCHIBALD CAMPBELL SWINTON, F.R.S., was born on the 18th October, 1863, and died on the 19th February, 1930. His death means a heavy loss to scientific research, for he carried out numerous valuable investigations, particularly in connection with X-rays and radio communication. He was the third son of Archibald Campbell Swinton, of Kimmerghame, Berwickshire, a professor of civil law in the University of Edinburgh from 1842 to 1862. Even in childhood Mr. Alan Campbell Swinton showed an interest in engineering, as is evidenced by an oil painting of him at the age of nine with a steam-engine in his hand which was exhibited at the Royal Scottish Academy Exhibition in 1872. At his first school—Cargilfield, Edinburgh—he was allowed to cultivate his scientific talent. He became a practised photographer, and gave exhibitions with a magic lantern for the entertainment of his schoolfellows. His dislike of games and the humdrum methods adopted in the teaching of the classics made life distasteful to him at Fettes College, the public school which he entered in 1878. He found a solace there, however, in his work in the carpenter's shop. In 1879, some two years after the invention of the telephone, he read an account of the instrument written by Prof. Dolbear. Although he was only fifteen, within a short time he had constructed an efficient pair of telephones unaided, a task which would have presented some difficulty even to a trained scientific worker. After two years at Fettes he was sent abroad for a short period. He studied mathematics and French at Havre, and was greatly delighted by the collection of electrical apparatus which he saw at the Paris Exhibition in 1881. Returning to England, he was in the following year apprenticed to Messrs. W. G. Armstrong, Mitchell and Co. at their Elswick works. Here he took part in the work of equipping a battleship with electric gun-firing control. At the close of his period of apprenticeship in 1887 he became an electrical contractor and consulting engineer in London. He had previously published a book, "The Principles and Practice of Electric Lighting," and his work now included the installation of electric light in many large town and country houses. His connection with X-rays began in January, 1896, when—inspired by a newspaper account of Prof. W. K. Röntgen's discovery—he employed a Crookes tube to obtain the first X-ray shadow photograph ever produced in this country, a photograph of the bones in his own hand. With Sir Charles Parsons he heated a diamond in a vacuum by means of cathode rays. The diamond was converted into coke at a temperature of 1890° C., at the same time undergoing a considerable increase in size. From 1904 onwards he devoted his entire attention to consulting work and became particularly interested in radio engineering. He introduced the Marchese Marconi to Sir William Preece on the occasion of the first visit of the former to this country, and radio telegraphy made rapid strides shortly afterwards. In 1924 Mr. Campbell Swinton became a member of the Broadcasting Board. He was a director of the Parsons Marine Steam Turbine Co., Ltd., and was connected with the development of the Parsons turbine and the first turbine-driven boat, the "Turbinia." He was also a director of Crompton, Parkinson, Ltd., of W. T. Henley's Telegraph Works, Ltd., and of Ricardo and Co., Worthing. In 1915 he was elected a Fellow of the Royal Society, and twice served on the council of that body. He was one of the managers of the Royal Institution for the period 1912–15, and had been president both of the Röntgen Society and the Radio Society of Great Britain. For periods of varying length he had been a member of the general board and of the executive committee of the National Physical Laboratory, and vice-president and chairman of the council of the Royal Society of Arts. Throughout his life he was a great believer in self-education, and he considered the passing of advanced examinations to be a waste of time. In his opinion his own success was due to the cultivation of scientific friends, and attendance at lectures such as those delivered at the Royal Institution and the Royal Society of Arts. At his home (he was unmarried) he showed great hospitality, delighting to entertain his guests with demonstrations of the most recent achievements in radio communication and with a collection of photographs which he had taken of eminent scientists. He joined the Institution as an Associate in 1886, was elected a Member in 1890 and was a Vice-President during the years 1921–25. A. R.

[This notice is largely based on one which appeared in the issue of *Nature* dated 8th March, 1930.]

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(P) indicates a reference to the title or subject of a paper or address.

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(D) indicates a reference to a discussion upon a paper of which the title is quoted.

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